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ENVIRONMENTAL IMPACT ASSESSMENT OF UNDERGROUND COAL GASIFICATION (UCG) IN INDIAN COAL SEAMS

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Abstract
UCG is an innovative and promising technology that allows the utilization of deep, unmineable coal seams through controlled in-situ gasification to produce syngas. With India's extensive coal reserves, UCG presents a significant opportunity to meet the nation's growing energy demands sustainably. However, the technology's environmental impacts must be thoroughly assessed before large-scale implementation. This study provides a comprehensive Environmental Impact Assessment (EIA) of UCG operations in Indian coal seams, focusing on key parameters such as groundwater contamination, greenhouse gas emissions, surface subsidence, soil degradation, and ecological disruptions. Groundwater contamination due to toxic by-products like phenols, heavy metals, and hydrocarbons is identified as a major risk, alongside fugitive emissions that contribute to air quality deterioration. Subsidence and land instability caused by coal seam combustion further exacerbate environmental concerns. Using advanced EIA tools, including GIS-based impact modeling and baseline environmental monitoring; this research identifies mitigation strategies such as groundwater monitoring systems, subsidence prediction models, and gasification control mechanisms. The study emphasizes the need for stringent regulatory frameworks and environmental safeguards to balance energy production with ecological preservation. Findings demonstrate that while UCG holds immense potential for sustainable energy production in India, its success hinges on proactive environmental management and technology integration to minimize adverse impacts.
Keywords: Underground Coal Gasification, Environmental Impact Assessment, Indian Coal Seams, Groundwater Pollution, Greenhouse Gas Emissions, Sustainability.

1. Introduction

UCG is a process that converts coal into gas directly within the coal seam, effectively relocating the gasification process underground. The gas is generated and extracted using a network of wells drilled into the coal seam. An injection well introduces air to enable in-situ combustion of the coal, while a production well extracts the resulting syngas to the surface for further refinement [1].
Coal remains the primary source of electricity generation, accounting for 40% of the global market share, driven largely by expanding economies. Although renewable energy sources are growing, they are insufficient to meet the ever-increasing energy demands of society. Consequently, coal and other fossil fuels are expected to continue playing a significant role in global energy mix. The demand for coal is expected to increase at an average annual rate of 2.1% until 2019, maintaining its prominence for years to come. Notably, India ranks as the third-largest coal producer in the world[2]**.**
UCG has regained attention as a viable and promising technology for utilization and coal conversion. UCG allows the utilization of otherwise unreachable coal reserves by generating syngas that can be used for power generation and producing fuels like liquid fuels, synthetic natural gas, and hydrogen, all with strong economic potential. Its attractiveness has increased due to the growing emphasis on enhancing domestic energy security, overcoming constraints in North American natural gas production, and addressing environmental concerns such as mercury and sulfur emissions, along with reducing greenhouse gases[3]**.**
The expanding global population poses a twofold challenge: boosting energy production while minimizing carbon emissions. In 2018, global energy consumption increased by 2.3%, nearly twice the average growth rate since 2010, along with a 1.7% rise in CO_2 emissions from energy use. UCG,

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a clean coal technology, provides a promising solution by efficiently extracting energy from deep, otherwise unreachable coal seams and converting it into synthetic gas[4].

This paper aims to conduct an Environmental Impact Assessment for UCG operations in India, identifying potential risks, evaluating environmental consequences, and proposing mitigation measures to ensure sustainable implementation.

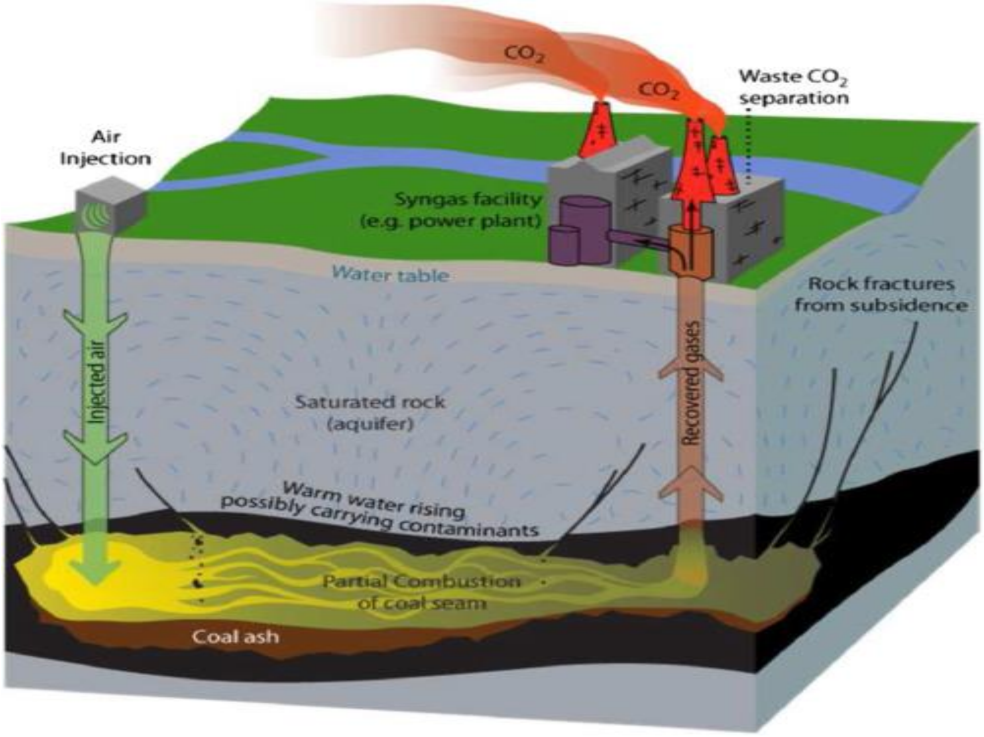

Fig.1: Principle of the Underground Coal Gasification (UCG) Process[5]

2. Methodology

UCG process requires the installation of injection and production wells within coal seams. Coal is ignited, and compressed gasification agents are injected through the injection wells to initiate and control an in-situ sub-stoichiometric combustion process that produces syngas[6]. The resulting syngas is collected through production wells and subsequently processed for various applications. Air and oxygen/steam are commonly used as gasification agents. Ignition of the coal is typically achieved using an electric coil or gas firing near the coal seam face. A continuous flow of oxidants through the injection well sustains the gasification process[7]. The process temperature is controlled by adjusting the oxidant flow to the reactor, with coal face temperatures in UCG systems exceeding 1,500ºK [8]. A basic representation of the UCG concept is shown in Figure 2.

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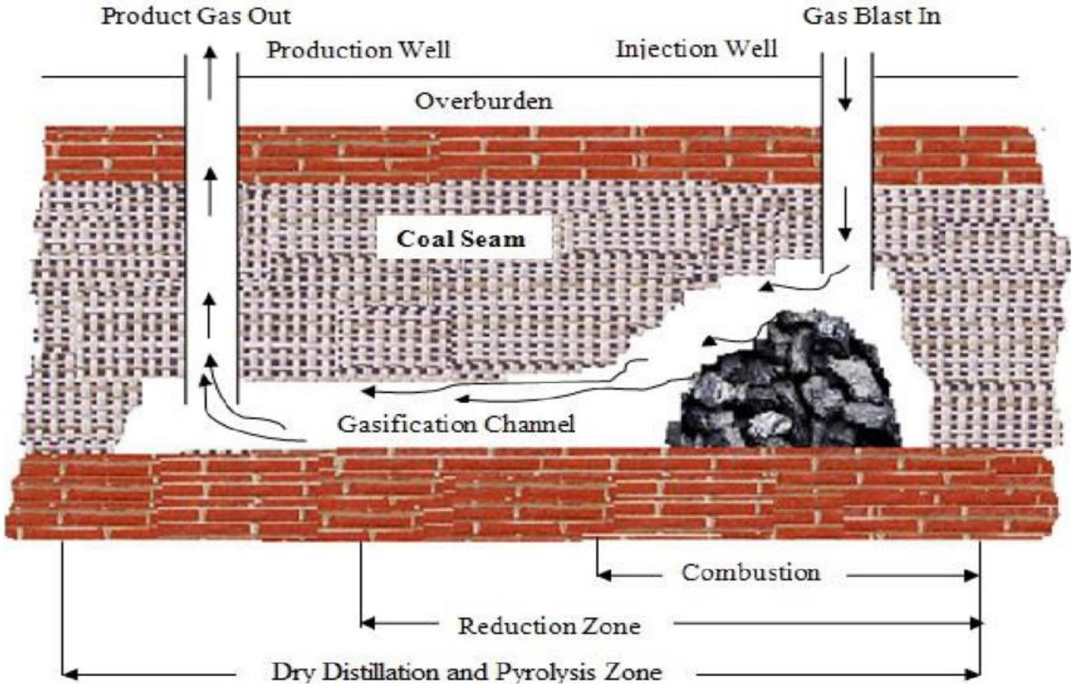

Fig.2 Overview of UCG processes[9]

2.1. UCG transforms coal directly within the coal seam into "syngas" using chemical reactions similar to those in surface gasifiers. The process relies on incomplete combustion to facilitate the essential gasification reactions, converting underground coal into syngas under elevated pressure and temperature conditions. The first UCG experiment took place in 1912, and subsequent research efforts, particularly in the Former Soviet Union and China, concentrated on its applications for power generation, hydrogen production, and chemical feedstocks[3]**.**

2.2. Current Status of Underground Coal Gasification (UCG) Pilots: At present, two pre-commercial UCG pilot projects are actively underway.

I. **The Majuba Project Eskom in South Africa:** nitiated in January 2007, this project generates 100 kilowatts of electricity by producing 5,000 m³/hr of syngas. Its success, led by Ergo Energy, has led to plans for a 2,100 MW Integrated Gasification Combined Cycle (IGCC) power plant, designed to run entirely on UCG syngas at a production rate of 375,000 m³/hr.

II. **ENN's Pilot Project (Inner Mongolia, China):** The pilot project, initiated in October 2007, successfully demonstrated sustained syngas production, maintaining consistent rates and composition over a duration of five months.

New UCG pilot projects have been proposed in India, Canada, New Zealand, Wyoming (USA), China, and Australia, with operations scheduled to begin between 2009 and 2010. These pilot projects aim to establish a foundation for commercial initiatives targeting the production of hydrogen, liquid fuels, electricity, and chemicals.

UCG specifically targets coal resources that are otherwise unreachable due to challenges like depth, overburden properties, geological complexity, or land use constraints. As a result, it is being developed as a complementary method to traditional coal mining and transportation[3].

The quality of UCG syngas is affected by various factors, such as the thickness and depth of the coal seam, water content, temperature within the gasification cavity, and the type of injection agent (air or oxygen). Syngas, or synthetic gas, mainly consists of a mixture of carbon monoxide (CO) and hydrogen (H_2).

The composition of UCG syngas varies depending on its intended use and the geological conditions of the coal reserves. The entire UCG process can be generally divided into three main stages:

1. Oxidation
2. Gasification

3. Pyrolysis/De-volatilization

For ideal cases the major thermo-chemical reaction processes are described in the Table-1[10].

Table1. The reactions involved in coal gasification[10]

S. No.	Chemical Synthesis	Reaction	Thermodynamic state
1	Exothermic Water-Gas Shift Reaction	$C + H_2O \rightarrow H_2 + CO$	ΔH = +118.5 kJ/mol
2	Endothermic Shift Reaction	$CO + H_2O \rightarrow H_2 + CO_2$	ΔH = -42.3 kJ/mol
3	Endothermic Methanation	$CO + 3H_2 \rightarrow CH_4 + H_2O$	ΔH = -206.0 kJ/mol
4	Endothermic Gasification with Hydrogenation	$C + 2H_2 \rightarrow CH_4$	ΔH = -87.5 kJ/mol
5	Endothermic Partial Oxidation	$C + \frac{1}{2}O_2 \rightarrow CO$	ΔH = -123.1 kJ/mol
6	Endothermic Complete Oxidation	$C + O_2 \rightarrow CO_2$	ΔH = -406.0 kJ/mol
7	Exothermic Boudouard Reaction	$C + CO_2 \rightarrow 2CO$	ΔH = +159.9 kJ/mol

3. Environmental Impacts of UCG

3.1 Groundwater Contamination

Groundwater contamination is recognized as one of the most significant environmental risks associated with underground coal gasification (UCG). During the gasification process, various substances, including phenols, polycyclic aromatic hydrocarbons, benzene, carbon dioxide, ammonia, and sulfides, are generated within the coal seam. These compounds have the potential to migrate from the gasification zone and pollute nearby groundwater sources. For instance, research conducted in the Soviet Union during the 1960s indicated that UCG could lead to extensive groundwater pollution. However, on a larger scale, most UCG projects have demonstrated minimal environmental consequences. European experiments reported no signs of environmental contamination during the process or up to five years afterward. Similarly, a UCG test conducted in Chinchilla, Australia, found no evidence of groundwater pollution during or after the operations[1].

Underground coal gasification (UCG) operations have been linked to the release of various hazardous waterborne contaminants, with some locations facing prolonged groundwater pollution. The organic pollutants commonly identified after UCG processes include phenols, benzene and its derivatives, polycyclic aromatic hydrocarbons (PAHs), heterocyclic compounds, as well as ammonia, mercury, zinc, sulfates, cyanides, and other heavy metals. Phenols are particularly concerning due to their high solubility in water, making them a significant threat to groundwater quality. Consequently, it is essential to select UCG sites away from water aquifers to minimize the risk of contamination. Research and established guidelines also emphasize strategies to mitigate the negative impacts of UCG on groundwater resources [11].

3.2 Greenhouse Gas Emissions

Bitumen, a highly viscous fluid, undergoes chemical and physical processing, known as bitumen upgrading, to lower its viscosity, density, and concentrations of sulfur, carbon, and metals. The production of synthetic crude oil from Canada's oil sands is expected to increase from 51.1 million m^3 annually in 2012 to 73.3 million m^3 annually by 2022. Alberta's oil sands industry accounts for approximately 23% of the province's total greenhouse gas emissions—surpassing sectors like electricity and heat generation, transportation, and others. This has led to growing pressure on the industry to implement cleaner energy production methods to curb greenhouse gas emissions. The significant greenhouse gas footprint associated with hydrogen production for bitumen upgrading underscores the importance of exploring alternative fossil-fuel-based hydrogen production methods, such as underground coal gasification[12].

3.3 Land Subsidence

Ground subsidence is arguably the most significant challenge to the commercialization of UCG. This phenomenon can result in the flooding of affected areas and lead to ground deformation, which has potentially severe consequences, such as creating flow paths between underground aquifers and causing damage to surface structures and buried infrastructure. Zhukov (1963a) emphasized the critical importance of understanding surface subsidence for the effective design of gas generators and gasification technology. For instance, Zhukov et al. (1963) suggested that wells located at the center of subsidence troughs are less likely to sustain damage[13].

Subsidence is the downward movement of the ground surface caused by the collapse or compression of underlying rock layers. It is often linked to activities such as underground mining or extensive groundwater withdrawal [13].

During UCG, the burning of coal seams creates voids, potentially causing the overlying geology to collapse. This may lead to subsidence and loss to surface foundations, including UCG boreholes. While subsidence risks are comparable to those in conventional underground mining, they are less severe in UCG due to the residual ash remaining underground. In Uzbekistan, UCG operations have shown negligible land subsidence. Potential subsidence problems can be addressed by carefully selecting suitable sites, utilizing subsidence modeling, and implementing surface monitoring. Monitoring typically involves surveying pre-installed monuments to identify any changes in elevation during or after operations [14].

In addition to UCG, coal mining in China has caused extensive surface subsidence (30×10^8 m²), land occupation, waste rock pollution (1.2×10^8 m²), soil erosion, water resource degradation, and the release of greenhouse gases like CH_4, among other environmental challenges[15].

4. Case Study: UCG in Indian Coal Seams

Efforts to gasify coal in India have been ongoing since the 1960s, spanning various capacities and scales. These initiatives primarily aim to achieve self-reliance by utilizing high-ash domestic coal to produce key materials like fertilizers, methanol and power. Additionally, several companies of Indian have acquired valuable expertise by successfully commissioning gasification projects in international markets[16].

4.1 The past Indian scenario of coal gasification can be summarized as follows:

Over the years, several efforts have been made to implement coal gasification in India. In the 1960s, the fertilizer plant at Sindri utilized coal gasification for fertilizer manufacturing, although it is no longer operational. At its Angul plant, JSPL experimented with blending imported coal with local coal for the gasification process, but the plant is either non-operational or functioning below its optimal capacity. Talcher Fertilizer Limited is progressing with a project that combines pet coke with high-ash domestic non-coking coal to produce syngas.

Bharat Heavy Earth limited has set up a pilot plant in Trichi, where it successfully generated 6.2 Megawatt of power; however, the plant has encountered challenges in processing coal with high ash content. Thermax, with support from NITI Aayog and funding from the Department of Science and Technology (DST), has also launched a pilot plant for coal-to-methanol production in Pune. Furthermore, Larsen & Toubro has commissioned several gasifiers in China and is actively engaged in the installation and commissioning of gasifiers [16].

4.2 Existing coal gasification plants in India include

I. Hydrogen and Carbon monoxide in syngas act as vital reducing agents in steelmaking, providing an eco-friendly alternative through the Direct Reduced Iron (DRI) route. Jindal Steel & Power Limited has pioneered the use of coal gasification technology with domestic coal, establishing the world's first DRI plant in Angul District, Odisha. Initiated in 2007 and commissioned in 2014, this syngas project serves as a technological milestone, showcasing the potential for sustainable and green development in India. With a national target to achieve 300 million tons of crude steel production by 2030, the adoption of coal gasification technique presents significant opportunities for capacity expansion. This approach not only supports domestic industrial growth but also reduces dependency on imported coking coal, aligning with India's goals for energy self-sufficiency and environmental sustainability[16].

II. Bharat Heavy Electricals Limited has established a pilot plant in Trichi, generating 6.2 Megawatts of power. However, the plant has faced significant challenges in processing coal with high ash content[16].

III. The Thermax pilot plant was set up in Pune in 2014 for coal-to-methanol production, with financial support from the Department of Science and Technology (DST) under the guidance of NITI Aayog [16].

IV. Larsen & Toubro has successfully authorized multiple gasifiers in China and continues to play an active role in the installation and commissioning of gasification systems [16].

4.3 Current Surface Coal Gasification Projects

Setting up a coal gasification plant is a capital-intensive endeavor, and the experience with coal gasification in India is still limited. Therefore, the success of the initial coal gasification projects is crucial for the national mission. To establish the technology, it is planned to set up two pilot coal gasification projects: one using a blend of high-ash coal and pet coke, and the other using low-ash coal[16].

The specifics of these two projects are provided below:

4.3.1 Talcher Fertilizer Plant

A joint Venture Company named Talcher Fertilizers Limited (TFL) comprising of RCF, CIL, GAIL and FCIL has been constituted (2016) to set up a Surface Coal Gasification based integrated fertilizer complex using high ash coal from nearby Talcher Coalfields mixed with pet coke from Talcher refinery with an Investment of Rs 13277 cr. Coal blended with pet-coke up to 25% shall be gassified to produce syngas, which shall be converted into Ammonia and subsequently to 1.27 Mt tonnes of neem coated Urea annually. TFL Board approved coal gasification technology of M/s Air Products (earlier M/s Shell) for the proposed plant. Exclusive subsidy policy for urea produced through coal gasification route by TFL has been approved by the cabinet in 2021. This will ensure concession rate/subsidy for the urea produced through coal gasification route by TFL for a period of 8 years from the date of start of production and will be determined by providing 12% post tax IRR on equity. Hon'ble Prime Minister of India had laid the Foundation Stone of the plant at Talcher on 22.09.2018. M/s Projects & Development India Limited (PDIL) is the Project Management Consultant (PMC) for this project. The project is being implemented on partial Lump Sum Turn Key (LSTK) basis. LSTK tenders for major plants (Coal Gasification & Ammonia-Urea) are under evaluation. NIT for Captive Power Plant and other Off-sites & Utilities are under preparation by the consultant. Currently, all pre-project works such as Commissioning of Water System, Supply-cum-Erection for Power Works, Land Development etc. are progressing in full swing[16].

4.5 Dankuni Coal to Methanol Plant

In pursuance to initiatives towards development of Clean Coal Technology and alternate use of coal, CIL has floated a tender for engagement of an agency on BOO basis for setting -up a coal-based Methanol plant of a 2050 MTDA (0.676) capacity in the premises of Dankuni Coal Complex (DCC) near Kolkata. Coal sourced from Raniganj coalfields shall be gassified to produce syngas which shall be subsequently converted into methanol. The project will require an investment of approximately Rs 5,800 crores, with 1.5 million tons of coal to be supplied from the Sonepur Bazari Mines of ECL[16].

Other Proposed Projects:

Coal India Limited has identified four additional coal projects of gasification across ECL, SECL, WCL, and CCL, with plans to produce methanol, ammonia, ammonium nitrate, and urea. A pre-feasibility report has been prepared by Project & Development India Limited, and Central Mine Planning & Design Institute Limited has been designated as the principal implementing agency for completing these projects. Additionally, NLCIL has initiated a lignite-to-methanol project at Neyveli [16].

5. Mitigation Strategies

UCG offers several advantages over conventional opencast and underground mining, but it also presents some distinct disadvantages. The technology requires significant capital investment and has been successfully implemented in limited number of locations worldwide. Environmental concerns, such as the potential contamination of aquifers near UCG operations and the risk of surface subsidence, are notable challenges. These issues can be mitigated through proper site management and monitoring [14].

Other important environmental difficulties that require attention include:

1. Migration of volatile organic compounds (VOCs) in vapor form into potable groundwater.
2. Groundwater contamination within the coal seam caused by organic compounds originating from coal and soluble metals from the associated minerals..
3. Upward migration of contaminated groundwater into potable aquifers, influenced by factors such as:

3.1.Thermally-induced flow away from the burn chamber.

3.2. Buoyancy effects caused by fluid density gradients due to variations in dissolved solids and temperature.

3.3. Alterations in the permeability of reservoir rocks resulting from UCG operations [14].

UCG integrated with power generation is projected to be 25% less greenhouse gas-intensive per MWh compared to a supercritical coal plant, assuming neither employs post-combustion carbon capture nor storage. The greater potential of UCG, however, lies in its capability to produce syngas that is well-suited for pre-combustion carbon capture, offering a more sustainable approach to energy production[17].

UCG operations involve treating syngas at surface facilities near the site to reduce air emissions before transporting it via pipeline to power generation facilities. The process generates two main types of non-GHG emissions: criteria air contaminants, such as nitrogen oxides, sulfur dioxide, and particulate matter, and volatile trace elements, including mercury, arsenic, and selenium. Effective syngas treatment significantly reduces these emissions, contributing to improved air quality and cleaner energy production[17].

6. Regulatory Framework for UCG in India

The implementation of UCG in India requires a robust regulatory framework to ensure environmental sustainability. Key regulations include:

1. **Environmental Protection Act (1986)**:

Empowers the Indian government to improve and protect the environment. It provides authority to regulate pollution, set standards, and enforce compliance for air, water, and hazardous substances. The Act enables strict penalties for violations and establishes mechanisms to address ecological concerns effectively, ensuring sustainable development [18].

2. **Water (Prevention and Control of Pollution) Act (1974)**: Addresses groundwater protection, aims to prevent and control water pollution in India. It establishes Pollution Control Boards to regulate water quality, prevent contamination, and enforce standards. The Act empowers authorities to penalize violations, ensuring sustainable water resource management for public health and environmental protection[19].
3. **Air (Prevention and Control of Pollution) Act (1981):** Regulates emissions from gasification processes, seeks to prevent, control, and reduce air pollution in India. It establishes Pollution Control Boards to monitor air quality, regulate industrial emissions, and enforce air pollution standards. The Act empowers authorities to penalize violators, promoting cleaner air and environmental sustainability[20].

7. Conclusion

The study of UCG's environmental effects in Indian coal seams emphasizes the need for a careful evaluation and mitigation plan to reduce UCG's negative environmental effects while optimizing its potential for sustainable energy production. Important conclusions show that, compared to traditional mining and power generation techniques, UCG can help meet India's energy needs using less surface area and emitting fewer greenhouse gases. However, issues like subsidence, groundwater contamination, and the release of hazardous by-products call for strict environmental monitoring and the incorporation of cutting-edge technologies.

To ensure safe and effective UCG operations, the Indian coal seams, with their distinct geological features, require site-specific impact assessment methods and strong regulatory frameworks. It is crucial to implement technology such as integrated water management systems, predictive subsidence models, and real-time gas monitoring. Future studies should concentrate on long-term social and environmental effects, promoting UCG as a practicable for India's transition to cleaner energy.

Declaration of competing interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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