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Methane Risk Analysis for Sustainable Occupational Safety in Underground Coal Mines

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Abstract

This study introduces a comprehensive methane gas risk analysis model applied for underground coal mines to assess explosion risks and promote sustainable occupational safety practices. The model calculates the methane risk score (%MRS) on a percentage scale, integrating three critical parameters: methane concentration (%C), ventilation performance (%V), and coal gas emission capacity (%G). A 30-day field study conducted in Turkey's Soma region revealed %MRS values ranging from 15% to 38%, with the highest risks observed on days with elevated methane concentrations (0.66%), reduced ventilation performance (79.41%), and high gas emission capacity (20.38%). These findings validate the model's capability to provide practical and reliable evaluations of combined risk factors. The modular structure of the model allows for recalibration to assess other hazards, such as dust explosions or roof collapses, and preliminary evaluations demonstrate its adaptability to regions with varying geological conditions and ventilation configurations. By offering a scalable and user-friendly approach, the model supports occupational safety professionals in implementing proactive measures, contributing to the sustainability of mining operations.

Keywords:
sustainable mining; methane; risk analysis; coal mining

1. Introduction

In coal mining, methane gas is a crucial factor that must be monitored and managed to ensure occupational health and safety (**Kissell, 2006**). Naturally present in coal seams, methane gas can combine with air at certain concentrations to create an explosive atmosphere (**Karacan et al., 2011; Su et al., 2005**). This risk poses serious threats to both miners and the mining environment, leading to potential fatalities, operational disruptions, and environmental damage (**Dursun, 2020; IPCC, 2014**). Additionally, methane-related incidents complicate rescue operations, creating further risks (**Zipf et al., 2007**). Therefore, effective monitoring and control of methane gas are fundamental to achieving sustainable occupational safety (**Srivastava, 2015**). The concept of sustainable occupational safety aims to manage natural resources in a way that prioritizes safety, minimizes risks through analysis, and maximizes societal benefits (**Azapagic, 2004**). Methane gas risk analysis directly influences the sustainability of mining operations. Explosions, equipment damage, and environmental harm resulting from methane incidents adversely affect economic sustainability (**Pradeep et al., 2016**). Furthermore, the release of methane and other hazardous gases after explosions conflicts with environmental sustainability goals (**Kholod et al., 2020**). Effective management of methane gas and prevention of explosion risks form the foundation of sustainable mining practices (**Hilson & Murck, 2000**). Consequently, implementing methane drainage before production and using the extracted gas for energy generation are measures that enhance safety and boost economic efficiency. Utilizing methane as an energy source reduces greenhouse gas emissions while generating additional revenue for mining operations (**Karakurt et al., 2011**). These practices contribute to the mining sector's sustainability goals, supporting the reduction of environmental impact and diversifying energy sources (**Bibler et al., 1998**). International climate change policies and greenhouse gas reduction targets have made methane management a priority in the mining sector. Effective methane management contributes to efforts to mitigate global warming, allowing the mining sector to meet its environmental responsibilities (**Liu et al., 2021**). Methane gas risk analysis is essential for ensuring miner safety and implementing sustainable mining practices. Advanced monitoring systems, risk analy-

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sis, and evaluation models, as well as the enforcement of safety standards, support occupational safety while promoting environmental and economic sustainability (**Shi et al., 2017**). In this context, effective management of methane gas risk analysis is closely tied to sustainable mining and constitutes a strategic priority for the future of the mining industry.

In recent years, methane gas risk analysis has become a significant area of research concerning safety and sustainability in underground coal mines. Various approaches have been proposed in the literature to analyze the risks associated with methane gas. **Kumar & Gupta (2021)** and **Fidalgo-Valverde et al. (2024)** examined the physical and chemical properties of methane gas and assessed its environmental and health risks, highlighting that effective methane management reduces explosion risk and contributes to sustainable mining goals. Researchers such as **Shi et al. (2017)**, **Cheng et al. (2016)**, and **Wang et al. (2019)** developed models to quantitatively assess explosion risks by considering factors such as methane concentration, ventilation conditions, and potential ignition sources. Notably, the model proposed by **Shi et al. (2017)** enables more reliable explosion risk prediction in underground mines by incorporating critical parameters like ventilation. Hybrid models, including Fuzzy Logic and Bayesian Networks, are also widely used in methane gas risk analysis. **Li et al. (2020)** proposed a model based on Fuzzy AHP and Bayesian Networks, contributing significantly to the weighting and probabilistic modelling of risk factors. This hybrid approach improves the reliability of risk analysis by accounting for uncertainties and expert opinions. Human factors and unsafe behaviours are also recognized as critical risk elements. **Meng et al. (2019)** emphasized the importance of improving safety culture and implementing training programs to reduce human-related risks in underground coal mines. Similarly, **Tyuleneva et al. (2021)** advocated for a proactive risk management system to mitigate explosion risks. Overall, the literature reveals the development of various models for methane gas risk analysis in coal mines. Quantitative and qualitative analyses, expert-based methods, artificial intelligence, and advanced modelling techniques are commonly employed, reflecting the complexity and multidimensional nature of methane gas risk. Effective risk assessment requires a comprehensive approach that includes technical factors as well as human and environmental considerations. Developing and implementing these models is crucial for enhancing miner safety and ensuring the sustainability of mining operations.

Underground coal mines face significant threats from methane gas explosions, posing risks to worker safety and environmental sustainability. This study presents a quantitative risk analysis model designed to evaluate methane risk based on three key parameters: methane concentration, ventilation performance, and coal gas emission capacity. Unlike existing models in the literature, which are often complex and less practical for field application, this approach offers a simple yet reliable tool for risk assessment. The development and application of the model aim not only to mitigate explosion risks but also to support the sustainable management of mining operations.

2. Methodology

The methodology begins with a comprehensive identification of occupational safety hazards associated with methane gas. Within this framework, parameters such as methane gas concentration, ventilation system efficiency, and coal gas emission capacity are considered fundamental risk factors. Defining these risk factors is essential for developing a realistic risk assessment model tailored to underground coal mines.

This model integrates these key variables to calculate the methane gas risk analysis level. Additionally, it serves as a predictive occupational safety management model capable of assessing both current and potential future risks. The primary objective of this model is to provide a simple and practical risk analysis tool that can be readily understood and used daily by occupational safety professionals and mine managers. The study is grounded in an extensive literature review focused on determining the critical risk parameters associated with methane gas risk analysis in coal mines. By analyzing past mining accidents, safety analyses, and industry best practices, critical parameters such as methane gas concentration, ventilation performance, and coal gas emission capacity were identified. The selection of these parameters ensures that the risk analysis is scientifically sound, reliable, and adaptable to real-world mining conditions.

2.1. Methane Gas Concentration (%C) Parameter

Methane gas concentration (%C) is one of the most critical parameters for determining the risk level of methane explosion hazards in underground coal mines. Methane gas, released from coal seams following excavation, can mix with air at certain concentrations to create an explosive atmosphere. Therefore, effective monitoring and control of methane concentrations, before reaching hazardous thresholds, is crucial for ensuring the safety of mining operations (**Kursunoglu, 2024**). According to mining regulations in Turkey, specific safety measures must be implemented when methane concentrations exceed certain threshold values. The Occupational Health and Safety Regulation for Mining Workplaces mandates that, in areas where methane levels exceed 1%, the use of explosive materials is prohibited. When methane concentration reaches 1.5%, electrical equipment must be shut down, and if methane exceeds 2%, evacuation of personnel is required, with only emergency and rescue operations permitted in these conditions (**Resmi Gazete, 2013**).

Table 1: Methane Gas Concentration and Risk Levels

Level	Methane Concentration (%)	Description	Reference
1	0.00 - 0.30	Safe level, normal working conditions	**Resmî Gazete, 2013 Kirchgessner et al., 1993**
2	0.31 - 1.00	Low risk, monitoring frequency should be increased	**Diamond, 1993**
3	1.01 - 1.50	Medium risk, preventive measures needed, use of explosives prohibited	**Brodny &Tutak, 2016** **Bibler et al., 1998**
4	1.51 - 2.00	High risk, electrical equipment shut-off, work halted	**Kholod et al., 2020**
5	>2.00	Very high risk, work prohibited, only emergency and rescue operations allowed	**Resmî Gazete, 2013** **Diamond, 1993**

In this study, methane risk analyses were conducted by examining methane properties, industry standards, underground coal mine conditions, existing projects, relevant literature, and regulatory guidelines. The risk levels associated with methane gas concentration and corresponding preventive measures are presented in **Table 1**. These levels were defined based on comprehensive literature reviews and regulatory guidelines to ensure reliability and alignment with international standards.

As shown in **Table 1**, the risk of explosion increases with rising methane concentration. Concentrations above 1% are considered critical thresholds in terms of mine safety, necessitating special safety measures at these levels. A methane concentration of 4% represents the lower explosive limit (LEL) for methane, beyond which an explosive atmosphere is formed, posing an immediate ignition or explosion hazard. This 4% value is widely recognized as a reference point in mining safety practices, enhancing the model's alignment with international standards.

The relationship between explosion risk and methane concentration is not linear; rather, as concentration increases, the risk rises rapidly. This indicates that once methane concentration surpasses a certain level, the explosion risk escalates sharply. Therefore, using a nonlinear function to model the impact of methane concentration on risk score is deemed more appropriate. To mathematically express the relationship between methane concentration and explosion risk, the following **Equation 1** was developed:

$$Risk_C = \ln \ln\left(1+\frac{C}{L}\right) \tag{1}$$

where:

$Risk_C$: Risk score associated with methane gas concentration.

C: Percentage concentration of methane gas.

L: Lower explosive limit of methane (4%).

ln: Natural logarithm function.

Equation 1, which models the impact of methane concentration on explosion risk using a nonlinear structure, enables the risk score to rise more sharply as concentration increases. This approach captures the exponential relationship between methane concentration and explosion risk, providing a more accurate risk model. The natural logarithmic function allows risk to increase more gradually at low methane concentrations, while permitting a rapid increase at higher concentrations.

To validate this relationship, **Equation 1** was analyzed across a range of methane concentrations (0–11.5%). The results confirm that at concentrations below the lower explosive limit (L=4%), the risk score increases gradually, reflecting the reduced hazard level. At higher concentrations (C > L), the risk escalates rapidly, capturing the significant explosion risk associated with methane accumulation. This behaviour aligns with the physical and chemical properties of methane and its explosive dynamics (**Brodny & Tutak, 2016**).

Additionally, concentrations exceeding the lower explosive limit have the potential to form explosive mixtures, as documented in regulatory and safety guidelines. Normalizing methane concentration with respect to the L value and using a logarithmic function provides a more realistic risk assessment framework for practical applications (**Nisbet et al., 2020**). This ensures that even lower levels of methane accumulation are effectively accounted for, emphasizing the model's robustness and applicability to real-world mining conditions.

The model has been designed in alignment with both national regulations and international standards. Threshold values outlined in Turkey's Occupational Health and Safety Regulation for Mining Workplaces and by the International Labour Organization (ILO) were considered during the calibration of this risk analysis model (**Altinoz & Ozmen, 2015**). This approach ensures that the model provides a scientifically grounded and legally compliant risk assessment system.

2.2. *Ventilation Performance (%V) Parameter*

Ventilation performance (%V) is one of the most critical parameters directly influencing methane explosion risk in underground coal mines. An effective ventilation system mitigates the accumulation of methane and other hazardous gases, significantly reducing explosion risk (**Tutak et al., 2020**). Inadequate ventilation, however, can cause methane concentrations to reach dangerous

Table 2: Ventilation Performance and Risk Levels

Level	Ventilation Performance (%)	Description	Reference
1	90 - 100	Good performance, normal working conditions	**McPherson, 1993; Belle, 2014**
2	80 - 89	Acceptable performance, increased monitoring needed	**Su et al., 2008**
3	70 - 79	Moderate performance, improvements necessary	**Kurnia et al., 2016**
4	60 - 69	Low performance, urgent intervention required	**Karakurt et al., 2011**
5	<60	Very low performance, work halted, ventilation system revision needed	**Setiawan et al., 2017**

levels rapidly, substantially increasing explosion risk (**Li et al., 2023**). In Turkey, the "Occupational Health and Safety Regulation for Mining Workplaces" mandates the establishment and safe operation of effective and sufficient ventilation systems in all mines (**Resmi Gazete, 2013**). This regulation requires regular monitoring, measurements, and necessary improvements to ventilation systems. When ventilation is insufficient or airflow is entirely halted, work must immediately cease until safe conditions are restored.

To assess the impact of ventilation performance on explosion risk, performance levels and their associated risk descriptions were defined. These levels, presented in **Table 2**, reflect a structured approach to evaluating ventilation efficiency. For instance, Level 1 (90–100%) signifies good performance, as indicated by **Belle (2014)** and **Karakurt et al. (2011)**, ensuring normal working conditions. Level 2 (80–89%) marks acceptable performance, requiring increased monitoring, aligned with **McPherson (1993)**. Levels 3 to 5 progressively represent worsening conditions, with Level 3 (70–79%) highlighting moderate performance where improvements are necessary, supported by **Setiawan et al. (2017)** and **Su et al. (2008)**. Level 4 (60–69%) indicates low performance needing urgent intervention per **Kurnia et al. (2016)**. Finally, Level 5 (<60%) corresponds to very low performance where work must halt, consistent with **Resmî Gazete, (2013)**.

Equation 2 presents a nonlinear model that quantitatively expresses the relationship between ventilation performance and explosion risk. This equation allows the risk score to approach its minimum as ventilation performance nears the ideal level, while it nears the maximum as performance decreases. As ventilation performance can never fully reach 100% in mining due to airflow friction and losses, a baseline value of 0.05 has been added to reflect the reality that risk can never be fully eliminated. This baseline value accounts for residual risks inherent in mining operations, even under optimal conditions. Additionally, the coefficient 0.95 scales the sensitivity of the risk score to changes in ventilation performance, ensuring that reductions in performance lead to proportionate increases in the risk score. These parameters were calibrated based on expert feedback, historical data, and industry standards, ensuring robustness and reliability.

The corrected form of the **Equation 2** is as follows:

$$Risk_V = 0.05 + 0.95\left(1 - \frac{V}{V_{ideal}}\right) \tag{2}$$

where:

- Risk$_V$: Risk score associated with ventilation performance.
- V: Actual ventilation performance (in %).
- V$_{ideal}$: Ideal ventilation performance, defined as 100%.
- 0.05: A baseline value ensuring the risk score never reaches zero, reflecting the inherent risks of mining operations.
- 0.95: A scaling factor that adjusts the sensitivity of the model to changes in ventilation performance.

This equation mathematically expresses the inverse relationship between ventilation performance and explosion risk realistically. Although ideal ventilation performance is theoretically 100%, airflow friction and losses prevent it from being fully achieved in mines. Thus, **Equation 2** was developed to reflect that even if ventilation approaches ideal levels, the risk score does not reach zero, emphasizing that a minimal level of risk is always present.

Accepting that ventilation systems in mines can never be entirely risk-free, this modelling approach establishes a 4% lower limit for Risk$_V$ acknowledging the presence of low-level risk even at the minimum level. This lower limit prevents the Risk$_V$ score from reaching absolute zero, affirming the reality that, for safety purposes, some level of risk is inherent in mining environments.

This approach is grounded in scientific and engineering principles. **McPherson (1993)** highlighted that reduced ventilation performance contributes to methane accumulation, thus increasing explosion risk. **Kurnia et al. (2016)** further discussed the critical role of optimized ventilation performance in mitigating explosion risk. Establishing a 4% baseline for Risk$_V$ ensures that the model realistically reflects practical limitations and the ongoing presence of risk factors. Consequently, the model contributes to sustainable occupational safety assess-

Table 3: Coal Gas Emission Capacity and Risk Levels

Level	Coal Gas Emission Capacity (%)	Description	Reference
1	0 - 10	Low emission, standard ventilation sufficient for normal conditions	**Flores, 1998**
2	11 - 20	Moderate emission, increased monitoring, ventilation optimization required	**Palmer, 2010**
3	21 - 30	High emission, methane drainage systems necessary, ventilation performance improvement needed	**Talkington et al., 2014**
4	31 - 40	Very high emission, increased explosion risk, continuous monitoring, and urgent precautions necessary	**Wigley, 2011**
5	>40	Extreme emission, specialized safety measures and continuous gas monitoring required	**Wigley, 2011**

ment by acknowledging that even minimal ventilation performance retains some level of risk.

2.3. Coal Gas Emission Capacity (%G) Parameter

Coal gas emission capacity (%G) is a critical factor in determining methane explosion risk in underground coal mines. **Table 3** categorizes the risk levels based on coal gas emission capacity, supported by relevant literature. For Level 1 (0–10%), low emission levels allow standard ventilation to maintain safe working conditions, as stated by **Flores (1998)**. At Level 2 (11–20%), moderate emission levels necessitate increased monitoring and ventilation optimization, as highlighted in **Palmer (2010)**. When emissions increase to Level 3 (21–30%), high emission capacity requires the implementation of methane drainage systems and improvements in ventilation performance, as reported by **Talkington et al. (2014)**. At Level 4 (31–40%), very high emission levels demand continuous monitoring and urgent precautions to prevent catastrophic incidents, as discussed by **Wigley (2011)**. Finally, Level 5 (>40%) represents extreme emission levels that mandate specialized safety measures and continuous gas monitoring, also emphasized by **Wigley (2011)**.

As shown in **Table 3**, an increase in coal gas emission capacity significantly elevates explosion risk. In mines with high gas emission capacity, methane can accumulate more rapidly, increasing the likelihood of an explosion (**Lunarzewski, 1998**). The impact of coal gas emission capacity on explosion risk does not follow a linear trend; instead, risk rises steeply at higher emission capacities (**Noack, 1998**). In this study, a logarithmic function, shown in **Equation 3**, is employed to calculate the effect of coal gas emission capacity on risk score.

$$Risk_G = \log_{10} \log_{10}\left(1+\frac{G}{G_{\max}}\right) \tag{3}$$

where:

$Risk_G$: Risk score associated with coal gas emission capacity.

G: Coal gas emission capacity (in %).

G_{max}: Theoretical maximum gas emission capacity, assumed to be 50%.

Equation 3 defines the relationship between coal gas emission capacity and risk score through a logarithmic model. This function is chosen to prevent disproportionate increases in risk at high emission values, allowing for a more balanced rise in risk. Thus, even at extreme emission values, the risk score remains at a manageable level. The selection of a logarithmic function allows the risk score to increase in a meaningful way even at low gas emission capacities. Although emission capacity may be low, methane accumulation and explosion risk are never completely eliminated; thus, maintaining a meaningful risk score at lower emission levels is essential. Mathematically, the value of G ranges between 0 and G_{max} value normalizes gas emission capacity, ensuring consistent calculations and facilitating comparisons across different mines and operational conditions.

2.4. Calculation of Methane Risk Score

Methane explosion risk in underground coal mines is of utmost importance for occupational health and safety. In this study, three main parameters – methane gas concentration (%C), ventilation performance (%V), and coal gas emission capacity (%G) – were considered to quantitatively assess explosion risk. Risk scores developed for each parameter collectively provide an assessment of explosion likelihood. The calculation of explosion risk considers the sum of the risk scores associated with these parameters, as presented in **Equation 4**:

$$MRS = Risk_C + Risk_V + Risk_G \tag{4}$$

where:

MRS: Total risk score representing the likelihood of a methane explosion,

$Risk_C$: Risk score associated with methane gas concentration,

$Risk_V$: Risk score associated with ventilation performance,

$Risk_G$: Risk score associated with coal gas emission capacity.

To present the total risk score on a more interpretable scale, it is expressed as a percentage. This transformation is achieved by normalizing the total risk score against a predefined maximum value, as defined in **Equation 5**:

$$MRS(\%) = \left(\frac{MRS}{MRS_{\max}} \right) \times 100 \quad (5)$$

where:

MRS (%): Methane risk score as a percentage,

MRS: Calculated total risk score,

MRS_{max} = Maximum achievable total risk score.

In this study, the values for $RiskC_{max}$, $RiskV_{max}$ and $RiskG_{max}$ were determined to be 0.693, 0.43, and 0.301, respectively, resulting in an MRS_{max} value of 1.424. In this percentage transformation, the minimum risk score represents a value close to zero but not exactly zero, reflecting the practical impossibility of eliminating all risk. Therefore, the simplified formula shown in **Equation 6** enables the conversion of the risk score into a percentage, allowing the explosion likelihood to be expressed within a range from near 0% to 100%:

$$MRS(\%) = \left(\frac{MRS}{1.424} \right) \times 100 \quad (6)$$

This approach provides a standardized scale for expressing explosion risk, facilitating the comparison of risk levels across different mines. Additionally, the expression of risk scores as percentages allows occupational health and safety (OHS) professionals and managers on-site to quickly and effectively evaluate risk levels.

The methane risk analysis model is designed to accommodate extreme and unexpected values of the input parameters (methane concentration, ventilation performance, and coal gas emission capacity). For methane concentration levels exceeding 1%, the model incorporates an exponential increase in risk scores to reflect the heightened explosion hazard. Similarly, when ventilation performance drops below 50%, the risk scores sharply rise, aligning with industry practices and safety regulations that mandate immediate intervention. These responses are governed by the mathematical structure of the equations used for each parameter, which ensure that risk scores escalate proportionally to the severity of the conditions. Furthermore, the model is calibrated to provide meaningful outputs even at extreme values, avoiding unrealistic or unmanageable predictions. For instance, at methane concentrations above 2% or ventilation performance below 30%, the model reflects critical risk levels requiring emergency actions. This calibration process was informed by historical data, industry standards, and expert feedback, ensuring robustness and reliability in various operational scenarios.

Additionally, the model accounts for the interactions between methane concentration, ventilation performance, and coal gas emission capacity through its integrated risk calculation approach. Each parameter's individual effect on the risk score is mathematically modelled using nonlinear functions, ensuring that their unique contributions are accurately represented. The combined influence of these parameters is captured by summing their individual risk scores, providing a comprehensive assessment of explosion likelihood. To ensure that the model reflects real-world conditions, statistical correlation analyses were performed to evaluate the relationships between these parameters. For instance, higher methane concentrations are often observed in scenarios with poor ventilation performance, a trend that is incorporated into the model's structure. This approach ensures that the calculated methane risk score (%MRS) reflects both individual parameter effects and their combined impact, offering a holistic view of explosion risk in underground coal mines.

Furthermore, to ensure the accuracy of the developed methane risk analysis model, a systematic validation process was conducted. The model was tested over a 30-day period in an underground coal mine located in Soma, Turkey. Critical parameters, including methane gas concentration (%C), ventilation performance (%V), and coal gas emission capacity (%G), were continuously monitored using advanced detection and measurement technologies calibrated to international standards. Risk scores calculated by the model were compared with real-time field data to assess consistency and reliability. Feedback from occupational health and safety professionals and mining engineers working in the field further supported the model's applicability and accuracy. These evaluations confirmed that the model aligns well with observed risk patterns and accurately reflects the dynamic nature of methane-related hazards in underground coal mines. Future studies are planned to extend this validation process to mines in different geological and operational contexts, further enhancing the model's adaptability and reliability.

2.5. Case study: Soma Eynez region

The Soma region, located in western Turkey, is a prominent mining center with some of the largest lignite coal reserves in the country. This area was chosen as the focus of this study due to the history of severe mining incidents, most notably the 2014 disaster that resulted in the loss of 301 miners, highlighting the critical risks posed by methane gas explosions (**Yetkin et al., 2024**). The high methane emission capacity, complex geological structures, and inadequate ventilation systems in the region increase the importance of risk assessment models. Applying the developed risk assessment model to an underground coal mine in Soma not only serves to test the model's effectiveness but also aims to enhance safety measures in this high-risk area. The Eynez basin is known for its thick coal seams, necessitating meticulous examination of technical parameters for production. Since the 1960s, lignite production in the region primarily relied on open-pit mining; however, as near-surface reserves were depleted, underground mining gained

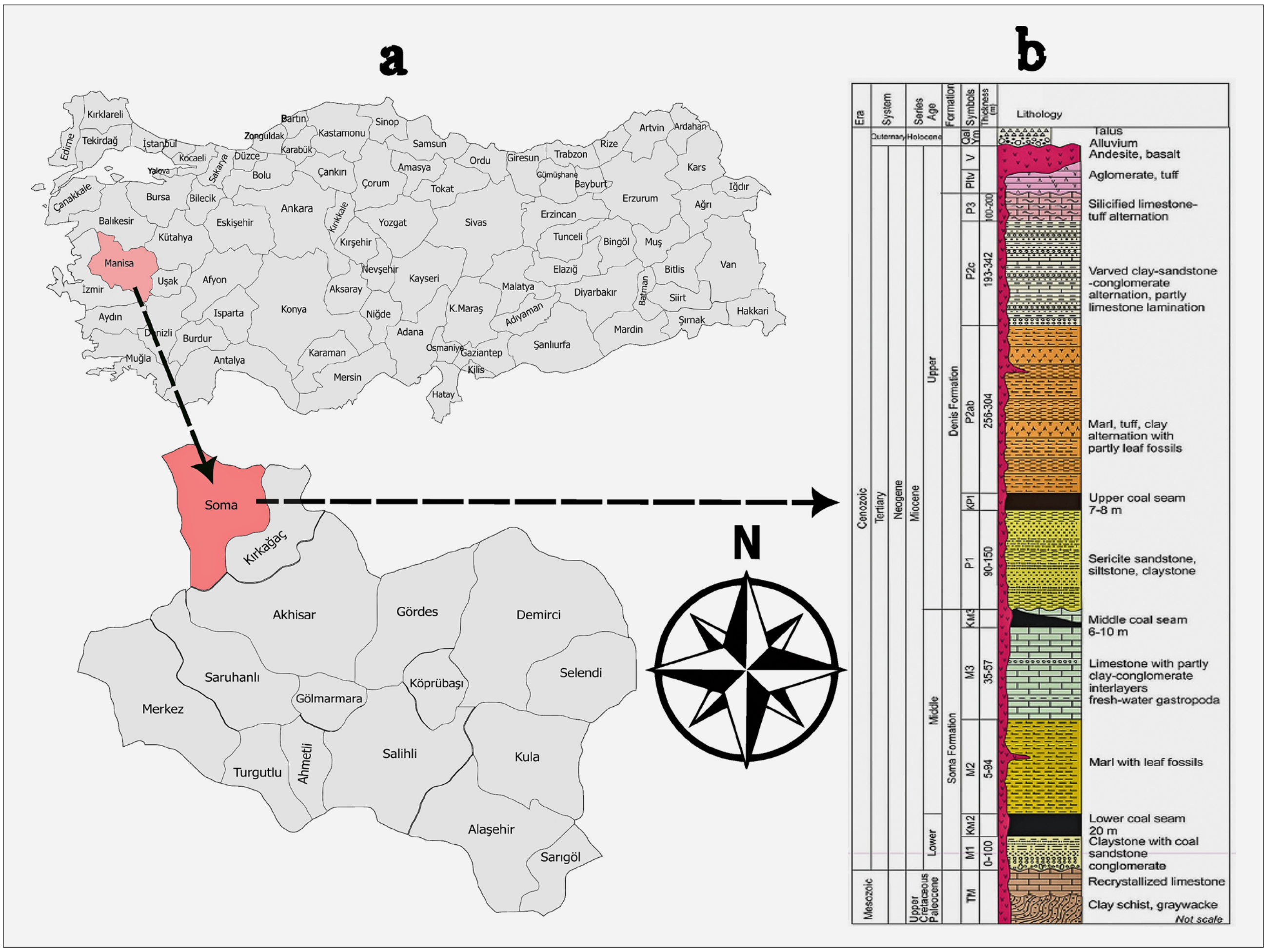

Figure 1: (a) Location and geological map of Soma and surroundings, (b) general stratigraphic columnar section of the study field (revised from (**Hokerek & Ozcelik, 2015**)).

prominence, as illustrated in **Figure 1a**. The thickness of the coal seams requires rigorous control of methane management and spontaneous combustion risk as production extends to greater depths. Understanding the geological characteristics of the site is essential for production planning and gas control. The foundational layer consists of Paleozoic-era fine-grained greywacke, overlaid by fractured Mesozoic-aged crystalline limestones. These are topped with Miocene-age conglomerates, sandstones, and claystones from the Cenozoic era. The marl layer, which serves as the roof rock for the coal seam, is approximately 80-130 meters thick, while the overlying lignite seam is about 30 meters thick. This geological formation is depicted in detail in **Figure 1b**.

In Soma's Eynez basin, coal production is conducted using the slice mining method with roof caving. Mechanized panels employ drum shearers, while traditional panels use drilling and blasting techniques for coal extraction. Roof caving, an essential part of the production process, is depicted in **Figure 2**. In longwall mining, clean air is directed underground, and contaminated air is channelled to the surface, ensuring non-intersecting airflow. Water is sprayed from drum shearers to reduce dust during excavation, and roof supports are installed to maintain underground safety. Extracted coal is transported to the surface via chain conveyors, as illustrated in **Figure 2**.

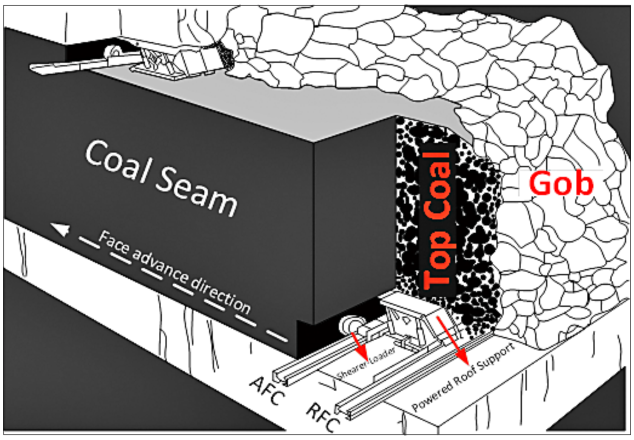

Figure 2: Longwall Top Coal Caving Method in Thick Coal Seam Mining

A systematic 30-day data collection period was conducted in the selected underground coal mine in Soma to monitor and report critical parameters such as methane gas concentration, ventilation performance, and coal gas emission capacity. Advanced monitoring techniques and calibrated equipment were utilized to ensure reliable and precise measurements throughout this period. To continuously monitor methane gas concentration, both fixed and portable gas detectors were strategically placed at key points within the mine. These detectors, calibrated in accordance with international standards, provide real-time data, enabling the detection of sudden increases in methane levels and allowing rapid response to potential hazards. Ventilation performance was assessed through regular measurements of air velocity and pressure differentials across various sections of the mine. Using sensitive devices such as anemometers and manometers, these measurements were analyzed to evaluate the effectiveness of the ventilation system. Regular maintenance of ventilation channels and rigorous calibration of measurement devices contributed to the reliability of the collected data. To determine coal gas emission capacity, coal samples were collected for laboratory analysis. The gas content and desorption characteristics of the samples were examined following standard testing methods, providing insight into the gas release potential of the coal seams. These analyses contributed to a more accurate assessment of methane explosion risk within the mine.

3. Results and discussion

In the selected underground coal mine in the Soma region, methane concentration (%C), ventilation performance (%V), and coal gas emission capacity (%G) were measured over a 30-day period, and these data were used to calculate methane risk scores (%MRS). The collected data and calculated %MRS values are presented in **Table 4** also graphs of 30-day distribution of parameters affecting methane risk score are given in **Figure 3**. Upon examination, %MRS values were observed to range between 15% and 38%. The highest risk levels were recorded on days when methane concentration and coal gas emission capacity were high, and ventilation performance was low. Specifically, on days 3 and 19, methane concentration reached 0.66%, ventilation performance fell to 79.41%, and coal gas emission capacity reached 20.38%, resulting in the highest observed explosion risk. An analysis of the effects of each parameter on the risk scores reveals that an increase in methane concentration significantly raises the risk score. Particularly on days when methane concentration exceeded 0.3%, there was a notable increase in risk levels. Low ventilation performance is another key factor that raises the risk score; on days when performance fell below 80%, the likelihood of methane accumulation increased, subsequently elevating explosion risk. Coal gas emission capacity is the third significant parameter that contributes to the risk score. High emission capacities increase the release of methane into the mine atmosphere, thereby heightening the explosion risk. On days when emission capacity exceeded 20%, risk scores were observed to be higher.

Table 4: 30-Day measured data and Methane Explosion Probability Values

Day	%C	%V	%G	MRS (%)
1	0.10	81.61	18.94	27.31
2	0.18	80.50	19.67	29.65
3	0.66	79.41	20.38	38.45
4	0.10	86.57	15.68	22.52
5	0.22	80.40	19.74	30.55
6	0.10	81.94	18.73	27.00
7	0.10	90.00	11.52	18.24
8	0.44	79.90	20.06	34.60
9	0.20	80.45	19.70	30.05
10	0.10	90.00	10.00	15.38
11	0.46	79.87	20.08	34.81
12	0.10	85.93	16.11	23.15
13	0.14	80.57	19.63	29.05
14	0.10	83.84	17.48	25.17
15	0.10	89.15	13.99	20.01
16	0.43	79.94	20.04	34.32
17	0.13	80.67	19.56	28.65
18	0.10	90.00	10.00	17.43
19	0.66	79.41	20.38	38.45
20	0.10	83.51	17.70	25.49
21	0.10	86.25	15.90	22.84
22	0.33	80.17	19.89	32.45
23	0.10	88.80	14.22	20.35
24	0.13	80.63	19.59	28.76
25	0.10	90.00	10.00	17.24
26	0.44	79.90	20.06	34.60
27	0.17	80.51	19.67	29.55
28	0.10	85.93	16.11	23.15
29	0.32	80.18	19.88	32.30
30	0.10	90.00	10.00	15.38

The data reveal considerable day-to-day fluctuations in %MRS values, showing that risk levels vary in response to methane concentration, ventilation performance, and coal gas emission capacity. Specifically, on days 3 and 19, when methane concentration rose to 0.66% and ventilation performance dropped to 79.41%, the risk reached its peak levels. These findings underscore the importance of daily monitoring of risk factors and implementing preventive measures based on parameter fluctuations. Evaluating data in this way contributes to a dynamic approach to mine safety conditions and supports the development of effective early warning systems against explosion risks.

The developed model offers both safety and environmental benefits from a sustainable mining perspective. Keeping methane concentrations at low levels not only

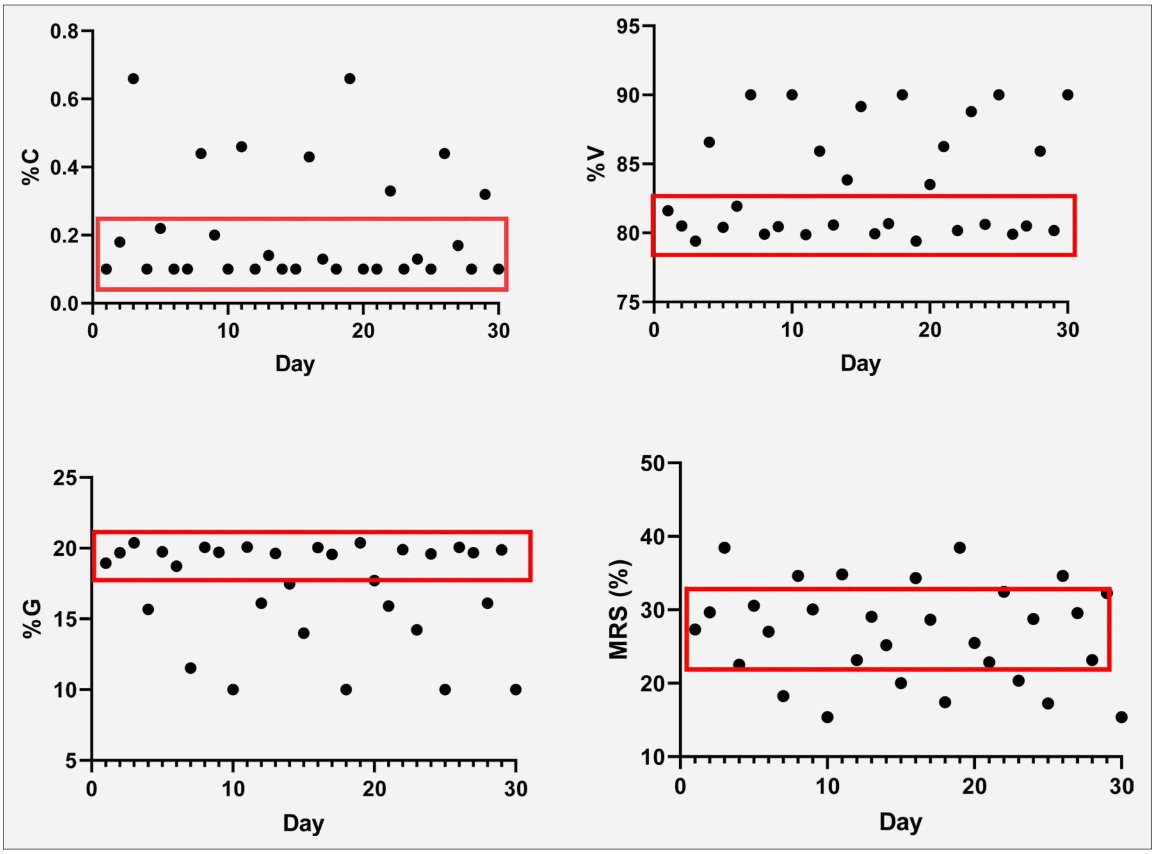

Figure 3: 30-Day distribution of Parameters Affecting Methane Risk Score (%C, %V, %G) and Methane Risk Score (%MRS)

reduces explosion risk but also contributes to environmental sustainability by lowering greenhouse gas emissions into the atmosphere. Additionally, utilizing methane for energy production provides an alternative income source for mining operations while mitigating environmental impact.

Beyond methane explosion risk, the model's framework can be extended to other mining hazards such as dust explosions and roof collapses. For instance, the mathematical principles underlying this model could be recalibrated to assess risks associated with combustible coal dust or geological instability. This adaptability is due to the modular design of the model, allowing parameter substitutions relevant to specific hazards.

The model has been tested in Soma's high-methane coal mines, but its adaptable structure makes it applicable to other regions with varying geological and operational conditions. Preliminary evaluations suggest that the model performs effectively in areas with lower methane concentrations and alternative ventilation configurations, providing meaningful risk assessments aligned with local mining practices. By addressing site-specific conditions, this model can offer tailored safety strategies, ensuring both its versatility and reliability across different mining environments.

Integrating the model as a practical risk assessment tool into daily mining operations facilitates the development of risk mitigation strategies. Continuous monitoring of parameters and the proactive measures guided by the model's scores provide a robust solution for minimizing explosion risk. The model's simplicity and ease of application aid field workers in understanding risk levels and support mine managers in making informed decisions. This model contributes to the establishment of a reliable monitoring and prevention system within the occupational health and safety framework.

Compared to the probabilistic models proposed by **Wang et al. (2019)** and **Li et al. (2020)**, which rely on Bayesian networks and Fuzzy AHP techniques, the developed model offers a straightforward calculation methodology without compromising reliability. Unlike these complex approaches, the simplicity of this model enhances its practicality for daily use by occupational safety professionals and managers. The validation of this model against real-time field data collected in the Soma region further distinguishes it from laboratory-based approaches, such as those of **Fidalgo-Valverde et al. (2024)**. By aligning closely with on-site conditions, this model ensures actionable insight for immediate implementation. Additionally, the modularity of the model allows for seamless recalibration to address varying geological and operational conditions, a feature that is rarely emphasized in existing literature. These combined attributes highlight the model's originality and establish its potential as a robust tool for sustainable occupational safety management.

The 30-day data analysis presented in **Figure 3** encompasses the daily fluctuations of the three primary parameters (%C, %V, and %G) influencing the methane risk score in the underground coal mine environment, along with the combined impact of these parameters on the methane risk score (%MRS). Methane gas concentration (%C) generally remains low but shows a notable upward trend on a few critical days, exceeding 0.3%. Ventilation performance (%V) predominantly falls within the 80-85% range; however, it dips below the ideal level on certain days, thereby elevating the risk level. Coal gas emission capacity (%G) generally stabilizes around 20%, but on days when it drops to lower levels, it potentially reduces the explosion risk. The %MRS, calculated based on these variables' combined influence, concentrates within the 25-35% range but reaches higher values on critical days. These data underscore the importance of daily monitoring of the %MRS and highlight the direct impact of methane concentration, ventilation performance, and gas emission capacity on explosion risk.

4. Conclusions

This study highlights the development and application of a methane gas risk analysis model applied for underground coal mines. By integrating critical parameters – methane concentration (%C), ventilation performance (%V), and coal gas emission capacity (%G) – the model offers a comprehensive framework for evaluating explosion risks. The case study conducted in the Soma region validates the model's effectiveness in accurately assessing methane risk levels and informing preventive strategies. Its simplicity and structured approach make it a practical tool for occupational safety professionals to implement in field operations, facilitating early warnings and proactive safety measures.

Beyond methane explosion risk, the model demonstrates adaptability to a variety of mining scenarios and geological conditions. Preliminary evaluations confirm its utility in regions with low methane concentrations and alternative ventilation systems, as well as its potential application to other hazards, such as dust explosions or roof collapses. This versatility underscores the model's broader applicability within the mining industry and enhances its role as a robust occupational safety tool.

However, the model currently focuses exclusively on methane gas and does not incorporate other gases or additional risk factors. Expanding its scope to include parameters for other hazards or environmental risks could enhance its value as a comprehensive safety management system. Additionally, future studies should explore its adaptability to diverse mining operations with varying geological features and operational constraints. By refining and extending its application, the model has the potential to contribute significantly to sustainable mining practices, reducing environmental impacts while improving safety outcomes.

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SAŽETAK

Analiza rizika od metana u podzemnim rudnicima ugljena u svrhu održive zaštite na radu

Ova studija predstavlja sveobuhvatan model analize rizika od metana prilagođen za podzemne rudnike ugljena u procjeni rizika od eksplozije i promicanje održivih praksi zaštite na radu. Model izračunava stupanj rizika od metana (% MRS) integrirajući tri kritična parametra: koncentraciju metana (% C), učinak ventilacije (% V) i kapacitet emisije ugljenoga plina (% G). Tridesetodnevna terenska studija provedena u turskoj regiji Soma otkrila je % MRS vrijednosti u rasponu od 15 % do 38 %, najviši rizici uočeni su u danima s povišenim koncentracijama metana (0,66 %), smanjenim performansama ventilacije (79,41 %) i visokom emisijom plina (20,38 %). Ti nalazi potvrđuju sposobnost modela da pruži praktične i pouzdane procjene kombiniranih čimbenika rizika. Modularna struktura modela omogućuje ponovnu kalibraciju za procjenu drugih opasnosti, poput eksplozije prašine ili urušavanja krovine, a preliminarne procjene pokazuju njegovu prilagodljivost regijama s različitim geološkim uvjetima i konfiguracijama ventilacije. Nudeći fleksibilan pristup koji je jednostavan za korištenje, model može biti koristan stručnjacima za zaštitu na radu u provedbi proaktivnih mjera pridonoseći održivosti rudarskih operacija.

Ključne riječi:
održivo rudarstvo, metan, analiza rizika, eksploatacija ugljena

Author’s contribution

Ali Kemal Eyuboglu (1) (Asst. Professor): Compiler of all articles, author of the complete manuscript, and implementer of the research concept. **Muharrem Kemal Ozfirat (2)** (Professor): Idea generator and supervisor on the review section related to the preparation parameters for analysis. **Mustafa Emre Yetkin (3)** (Assoc.Professor): Idea generator and supervisor on the drafting section related to methane risk analysis.