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Research Article

Overcoming Challenges and Charting the Future of Underground Green Mining Technology

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Abstract— The mining sector assumes a crucial role in the worldwide economy, providing essential raw materials for various sectors. However, the environmental impact of traditional mining practices, particularly in case of underground coal mining, has raised significant concerns. The paper explores the technological advancements and best practices that are shaping the future of green underground coal mining. These innovations include cleaner extraction techniques, methane capture and utilization, advanced ventilation systems and water management strategies.This paper presents an overview of the concept of "Green Mining" as it applies to underground coal mining, focusing on sustainable practices and technological innovations that can mitigate its adverse environmental effects. The challenges associated with implementing green mining technologies in underground coal mining are discussed in detail. These challenges encompass various aspects such as ventilation management, methane emissions control, water management and waste disposal. It also emphasizes the importance of collaboration among stakeholders, including government bodies, mining companies and local communities. Furthermore, the paper highlights the role of research and development in advancing green mining technologies and calls for increased investment in innovation and education within the mining industry. This paper sheds light on the evolving landscape of underground coal mining towards becoming a more sustainable and environmentally responsible industry.

Keywords— coal; underground mining; green mining; novel techniques

1. Introduction

The mining sector stands as one of humanity's most ancient industries. It involves the retrieval of valuable minerals or geological substances from earth, usually from ore bodies, veins, or coal seams. Mining operations broadly fall into two categories: opencast and underground methods [1]. The two common methods of underground mining include Bord and Pillar mining and Longwall mining. Coal is most widely distributed under diverse geological condition in nature. The total worldwide recoverable reserves of coal were about 1.16 trillion tons and 75% of the worlds proved coal reserves are situated in five countries as on December 2021 [2]. United States has largest coal reserve amounting 22% of proven reserve followed by Russia, Australia, China and India having 15%, 14%, 14% and 11% respectively [3]. Figure 1 shows the proven coal reserve available with several countries worldwide. However, China is yet the largest producer of coal [4].

The global energy landscape is evolving rapidly towards sustainable and environmentally responsible practices. In this context, the coal mining industry, which has long been associated with environmental degradation and greenhouse gas emissions, is facing unprecedented challenges [5]. This paper presents an overview of the concept of "green mining" as applied to underground coal mining and explores the challenges and opportunities in adopting eco-friendly practices in this sector. It then introduces the concept of green mining and highlights the potential benefits it can offer to the coal mining industry, including reduced environmental impact, improved safety, and enhanced resource recovery.

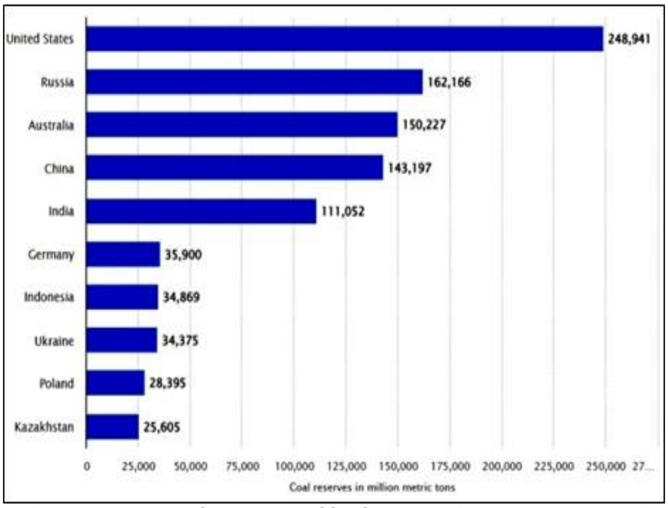

Figure 1. Proven coal reserves worldwide in 2020 (Source: Statista 2023)

The challenges associated with underground coal mining encompass various aspects such as ventilation management, methane emissions control, water management, and waste disposal [6]. Additionally, the socio-economic challenges related to workforce transition and community engagement in mining regions are addressed. To pave the way forward, the paper outlines a comprehensive strategy for the adoption of green mining technologies in underground coal mining. It also emphasizes the importance of collaboration among stakeholders, including government bodies, mining companies, and local communities [7]. By recognizing and addressing these challenges, the coal mining sector can contribute to a more sustainable energy future while ensuring the well-being of communities and ecosystems in mining regions. In conclusion, this paper underscores the importance of embracing green mining technologies in underground coal mining to address the environmental and societal challenges associated with the industry. By recognizing and addressing these challenges, the coal mining sector can contribute to a more sustainable energy future while ensuring the well-being of communities and ecosystems in mining regions [8].

The paper is organized as follows, Section 1 discusses about introduction of underground coal mining. Section 2 discusses about the available or conventional methods being used in underground coal mining. Section 3 discusses about the green mining technologies and its trial being carried around the world. Section 4 presents the comparison between conventional and green mining technology. Status of Green mining in Indian context is also discussed. Section 5 explains about the future direction and conclusion of this study.

2. Existing Underground Coal Mining Techniques

The methodology adopted for this review paper is to discuss about current practices used in underground coal mining. Thereafter, green underground mining methods will be discussed in detail. A comparison of old mining and new green mining technology is also presented in this paper. The adoptability of the suggested method in context of Indian mines is also explored.
There are several underground mining methods. The most common underground mining methods are discussed below.

2.1 Bord and Pillar method:

The bord and pillar method of mining of coal seam is also referred as room and pillar mining. This method of mining is generally used for coal seams which are flat or gently dip. In this method a network of roadways is formed which is called ‘development’. Pillars of coal block are left in a rectangular or square pattern while the galleries between those pillars are mined out. The coal pillars which were left during development stage are extracted later in a systematic way which is called ‘depillaring’ [9]. The bord and pillar method is used as a method of mining in those coal seams which are having thickness of 1.5 m or more. The coal seam must be free from coal bed methane (gas), stone or dirt bands. Coal seam should present at moderate depth with strong roof and floor. Also, the coal present in the seam should have moderate crushing index. This method of mining becomes uncontrollable at a greater depth as effects of roof pressure becomes high. A typical layout of Bord and pillar method of mining is presented in figure 2.

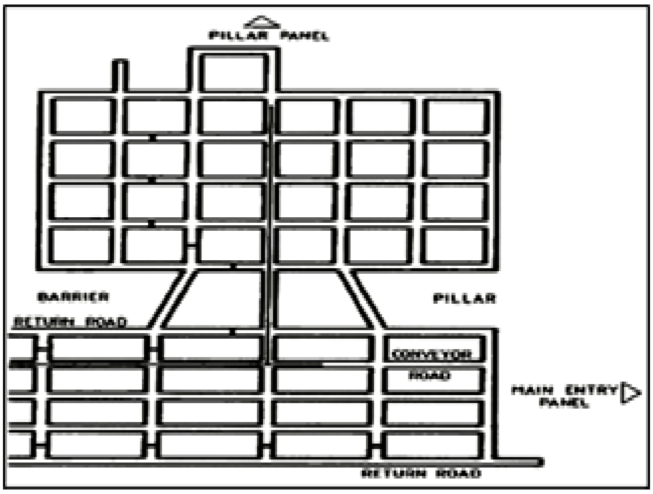

Figure 2. Layout of a typical Bord and Pillar method

2.2 Longwall Mining:

Longwall mining is an advanced mining technique characterized by the extraction of elongated coal blocks through a continuous operation using automated cutting machinery. This process involves the use of a movable roof support system to safeguard the working area during coal extraction [10]. This method is used where thickness of coal seam varies from 0.6 to 6m. As the mining operation advances, the roof above the coal seam is intentionally allowed to collapse behind a series of support structures as presented in figure 3 [11]. It has advantages with respect to bord and pillar method in terms of resource recovery (~80%), requirement of fewer support system, level of automation.

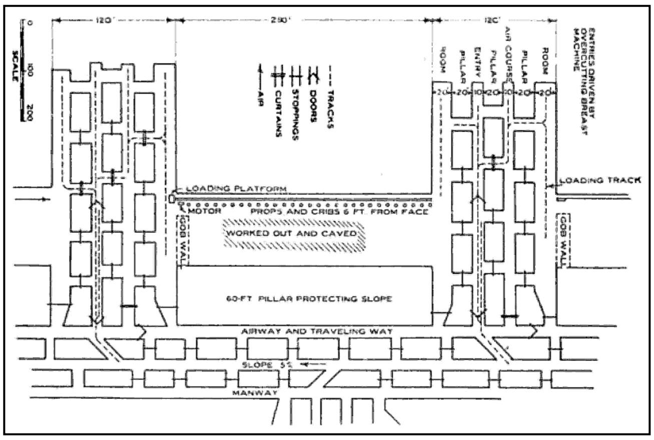

Figure 3. Longwall mining

2.3 Shortwall Method:

The shortwall method of coal seam extraction integrates elements from both the Bord and Pillar method and Longwall method. The approach of this method has resemblance of longwall mining, but with narrower coal blocks, typically no wider than 100 meters. The coal is extracted in slices up to three meters thick using a continuous miner, and it is then transported using a face conveyor or similar equipment [12]. The same is presented in figure 4. Specially designed shields, similar to those used in longwall mining, support the roof during the operation. The Shortwall method of coal mining incorporates both the advantages and drawbacks of the bord and pillar methods, as well as those of the longwall methods.

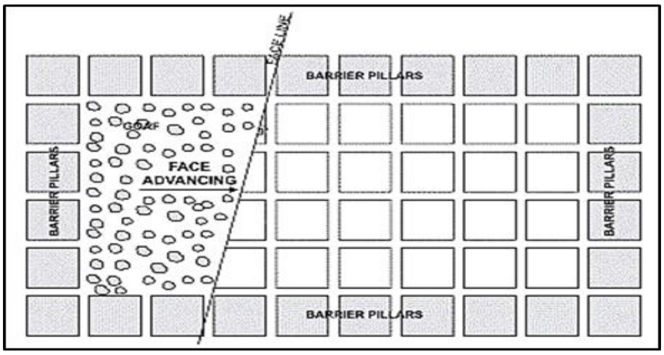

Figure 4. Shortwall mining

2.4 Thick Seam Mining:

In mining operations, the longwall method enables the extraction of coal seams up to five meters thick in a single cut. The coal seams having thickness up to seven meters have been successfully mined with traditional mining methods in one pass. However, when a coal seam having thickness more than 7 meter, it is typically divided into several slices, and each slice is mined separately using longwall, continuous, or conventional mining techniques [13]. These individual slices can have varying thicknesses, usually ranging from three to four meters. There are numerous approaches to extracting the entire seam. These slices are taken out either in increasing or decreasing order, i.e.; first approach is developed to the coal seam thereafter mining can be started in upward or downward coal seam in gradual manner. In cases where the roof conditions are adverse or there is a risk of spontaneous combustion in the coal seam, backfilling is carried out to fill the empty space created by extraction of coal seam. The backfilled material is used as an artificial roof or floor for the adjacent coal slice as given in figure 5.

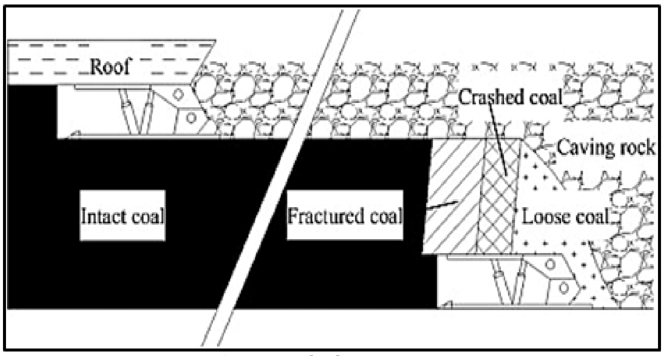

Figure 5. Thick seam mining

3. Green Underground Mining Techniques

Alternative underground coal mining methods are now being explored to reduce environmental impact as well as enhanced coal recovery. Several methods have been discovered so far. However, a few are being discussed here.

3.1 MDGBM technique for coal mining

This technique consists of mining-dressing-gas draining-backfilling-mining. This study addresses several significant engineering challenges encountered in mining operations such as difficulty in auxiliary lifting beyond a depth of 1000 m, working in highly gassy coal seam, unstable overlay coal seam as well as difficulty in maintaining productivity [14,15]. To tackle these issues, closed-cycle MDGBM technique is developed. The approach includes several key steps as shown in figure 6 as well as listed below:

A. The initial step involves the mining of protective coal seam.
B. Coal and gangue both materials are processed at the face of mining, utilizing the process of dense medium-shallow trough. It improves the coal recovery.
C. Gas drainage is then carried out to reduce pressure in the main coal seam before extraction.
D. The protected coal seam is extracted and backfilled with sand or stone and mining operations are conducted through the seam.

A specialized system is designed to facilitate gas drainage and mining in the rock stratum on the basis of geological strata of the location. Additionally, another system, connected to the production system, handles the dressing of coal as well as gangue. This mixed mining workface accommodates solid backfilling and conventional fully mechanized coal mining, streamlining the overall mining, dressing and backfilling operations.

This has resulted in enhanced workface length, reduction in gas pressure improvement in safety as well as improved production. In conclusion, the proposed MDGBM technique offers a comprehensive solution to the engineering challenges faced by mining operations, ensuring both safety and efficiency while addressing environmental concerns and economic considerations.

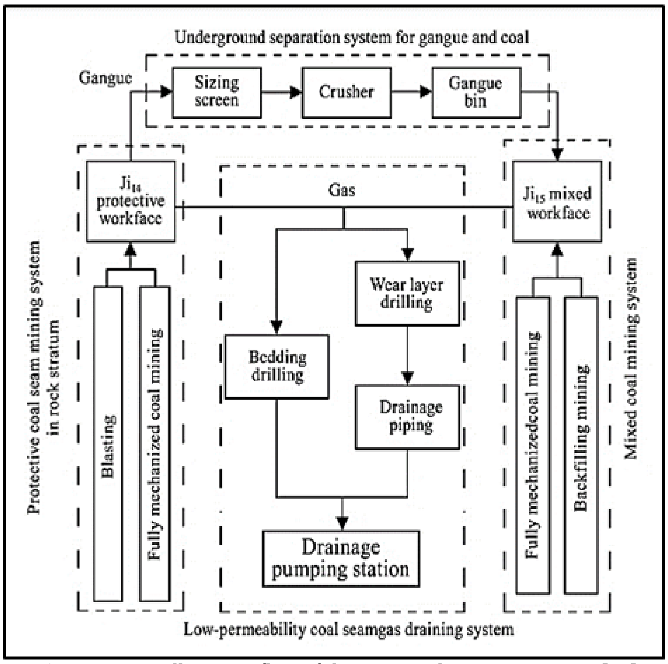

Figure 6. Overall process flow of the integrated MDGBM system [14]

Pilot projects:
This technique was successfully utilized in the two workfaces of Ji_{14} and J_{15} seam at No. 12 mine, China. These workfaces were highly gassy in nature. The result proved that the method used for mining is safe, efficient, productive and green for simultaneously exploiting coal seam and draining as well as utilization of gas.

3.2 SRPF technique

In response to the significant challenges faced by coal mining industries such as spontaneous heating, fire, caving, roof fall, ventilation, inundation, strata deformation etc., a novel mining approach called the Segmented Roadside Plugging-Filling (SRPF) method has been developed at Shandong province in eastern part of China. This SRPF method include the innovative reformulation of the gob-side retaining roadway structure and incorporates a new parameter called roadside filling coefficient (ξ), and the development of a specialized filling device. The mechanism of this innovative method is established through models, considering subsidence bending of initial cantilever beam, subsequent parallel subsidence and the direction of rock beam. The determination of the filling mode under this innovative method is based on geological mining parameters. The choice of filling material is a critical background parameter, and the calculation formula for filling strength yields trend curves for both the stages under several other models. The selection of suitable matching parameters is constrained by established thresholds [16].

The SRPF method demonstrated its capability to maintain the stability of both the support structures and the surrounding rocks of gob-side roadways which were planned to be retained. Successful implementation in a working coal face also validates practicality of this innovative method, with the added benefit of reducing mine-filling material costs by 50%. [17]. The approach is presented in figure 7.

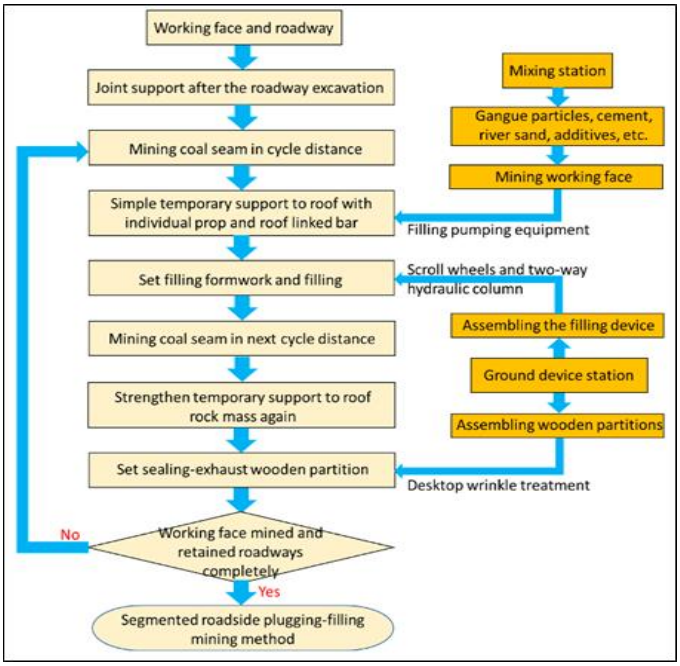

Figure 7. Schematic diagram of SRPF mining method [16]

Pilot projects:
This method was designed and implemented for Shandong Coal Zone mine in China. On-site monitoring confirmed that surrounding rock deformation ranged from 0 to 160 mm, and the filling material maintained its strength and stability. Successful mining operations were conducted in the working stope, affirming the method's applicability.

3.3 Green filling mining techniques

This method of mining focuses on determining suitable filling materials in goaf area and optimizing the filling mining technology for deep underground coal mines. This innovative method offers valuable speculative insights and data upkeep for such mining practices. The main key consideration for this method of mining are filling material selection by several experiments and theoretical analysis, mining technology selection based on coal seam conditions and field application. The practical application of this method demonstrates that continuous filling of goaf area of the working face significantly reduces ground pressure on the coal wall and increases the stability of surrounding rock effectively. The study achieves positive outcomes by ensuring the stability of the goaf's surrounding rock. It provides essential theoretical foundations and data support for safe, environmentally friendly and efficient mining of deep coal resources [18,19].
In summary, this research contributes to the development of green filling mining techniques which could be used for deep coal mines. It offers insights into material selection, technology optimization, and real-world applications, ultimately promoting safe, efficient, and sustainable mining practices in deep coal resource extraction. The working face for this method of mining has utilized a special paste filling support. The mining and filling process started with cutting the coal from seam itself. A net was hanged thereafter support system were moved to forward coal face. Then on pushing conveyor forward created an isolated area which was then filled with the special paste. It was left there for solidification. The whole process is shown in figure 8.

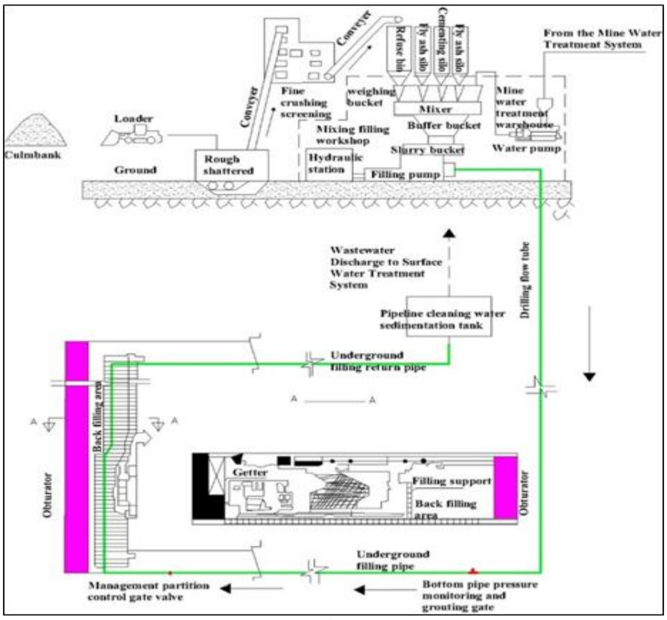

Figure 8. Paste filling mining [17]

Pilot projects:
In this study gangue produced in mines, fly ash, and cement from another unit at China was used as filling aggregates. The selection of this method was based on the technical conditions of coal seam. The coal mines at Xieqiao, China introduced a single face longwall mining technology which has automated back-filling also. Thus, pilot study was carried out at this mine. This technology enhances safety and efficiency in the filling mining process and involves improvements in supporting equipment, such as hydraulic support for the working face and filling the goaf area through special paste in pipeline.

3.4 Strip green mining technology

Strip mining stands as a sustainable mining technology that accomplishes the dual objectives of relocating villages and preserving the ecological integrity of mining sites. Practical implementation demonstrates that the adoption of strip mining, in the pursuit of green coal mining and ecological conservation, yields several advantages. These include reduced surface subsidence, minimized structural damage to buildings, and decreased disturbances to the environment. This approach contributes to the development of a sustainable mining system where energy, resources, and the environment coexist harmoniously, denoted as "energy - resources - environment" (ERE) [20].

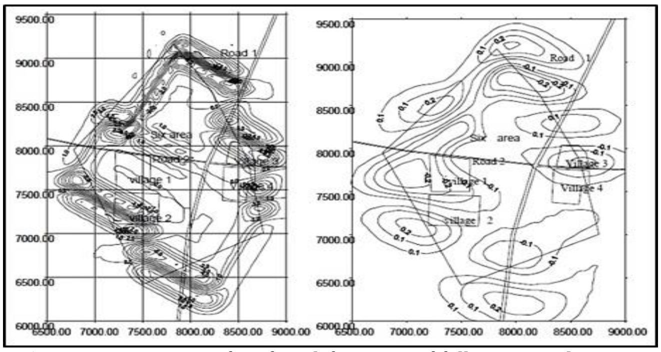

Figure 9. Comparison of Surface deformation of full mining and striping mining [20]

A comparison of full mining and strip mining with respect to surface deformation is presented in figure 9. The findings demonstrated that strip mining effectively managed surface deformation associated with mining activities. It emerged as a critical technical approach for coal mining beneath populated areas using existing technology [21]. Strip mining showcased broad social benefits by simplifying the interplay between industry and agriculture, preserving farmland and the environment.

Pilot projects:
The study conducted theoretical analysis and field measurements to assess the impact of strip mining on surface deformation, building damage, and environmental control in Jining No 2 Coal Mine. The goal was to enable efficient and environmentally friendly mining of thick coal seams beneath residential areas. This research holds significant practical importance by enhancing resource recovery, mitigating mining-related damages, and safeguarding the ecological environment.

4. Comparison of Green Mining Technologies

A comparison is being presented in Table 1 for different kind of technologies with respect to old vs green mining methods. The figure represents that using green mining technologies one can get benefit over power consumption, less specific water consumption, better resource utilization as well as less emissions to environment.

4.1 India on Green Mining Technology

India has been increasingly focusing on green mining technology to address environmental concerns and promote sustainable mining practices. The key initiatives renewable energy integration, reducing environmental footprint, digitalization an automation in mines, community engagement, research and development as well as monitoring of compliances. India is actively embracing green mining technology as a means to balance its mineral resource needs with environmental sustainability. Through policy initiatives, technological advancements, and a commitment to responsible mining practices, India aims to reduce the environmental impact of mining activities while promoting economic growth in the sector. In addition to bio-reclamation, green belt is also being created at the places where there is high air pollution such as mines, infrastructures as well as roads to mitigate air pollution. Green belt provided around the mine and residential colony also helps in noise attenuation. Proper reclamation which includes both technical and biological reclamation is given more thrust. Satellite surveillance for land reclamation for environmental protection is being used. This helps in up to date information as well as live status of the progress being done.

Table 1. Compared technologies for novel beneficiation techniques

Technology	Old Method	Green Mining Method
Power Use and Emissions	Large amount of grid power was necessary. Machineries deployed used high emission fuels like diesel/propane.	The mining site have their own heat and power plant running on natural gas EV/NG equipment may be used.
Water Consumption/ Waste water production	Amount of fresh water utilization is high. Thus, waste generation is also high. Then, it has to pumped away to evaporation ponds.	Entire fresh water is being recycled and fresh water consumption is reduced to 90%. Also, land for evaporation ponds are not required.
Tailings	Mine tailing was stored behind tailing pond along with waste water which further detoxicates groundwater.	Water is being recycled from tailings and create a paste. These pastes are layered to minimize harmful effect on environment.
Air Emissions	Harmful chemicals had been emitted from conventional methods of mining	Harmful gases are now sent to flue gas treatment plant to minimize CO_2 and other chemical emissions.

5. Conclusion and Future Scope

Underground green coal mining technologies represent a promising and environmentally responsible approach to meet the world's energy demands while minimizing adverse ecological impacts. These innovative methods prioritize sustainability by reducing emissions, water usage, and land disturbance, while also enhancing worker safety. With integrating cutting-edge technologies such as carbon capture and storage, efficient ventilation systems, and automated machinery, the coal mining industry can transition towards a greener and more sustainable future. Furthermore, the role of research and development in advancing green mining technologies is the need of the hour. This calls for increased investment in innovation and education within the mining industry. The significance of regulatory frameworks and policies that promote environmentally responsible mining practices. It is imperative that stakeholders, including governments, industries, and researchers, continue to invest in and support the development and implementation of these technologies to ensure a cleaner and more sustainable energy future.

Data Availability

The data analysed during the current study will be made available upon reasonable request due to privacy restrictions.

Conflict of Interest

Author of this study declares that he has no conflict of interest related to this study.

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Authors' Contributions

Author has conceptualized and designed the study, collected the data and wrote the initial draft of the manuscript. Also, he has performed the data analysis and contributed to the writing of the manuscript and provided critical revisions and approved the final version of the manuscript. Author read and obtained necessary approval before submitting the final manuscript.

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