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Safe Extraction of Developed Pillars by Opencast Method – An Overview

Avikant Khobragade* Prof G.K.Pradhan**

ABSTRACT

Coal mining in India has been traditionally underground intensive till early 80's, when coal extraction was by adopting Bord and Pillar Method of Mining. With mines not adopting depillaring a substantial quantity of coal was blocked in the pillars and the coal mining was restricted to solid blasting with semi-mechanised to mechanized means only. With the increased thrust on coal mining by opencast methods, and limitations on expanding in underground mining, the number of underground collieries/mines closed grew rapidly. These closed mines were later converted into opencast mines to extract coal in the locked/developed pillars and between contiguous seam workings. The extraction of coal from developed galleries by opencast had posed numerous problems and from time to time efforts were made to make operations safer by following special mining methods. Existence of fire, flooding of the old workings with non-availability of proper mine plan made the workings complex. An attempt has been in this paper to highlight the safe extraction methods being followed in Indian coalfields following safety guidelines set by DGMS and under provisions of CMR 2017.

INTRODUCTION

Coal will continue to be the major source of energy of India. Despite the growth in non-conventional sources of energy generation, coal based thermal power plants will be on the frontline. As of June 2025, India's total installed power capacity has reached a significant milestone with 476 GW, led by 240 GW of thermal, 110.9 GW of solar, and 51.3 GW of wind power, marking a strong shift towards renewable energy and energy security(Figure 1).

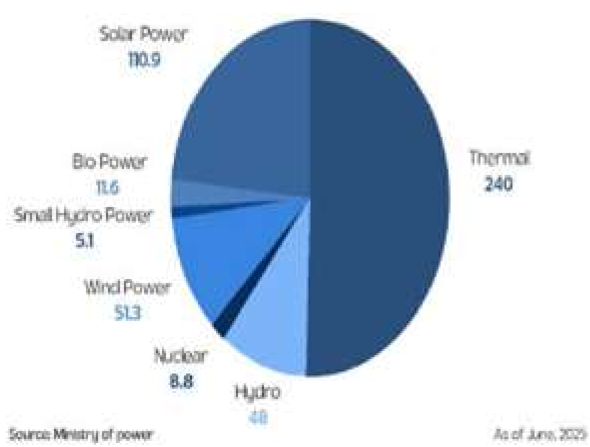

Figure 1 : India's installed Power Capacity mix as on April 2025(numbers in Gigawatt)(according to PIB).

This task of producing thermal power is supported by the growth in coal and lignite production both by Psus and private sector companies. India's coal production has reached 1047.57 MT (Provisional) in FY 2024-25, compared to 997.83 MT in FY 2023-24, marking a 4.99% growth. Production from Commercial & Captive mines. Similarly, lignite production had also touched 45.29 Million Tonnes in 2024-25. According to a Ministry of Coal report, opencast mining had a dominant role and underground mining is static (Figure 2).

Singh et al (2017) have reported that about 70% of the production of coal is being carried out by opencast mining (from coal benches) over underground developed galleries in Jharia and its adjoining coalfields.

Opencast mining had been facing several problems for most mining companies due to –

- Proximity of mines to human habitation
- Non-availability of land for mining and locating dumps
- Increase in stripping ratio and incidence of multiple seam workings
- Increase in depth of workings
- Conversion of underground mines to opencast was essential for mining locked coal from pillars etc.

Underground coal mining in India has been dominated by Bord and Pillar method of working and majority of mines are quite old and workings are uneconomical. With several restrictions on depillaring, the pillars are left intact. When

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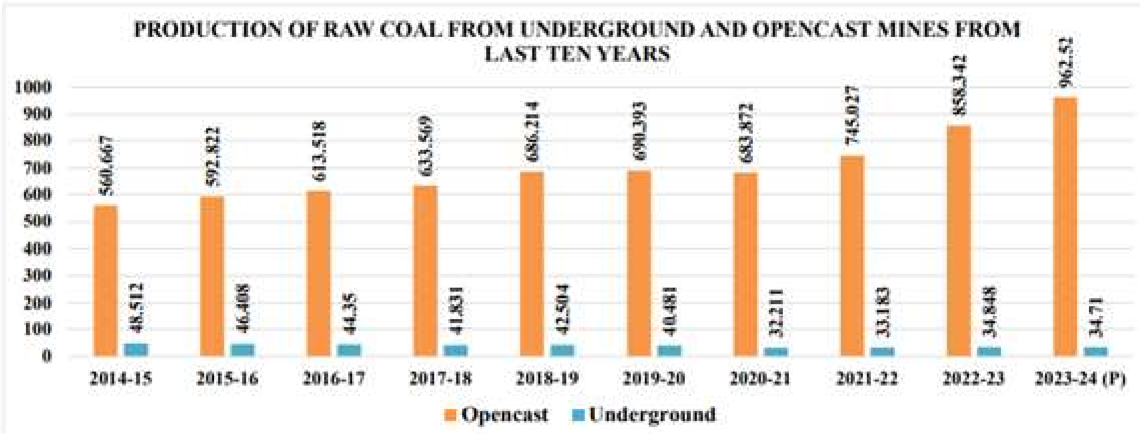

Figure 2 : Production of raw coal from underground and opencast mines from last five years(2014-15 to 2023-24(P).

these coal mines are converted to opencast, the mining involves overburden removal as well as mining of standing pillars. Panigrahi et el(2013) have reported that about 4000 million tonnes of coal are locked in standing pillars. To recover this coal only option is to switch over to opencast mining. By this approach several problems are faced, which include

- Ground instability from collapsing underground voids and galleries
- Fire hazards due to spontaneous combustion of exposed coal (Figure 3, shows Mine fire in opencast benches of Jharia Coalfields.

Figure 3 : Mine fire in opencast benches of Jharia Coalfields

- Drilling & Blasting complications when working above old workings
- Regulatory complexities in complying with stringent safety standards
- Non-availability of Mining Plan of the old workings

Figure 4 (Tose, 2022), explains the processes that occur when mining is undertaken over old underground workings by opencast methods. Arrows show the movement of air into the developed workings which result is the fire in the coal seam.

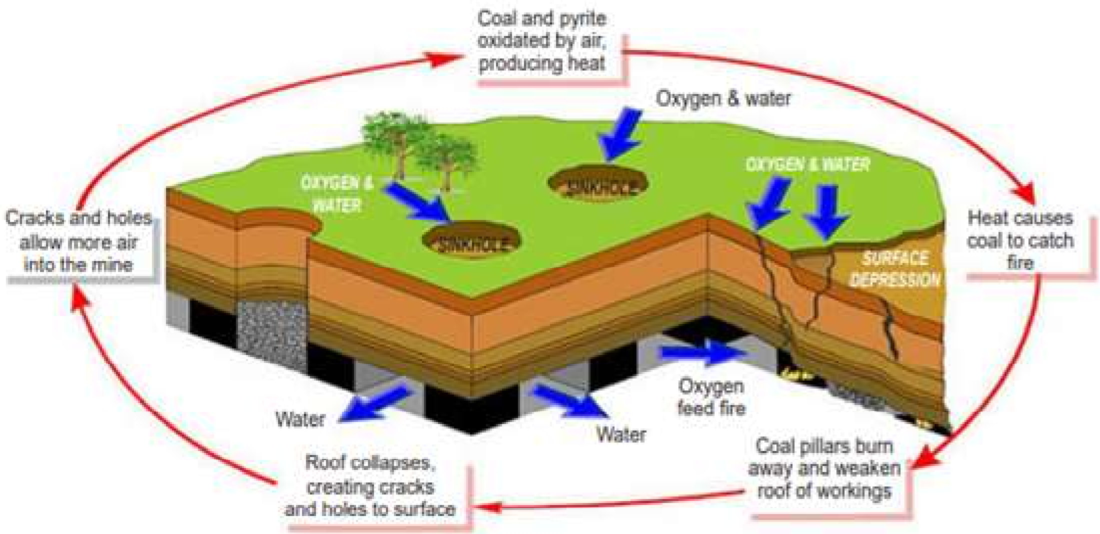

Figure 4 : Cycle of processes that occur when mining over old underground workings (Tose, 2022)

When it comes to safety in Mines due to presence of fire/ high temperature condition in blast holes or in the strata, a number of accidents have occurred. One recent case has been the Chirimiri Coal Mine incident in October 2025. Where after completing the opencast bench the workers moved out and during the process there was an explosion in the charged area. It was assumed that the cause may be due to hot strata/ground leading to premature detonation.

Laybourne & Watts (1990) from South Africa documented the extent of previously mined underground coal workings and possible method to mine them by strip mining. Jeffrey (2002), while working on his M.Sc thesis extensively studied the geotechnical factors associated with previously mined areas of coal and their impact on subsequent extraction. Thompson (2005) in his book Surface Strip Coal Mining Handbook, published by the South African Colliery Mine Managers Association dealt about this aspect of locked coal reserves and their mining safely. Schalekamp (2006) dealt on the financial viability of coal reserves within previously mined areas of the Witbank coalfield. Panigrahi et al (2013) studied into occurrence of ûre in opencast workings over developed coal pillars and evolving control parameters for its safe extraction for few Indian coal mines.

Panigrahi et al (2014) in their paper 'Safe extraction of developed coal pillars by opencast method: A case study of Ramagundam opencast mine' had dealt extensively on identifing controllable mining parameters that have strong bearing towards occurrence of fire. This may include mine design parameters, choice of equipment and/ or maneuvering mine operational parameters. A research work has been conducted over a dozen such mines operating across India during 2009-12 and not only critical parameters for occurrence of fire have been identified but also geometrical/empirical formulae have been evolved. The purpose of this study is to develop a safe extraction method of extracting locked coal pillars based on field observations evolved of empirical/geometrical formulae by using engineering empirics.

Mandal & Das (2016) proposed that the locked-up coal be extracted by replacing the developed coal pillars with artificial pillars, they presented an extraction methodology designed for this and its evaluation through numerical modeling for applied suitability underground.

Ngwenyama, et al (2017), documented the factors and challenges affecting coal recovery by opencast pillar mining in the Witbank coalfield in South Africa. Kumar, Ashok et el(2019) reported about the various developments made for mechanised extraction of Locked-Up Coal Pillars in Indian geo-mining Conditions.

Pal Roy, et al (2020), suggested safe exploitation of developed pillars of a coal seam above fire affected areas. Mpofu, et al (2024) came up with a detailed guideline for the management of hot holes in surface coal mines keeping safety and productivity of mining operations. Working further on this aspect Coaltech, Australia in the year 2022 published a book entitled 'Best Practice Guidelines (BPG) for managing hot holes in opencast coal mines'.

To recover the coal from developed galleries, the approaches involve –

Locating the fire areas (including in galleries) by consulting the mining plan of the old workings.

Locating fire by advanced techniques. Way back in 1994, Bhattacharya & Reddy reported about the use of airborne thermal infrared data for Underground and Surface Coal Fire Detection in India's Jharia Coalfield. Srivastava, V. et al (2018) studied the use of pixel values of the satellite data for determination of coal seam fire area in the Jharia coalfields. Pandey, J. et al (2024) had used remotely sensed and ground thermal data for detection of surface and sub-surface coal mine fire of Jharia Coalfields.

Using Thermal Data obtained from satellites. At present, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is the only available spaceborne sensor, which provides multi-channel thermal data. ASTER provides moderate-resolution thermal data useful for mapping of coal fires, which generally have small spatial dimension Mukherjee et el(2019) and Guha & Kumranchat(2012) reported about the use of satellite based data detect opencast coal mine areas.

BENCH DESIGN

Design of benches immediately over coal seam, in a manner such that the holes do not puncture into the galleries. While drilling holes care need to be taken to avoid puncturing.

TEMPERATURE CONTROL

Monitoring temperature rise and bringing down the temperature by water sprinkling as well as filling drilled holes with water.

TEMPERATURE MEASUREMENT

The best way to manage blasting and excavation in such mines is to have a proper temperature measurement system. Commence any operation in such mines, is to detect the temperature at different parts. For this need for accurate hot hole temperature measurement instruments are required. These are of three types –

1. Thermocouples,
2. Thermometers, and
3. Infrared devices

These devices have distinct features and differ according to the method used to detect the temperature. The devices can be classified as detecting the temperature in-hole or from surface. Those temperature measurement devices that detect the temperature while placed in-hole are recommended as they give a more accurate temperature reading while immersed in the hole environment. Table 1, presents the list of some devices.

BLAST DESIGN AND SELECTION OF EXPLOSIVES AND ACCESSORIES

Optimise number of holes to be blasted in a round that all operations are completed at the shortest possible time. In such mines where majority of holes are puncturing into galleries, having fire, to blast the hard strata of overburden as well as coal is a very challenging job. In India DGMS has brought out Technical Circular based on detailed extensive deliberation with PESO, coal mine operators, research institutions and explosive manufacturers. DGMS Circular (Tech) No. 2 of 1985 and No. 2 of 1990 shall be taken into strictest compliance. Globally, efforts were made to develop heat resistant explosives to use in developed gallery blasting. Pradhan (2025) had also re[ported about the blasting practices adopted in some BCCL coal mines.

Pal Roy et al (2023) had undertaken blasts in Jharia

Table 1 : Major type of temperature measurement devices(ABB, 2013 & Satyendra, 2020)

Measurement Methods	**Measurement Types**	**Temperature Ranges(^{0}C)**	**Error Limits**
Mechanical thermometers	Non wetting liquid filled glass thermometer	-38 to 630	As Mechanical thermometer standards
	Wetting liquid filled glass thermometer	-200 to 400	
Indicator Thermometers	Bimetal thermometer	-50 to 400	1-3% indicator range
	Liquid filled spring thermometer	-30 to 500	1-2% indicator range
	Vapour pressure spring thermometer	-200 to 700	1-2 % of scale length
Resistance thermometers with metal resistors	Pt-resistance thermometer	-200 to 1000	Temperature dependent (0.3 to 4.6^{0}C)
	Ni-resistance thermometer	-60 to 250	Temperature dependent (0.4 to 2.1^{0}C)
Radiation thermometers	Infrared radiation pyrometer	-100 to 2000	In the case of range -100 to 400 (0.4 to 2^{0}C) or 0.5 to 1.5 % of the temperature
	Thermography instrument	-50 to 1500	
	Quartz thermometer	-80 to 250	Resolution ^{0}C
	Gas thermometer	-268 to 1130	Design dependent
	Thermal noise thermometer	-269 to 970	0.1 %
Semiconductor resistance thermometers	Silicon measurement resistor	-70 to 175	0.2 to 3^{0}C
	Hot wire resistance thermometer, thermistor	-40 to 180;-60 to 200 and -100 to 400	Temperature dependent (0.1 to 1^{0}C and 0.5 to 2.5^{0}C)
Optical methods	Fibre optic luminescene thermometer	Max 400	5^{0}C

coalfield which is a massively fire-affected area. They dealt the fire area blasting of Kujama Colliery, Lodna Area of Bharat Coking Coal Limited (BCCL). The blast holes were quenched with water until the temperature of each blast hole came down to below 80^{0}C and total time of blasting operations including charging was restricted to two hours. Mixtures of bentonite, sodium silicate and water were poured to seal micro-fractures and cracks. The methodology discussed in their paper was adopted as standard guidelines to extract a sizable amount of coal under blazing fire. Sharma, M et al (2024), studied the rock fragmentation in a fiery seam of an open-pit coal mine in India and developed a prediction model.

The Australian Explosives Industry and Safety Group. (AEISG) had published a 'Code of Practice (COP): Elevated Temperature and Reactive Ground. The COP places emphasis on charging and blasting aspects such as the selection of explosives and accessories, the sleep time for explosives and shot design, in relation to hot and reactive ground. The four conditions that are encountered on mining blocks as developed by AEISG (2020) and adapted by Tose (2022) to include heat and reactivity values. These conditions are based on heat 20 (temperature of the ground) and the reactivity of the ground, and are explained as follows (in the context of South Africa):

- Normal conditions refer to conditions in which the temperature and the reactivity of the ground or drill holes are less than 40°C and 1% respectively.
- Hot hole conditions are those that have a temperature of 40°C or more and a reactivity of less than 1%.
- Extreme blasting (hot and reactive ground) conditions are those that have a temperature of 40°C or more and a reactivity of more than 1%.
- Reactive ground conditions are those that have a temperature of less than 40°C and a reactivity of more than 1%.

Tanaka et al (2003), Qian, et al(2019) studied the heat resistant explosives. Rakoma,(2013), rchanges/ modifications made in the selection of explosives and accessories reported about the blasting improvements at Landau Coal Mine of South Africa. At this mine there was a fatal accident due to blasting in 2009.

Liu et al. (2020) and Guo et al(2019) explored possibility of using ANFO in hot hole blasting. Indian mines have simply adopted slurry and emulsion explosives to blast in hot holes and have avoided use of ANFO. In case of accessories, the practice has been to totally eliminate shock tubes inside the hole and on the trunk lines. Detonating fuse is only used after ensuring temperature within 80^0C. Pal Roy, et al(2023) suggested and executed cautious blasting techniques to undertake blasting in massively fire-affected area of Jharia coalfields.

Wangÿet al(2025) extensively reported about the status quo and trend of blasting technology in open-pit coal mine fire areas. Their paper had summarized and analyzed the blasting technology in open-pit coal mine fire areas, and proposed efficient and safe blasting technology in fire areas by –

- constructing a three-dimensional engineering geological model of the temperature field in the fire area, using fiber Bragg gratings for full hole depth temperature measurement,
- developing a real-time monitoring system for the temperature field in the fire area, and
- realizing temperature monitoring and early warning system during blasting construction process;
- optimizing inhibitors and flash point enhancers for high-temperature resistant explosives,
- optimizing explosive formulations, and
- developing high-temperature resistant explosive material
- selection of cooling methods and insulation materials for high-temperature blast holes,
- design of insulation protection devices for drug packaging
- developing a failure apparatus of charge when the temperature safety threshold is exceeded for the charge inside the hole
- design an one-way blasting network for high-temperature fire areas;
- developing regulations for blasting operations in high-temperature coal seam fire areas to achieve information and intelligence in fire area blasting.

Some of the best and safe practices to manage hot holes to make them ready for charging of explosives etc are –

(a) Sealing at the collar with a cone or sealing agent, such as an expanding foam, to prevent the ingress of air into the bottom of the hole.

(b) Adopting ‘just-in-time drilling’, which ensures that newly uncovered coal is drilled, blasted, and immediately excavated after exposure to the air. This is similar to the hot-hole management practice of charging, tying up, and blasting as soon as drilling is completed to minimize the time spent time on the block (Eroglu, 2003; Phillips, et al., 2011; Sloss, 2015; Ngwenyama and de Graaf, 2021).

(c) African Explosives and Chemical Industries (AECI) and Bulk Mining Explosives (BME) have developed system of management of hot holes. Rorke and Conradie (2018) reported on small-scale tests, carried out by BME, to characterize the behavior of two explosive product types at high temperatures (up to 750°C). Their research and test concluded that the risk of premature detonation in hot holes is likely to be caused by charging accessories, such as initiators, that are sensitive to detonation above 80°C. Tose (2018; 2022) reported on small- and large-scale tests conducted by AECI to investigate the behaviour of explosives in hot environments. These tests enabled the determination of temperatures at which:
  - ➤ grey-white fumes start to form (110°C);
  - ➤ emulsion product is ejected (140°C–220°C);
  - ➤ brown fumes are released (180°C);
  - ➤ detonation/ deflagration occurs (220°C–260°C)

Hazards/Dangers associated with the working in such environments may expose workers to hazards such as (AEISG, 2020; Tose, 2022):

- ➤ hot air exhausted from underground;
- ➤ high concentration of noxious gases, such as carbon dioxide, carbon monoxide, and sulfur dioxide;
- ➤ premature detonation due to: • temperature increase, which affects the chemical composition of explosives products; • softening and/or melting of initiating system components.

FIRE MANAGEMENT

Singh & Singh(2018) developed and adopted a mechanised spraying device for spraying the fire protective coating material for preventing spontaneous combustion in coal benches of opencast mines jointly by Central Mining Research Institute, Dhanbad and M/s Signum Fire Protection (India) Pvt. Ltd., Nagpur under Science & Technology (S&T) project funded by Ministry of Coal, Govt. of India. Their main objective has been for the mechanised spraying device and its application.

Liu, Y et al(2024) explained that the Infrared thermal imaging is only applicable to the detection of high-temperature anomaly areas on the shallow surface. An integrated use of the spontaneous potential method and drilling detection can accurately delineate the range of the outcrop fire area and lay a foundation for subsequent fire area management. They also reported about the application of comprehensive fire prevention and extinguishing technologies, such as three-phase foam filling fractures for fire extinguishing and cooling, colloid injection for plugging air leakage channels, and loess backfilling for re-combustion prevention, can effectively remove the threats of outcrop fire areas and ensure the safe production of coal mines.

MECHANISATION

Deployment of small capacity HEMM so that while extracting OB & Coal the machineries do not get sunk.

ENVIRONMENTAL IMPACT

Apart from land subsidence this method causes severe environmental problems. Mohalik, N.K. et al (2004) dealt on the environmental impact of coal mine fire during excavation of developed galleries by opencast method in Jharia coalfields.

STABILITY OF MINE OPERATIONS

Rajak, G.et el (2022) applying Three-Dimensional Finite Element Method studied the stability analysis of underground developed pillars of opencast coal mine of Jharia coalfields. For this, 3D numerical modelling technique was applied by them to assess the condition of the underground pillars and galleries. From their study, it can be concluded that the pillars and galleries of the workings for a maximum of 15 m from the slope surface fails severely. They recommended for special precautions while approaching the developed coal seam/workings.

Rajak & Hemant (2023) presented the effect over developed underground workings on the stability of the opencast slope. They compared the various parameters like critical Strength Reduction Factor (SRF), total displacement and maximum shear strain. Their study showed that the safety of the slope made on standing pillars/developed galleries is less than a slope made on virgin strata. Islavath, and Deb (2018) using three-dimensional numerical modelling techniques studied the stability analysis of underground stope pillars. Their research also help in understanding the pillar stability in case of a developed gallery system.

SAFETY GUIDELINES OF DGMS

To ensure safe operations while mining over developed galleries, DGMS had issued CircularTech.3/1980, which mandates minimum 3m parting between blastholes and coal seams, prohibits drilling in overburden above galleries. Similarly, the Circular Tech. 2/1985: Restricts explosives to slurry/emulsion types in fiery areas; requires temperature monitoring (<80°C) and asbestos lining for cracked holes The CircularTech.4 of 2006, relate to post-blast void inspections, 24-hour re-entry delays, and thermal imaging for fire detection. The latest circular in this series has been of 2018. Reproduced below the some of the recent Technical Circulars issued by DGMS Notification issued on 1st October 2018.

G.S.R. 986(E).—In exercise of the powers conferred on me under Regulation 202 of the Coal Mines Regulations 2017, I, Prasanta Kumar Sarkar, Chief Inspector of Mines, also designated as the Director General of Mines Safety, hereby, specify the Conditions for conducting blasting in fire Areas in an opencast coal mine, as follows:
Conditions for conducting blasting in fire areas in an opencast coal mine
(See Regulation 202 of the Coal Mines Regulations 2017)

1. Blasting operations shall be carried out under direct supervision of an Assistant manager in charge of Blasting operations.
2. Persons trained in the job of blasting in Fire area only shall be deputed for the said operation.
3. No explosive other than slurry or emulsion explosives shall be used.
4. Blasting shall be done with detonating fuse down the hole.

5. Temperature inside the blast holes shall be measured (before filling with water) and if the temperature exceeds 80°C, in any hole, such hole shall not be charged. Records of measurement of temperature in each hole shall be maintained in a bound paged book and shall be signed by the Assistant manager incharge of Blasting operations and countersigned by manager.
6. All blast holes shall be kept filled with water. When any hole is traversed by cracks or fissures, such hole shall not be charged unless it is lined with an asbestos pipe and the hole filled with water. In addition, bentonite or any other effective material shall be used for sealing any cracks at the bottom of the holes.
7. Detonating fuse shall not be laid on hot ground without taking suitable precautions which will prevent it from coming in contact with hot strata.
8. Hottest holes shall be loaded last. Uncharged holes shall be filled with water/ sandy material.
9. Carbonaceous material shall not be used for stemming.
10. The charging and firing of the holes in any one round shall be completed expeditiously and in any case within 02 hours.
11. Regular monitoring of Carbon Monoxide (CO) shall be done by a competent person authorized by the manager, during charging of the holes. If CO is more than 50 ppm, all persons from the area shall be withdrawn.
12. Water spraying/quenching arrangements shall be kept available at the blasting site to deal in case of emergency.
13. Precautions while drilling in Overburden or Coal over the underground workings in Opencast Mines.

A. Where the underground workings are accessible: Before commencement of blasting operations in the quarry:
(1) Such workings shall be surveyed and cleaned of coal dust and thickly stone dusted.
All persons shall be withdrawn from the underground in the same working seam or any other seam or section connected therewith and no work person shall be re-admitted into the said underground workings unless the same have been inspected by a competent person duly authorized for the purpose by the manager and found free from any noxious gases and or signs of fire, etc.

(2) The underground workings to be quarried shall have sufficient thickness of horizontal barrier as stipulated in the Regulation 121(2) of the Coal Mines Regulations, 2017, otherwise shall be isolated by explosion proof stoppings such as to withstand the force of vibration of blasting, from any active working area either in the same or different seam or section or /mine as the case may be, so as to prevent transfer of danger of blasting to the said active underground workings.

B. Where the underground workings are not accessible: Before commencement of blasting operations in the quarry:
Such workings shall be treated with incombustible dust ahead of the quarry face fed through surface boreholes and dispersed by compressed air. The following procedure is recommended for treating the inaccessible workings underground with stone dust:
(a) Ahead of the bottom bench in overburden, holes shall be drilled 18 metre apart in grid pattern from top bench in overburden or surface to the underground galleries. The distance between the 1st row of holes and quarry face should be 06 metre or less.
(b) After holing through of the galleries in coal, the drill rod shall be withdrawn and at least 02 tonne of stone dust fed through the borehole.
(c) The drill rod shall then be lowered through the borehole again so that it is well in the heap of stone dust dropped on the floor of the underground galleries.
(d) Compressed air shall then be blown at the rate of not less than 20 cu. m. per minute under pressure of at least 3.5 kg/ cm2 for a minimum of 45 minutes. This time can be proportionately reduced if compressed air at higher pressure is available.
(e) The steps (b), (c) and (d) shall be repeated with 02 tonne or more of stone dust dropped in each hole.
(f) If perimeter of galleries exceeds 14 m, the quantity of stone dust dispersed shall be proportionately increased by repeating the whole process a second time.
(g) For greater effectiveness, the holes shall be drilled in the junctions of the galleries.
(h) For better dispersability, it is desirable to use pure limestone dust or dolomite dust with least possibly silica content. The stone dust should preferably be water-proofed in humid and wet conditions.
(i) It shall be possible to improve the efficiency of the operation by fabricating special equipment or device which would enable the stone dust to be airborne

near about the mouth of the borehole instead of dumping the stone dust at the bottom of the hole and then attempting to disperse it with compressed air as outlined in the procedure given above.

Note: None of the holes put down for stone dusting the underground workings are to be utilised for any other purpose, except for determining the thickness of overburden, etc. and other monitoring purposes.

C. General Precautions:

(1) Surveying: Before commencement of the drilling of shot hole over the underground workings in the opencast mine, surveying shall be done to legibly mark the galleries, pillars & staple pits in the blasting area.

(2) Location of holes: The holes drilled in the overburden bench lying immediately above the coal seam (referred to hereinafter as last overburden bench) shall not lie immediately above the galleries in order to ensure that the blast-holes do not directly fire into the underground workings.

(3) Safe parting: The depth of holes in the last overburden bench shall be such as to leave atleast 06m thick overburden above the coal seam, and to ensure compliance with this requirement, a pilot hole shall be put for each round of blasting to determine the total thickness of overburden over the coal seam.

(4) Compacting of the galleries: After blasting the last overburden bench over developed galleries, loading operations shall not be started till the blasted area is fully compacted to prevent any chance of pot holing and declared free from any fire and safe by the blasting officer. Special care is to be taken to fill the shafts or staple pits whether vertical or inclined.

(5) Workings developed in more than one section: Where more than one section of the seam had been developed on pillars, the shot holes shall not be drilled to within 03 m of a lower section, and care shall be taken that the blast holes do not directly fire into any underground gallery.

(6) Delay detonators not to be used: Unless otherwise permitted by DGMS in writing and subject to such conditions as may be imposed, no delay action detonators shall be used in coal, and the manner of extraction of pillars shall be by drilling and blasting holes in coal pillars only from top downwards.

(7) Use of water ampoules/moist sand: All holes in the last overburden bench and/or in coal shall be charged with water ampoules or with moist sand of at least 0.6m in length at the bottom of the hole.

(8) Where there is any doubt and particularly where there are cracks and crevices, the bottom 02m length of the hole shall be filled with sand.

(9) No person including shot-firer shall take shelter within 100 m of the quarry opening and such shelters shall be of stable and strong construction to provide safe shelter to the shotfirer and his helpers.

(10) Sleeping of holes shall not be permitted.

(11) No PETN/TNT based cast booster shall be used for initiating non-cap sensitive slurry/emulsion explosive in coal benches and overburden benches of a fiery coal seam.

(12) Overburden benches immediately above the coal seams and other fiery areas in the mine, the explosive charge shall be fired by detonator attached to the detonating cord at the surface and not within the shot hole.

(13) All explosives, cast boosters, detonators and detonating cord shall be subjected to proper testing in an approved laboratory in respect of temperature sensitivity, impact sensitivity for safe handling in mines.

A certification to that effect shall be supplied for each batch.

[F. No. Z-20045/01/2018/S&T(HQ)]
PRASANTA KUMAR SARKAR, Chief Inspector of Mines

CONCLUSION

In this paper an attempt was made to analyse various aspects of mining of locked coal pillars or developed galleries by opencast methods both in India and abroad. Most Indian coalfields have such problems.

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India's Uranium Metamorphosis: A Tapestry of Strategies for Nuclear Grandeur

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ABSTRACT

India's exalted endeavour to magnify its nuclear capacity twelvefold to 100 GWe by 2047, a cornerstone of the Viksit Bharat ethos and the quest for net-zero emissions by 2070, is inextricably bound to the assurance of uranium plenitude. This discourse illuminates the revolutionary 2025 policy reforms that unshackle the erstwhile state monopoly over uranium pursuits, inviting private dominion in exploration, extraction, and importation. It scrupulously dissects India's energy exigencies, the abyssal gulf between uranium supply and demand—exacerbated by the burgeoning power requisites of artificial intelligence (AI) data centres, projected to devour 40–50 TWh by 2030 (3% of total electricity) and escalate to 1,000–1,500 TWh by 2070—and the dichotomous approaches of indigenous augmentation and international consortia to forge an unassailable fuel conduit. It further expounds upon the contemporary energy mosaic, wherein coal commands over 50%, renewables (solar, wind, hydro) approximate 40%, and nuclear but 3%, whilst elucidating nuclear's pre-eminence through superior capacity factors (81–93% versus solar's 17–28%), diminished emissions, and unwavering baseload reliability, rendering it indispensable for AI's incessant demands. Anchored in erudite treatises and contemporaneous policy mandates, this exposition advocates a harmonious alliance betwixt industry and academia to nurture adept human capital, thereby elevating India to a sovereign pinnacle in pristine energy whilst fortifying its energetic autonomy.

Keywords: Uranium exploration, extraction, nuclear expansion, workforce cultivation, , industry-academia synergy, Energy mosaic, AI data centres, Stratagems.

INTRODUCTION

India, the globe's third most prodigious consumer of energy, stands at a crossroads, contending with an insatiable appetite for power amid burgeoning urbanisation, industrialisation, and climate-induced exigencies for cooling (International Energy Agency [IEA]). As of September 2025, the nation's installed electrical capacity approximates 490 GW, with coal reigning supreme at over half the generation matrix (India Briefing, 2025). Yet, coal's dominion is marred by grievous environmental tolls: emissions of sulfur dioxide, particulates, and heavy metals precipitate up to 112,000 annual mortalities and decimate agricultural yields by 10% in afflicted regions (Vig et al., 2023). Operational frailties, exacerbated by high-ash content (up to 60%) and water paucity, have culminated in losses of 60 billion units since 2014. Hydroelectricity, contributing nigh on 47 GW, is fettered by ecological despoliation, community dislocations, and erratic yields due to drought-induced diminutions (Pandit et al., 2023). Wind power, approaching 48 GW, is beleaguered by infrastructural deficiencies, grid integration delays, and land acquisition impediments, yielding capacity factors below 30% (BillionBricks; Power Line, 2024). Solar energy, surpassing 100 GW, grapples with land scarcity, intermittency (capacity factors of 17–28%), and prohibitive costs for storage to mitigate variability (PV Magazine India, 2024; Fenice Energy).

The extant energy mosaic reveals coal's hegemony at over 50% of the mix, renewables (encompassing solar at ~21%, wind at ~10%, and hydro at ~10%) aggregating to approximately 40%, and nuclear constituting a mere 3%, a composition ill-suited to the imperatives of sustainability and reliability (MoSPI, 2025). In contradistinction, nuclear energy emerges as a paragon of virtue, boasting capacity factors of 81–93%, ensuring steadfast baseload provision, in stark contrast to solar's 17–28%, necessitating 3–6 GW of installed solar to rival 1 GW of nuclear output (Stanford, 2024; U.S. Department of Energy). Its lifecycle emissions

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are fourfold lower than solar's, and its land footprint is 27 times inferior to coal and 34 times less than solar, whilst modern reactors enhance safety (Carnegie Endowment, 2024; U.S. Department of Energy). This aligns impeccably with India's aspirations for 100 GWe nuclear capacity by 2047 and net-zero emissions by 2070, alleviating fossil fuel import burdens equating to 5% of GDP and harnessing indigenous thorium reserves for enduring sovereignty (World Nuclear Association, 2025; MoSPI, 2025). The ascent of indigenous artificial intelligence (AI), propelled by the India AI Mission, further intensifies this mandate; AI data centres and encryption facilities are poised to escalate demand from 960 MW to 9.2 GW by 2030, consuming 40–50 TWh annually—potentially 3% of total electricity—and surging to 500–800 TWh by 2050 (2–5% of capacity), culminating in 1,000–1,500 TWh by 2070 (CBRE, 2024; S&P Global, 2025). This computational voracity demands uninterrupted power, rendering nuclear energy, particularly via small modular reactors (SMRs), an indispensable bulwark for AI-driven innovation and decarbonisation, as its unwavering reliability obviates the intermittency plagues of renewables (World Nuclear Association, 2025). Meghalaya's uranium province is located in the Mahadek Basin and has sandstone deposits like Domiasiat (Kylleng-Pyndensohiong-Mawthabah or KPM, which has about 9,500 tonnes of U) and Wahkhyn-Wahkut. This area has 11% of India's total reserves, which are more than 20,000 tonnes of U at a concentration of 0.10% eUƒ Oˆ (EARFAM 2015). Environmental radiation surveys, such as the study conducted by Dhurandhar et al. (2020), create important standards for making sure that mining operations are safe. India wants to achieve energy security, reduce geopolitical risks, and show its leadership in sustainable nuclear innovation by using its large thorium reserves (25% of the world's total at 11.6 million tonnes) and moving forward with its three-stage nuclear program. Yet, the triumph of this vision hinges upon surmounting uranium supply constraints, necessitating policy reforms, global partnerships, and human capital fortification.

POWER REQUIREMENTS FOR AI AND DATA CENTERS UNTIL 2050

India's energy needs are growing a lot because of the growth of AI and data centers. By 2030, the capacity of data centers is expected to reach 2,000 MW, then 4,000 MW by 2035, and maybe even 10,000 MW by 2050. This is because of AI workloads, cloud computing, and digital transformation efforts like the India AI Mission (Dhurandhar, 2025). Training AI for big language models takes a lot of megawatt-hours, and data centers use 1-2% of the world's electricity right now. By 2030, that number is expected to rise to 3-4%. As of now, data centers in India use about 1% of the country's electricity (10–12 TWh per year). By 2040, this number is expected to rise to 50–75 TWh, and by 2050, it is expected to rise to 100–150 TWh. This means that an extra 15–20 GW of capacity will be needed (Dhurandhar, 2025). Nuclear power is great for baseload needs because it is very stable and doesn't produce much pollution, unlike coal or renewables that only work sometimes. AI-powered data centers could need 10 to 15% of India's goal of 100 GWe of nuclear power by 2050 (10 to 15 GWe). The strategic placement of nuclear facilities near data center hubs (like Mumbai, Bengaluru, and Hyderabad) and the use of small modular reactors (SMRs) could improve supply. The waste heat from reactors could also help data centers cool down more efficiently (Dhurandhar, 2025).

GLOBAL URANIUM DEPOSITS: A TAXONOMIC SURVEY

Uranium deposits, as catalogued by the IAEA's UDEPO compendium, are delineated by geological provenance, with global recoverable resources estimated at 7.935 million tonnes U (at costs up to $260/kg U) as of 2024 (Fig. 1), sufficient for nuclear demands through 2050 (IAEA/NEA, 2024; Dhurandhar, 2004, 2007, 2009). Historically, exploration burgeoned post-World War II, transitioning from sandstone and vein deposits to high-grade unconformity-related and hematite breccia complexes (Table 1). Key typologies include:

- **Unconformity-related Deposits**: Predominant in Canada's Athabasca Basin (53 deposits) and Australia (21 deposits), these high-grade formations, linked to sandstone-basement unconformities, encompass 79 global deposits, with Canada holding 1,074,449 tU.
- **Sandstone Deposits**: The most numerous, totalling 384, with prominence in Kazakhstan (25), the USA (152), Uzbekistan (24), and Niger (28); these low- to medium-grade deposits are amenable to in-situ leaching (ISL).
- **Hematite Breccia Complex Deposits**: Notable in Australia (7 deposits, e.g., Olympic Dam, 1,939,970 tU) and South Africa (26 deposits), associated with iron oxide-copper-gold systems.
- **Quartz-pebble Conglomerate Deposits**: Found in South Africa (26 deposits, 426,265 tU) and Canada

(8 deposits), these ancient low-grade formations bear historical import.

- **Volcanic-related Deposits**: Distributed across Australia (4), China (4), and Mongolia (4), tied to volcanic terrains.
- **Intrusive Deposits**: Prevalent in Namibia (10, 444,221 tU) and Canada (16), often granitic.
- **Vein Deposits**: Common in France (32), Kazakhstan (27), and Russia (20), structurally governed.
- **Metasomatite Deposits**: Occurring in Russia (10) and Ukraine (4), linked to sodium metasomatism.
- **Other Types**: Encompassing metamorphic, surficial, and phosphorite deposits, totalling 150 globally (e.g., USA 20, Morocco 4).

Global deposits number 1,024, aggregating 11,462,607 tU, with 2024 production at 60,213 tU, projected to rise to 62,200 tU in 2025, led by Kazakhstan (43%), Canada, Australia, Namibia, and Niger (OECD-NEA, 2025; World Nuclear Association, 2023) (Fig. 2). Demand is forecasted to surge 28% by 2030, necessitating sustained investment (Table 6) amid geopolitical vicissitudes (OECD-NEA, 2025) Fig. 3.

Table 1: Global Known Recoverable Uranium Resources

Country	Uranium Resources (tU)	Share of Global Reserves (%)
Australia	16,84,100	28
Kazakhstan	7,36,000	12
Canada	5,88,700	10
Russia	4,70,100	8
Namibia	4,70,100	8
Uzbekistan	3,85,000	6
South Africa	3,20,900	5
Niger	3,11,100	5
Brazil	2,76,100	5
China	2,23,900	4
Mongolia	57,000	1
Ukraine	57,000	1
Rest of World	4,49,500	7
Total	60,75,200	100

Source: *IAEA/NEA, 2024*

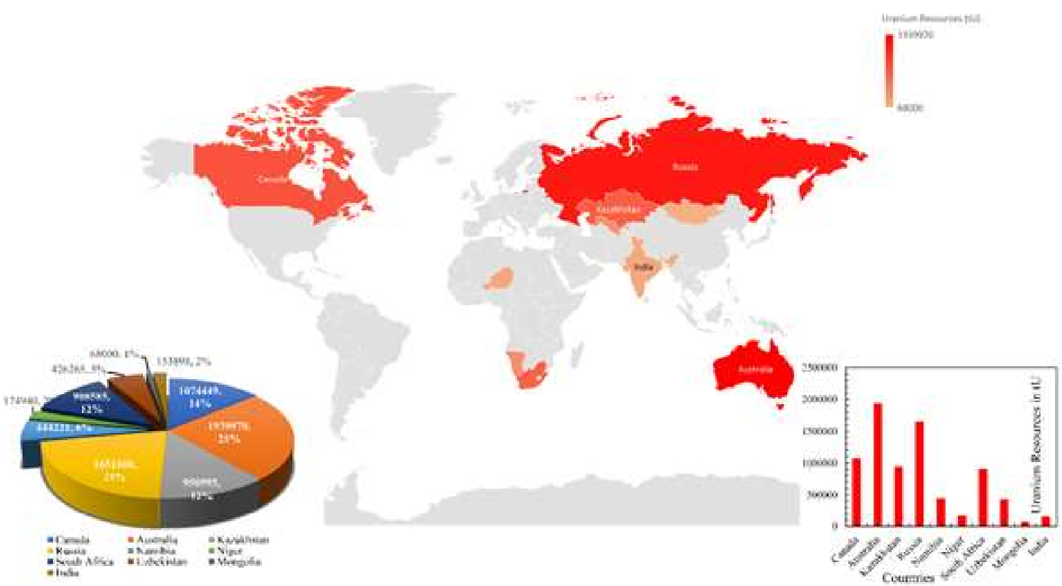

Figure 2: Uranium Resources by Key Countries/Regions (inset:Bar and Pie Charts)

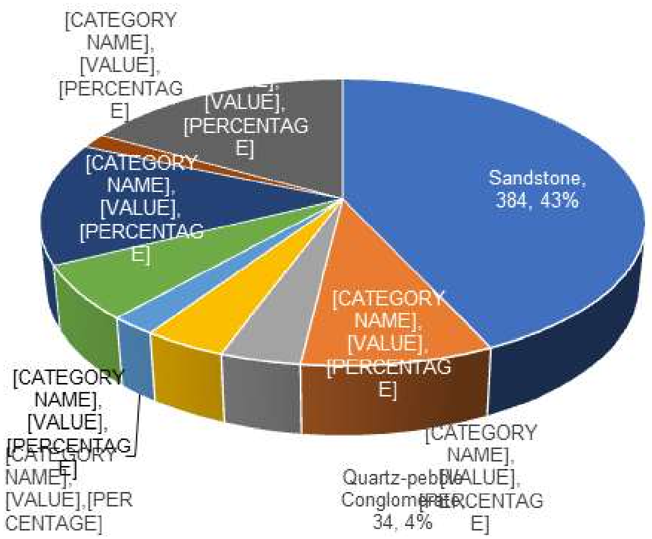

Figure 1: Global Uranium Deposits by Type (Number of Deposits)

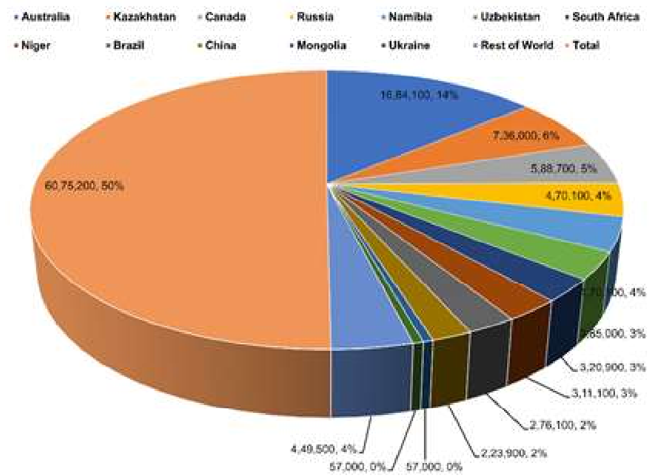

Figure 3: Global Recoverable Uranium Resources (tU and % Share)

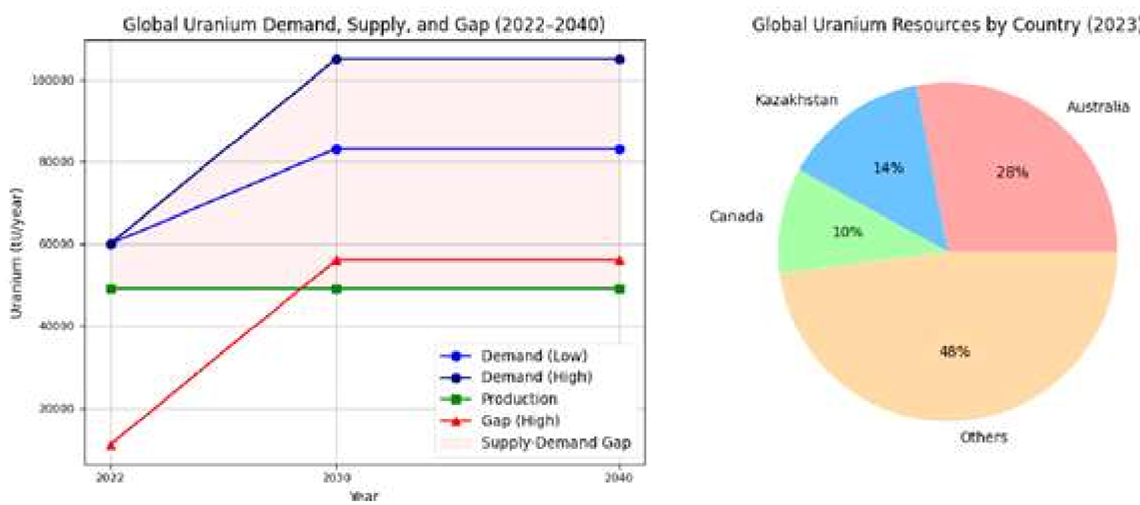

Figure 4: Global Uranium Demand-Supply and Resources Distribution by Countries

INDIA'S URANIUM ENDOWMENTS

India's uranium resources (Table 2), though domestically consequential, pale against global titans like Australia (1.7 million tU) and Kazakhstan (906,800 tU). As of 2025, in-situ resources total 292,867 tU, with 282,401 tU classified as reasonably assured and 10,466 tU as inferred at costs up to $260/kg U, while recoverable reserves approximate 76,000 tU, sufficient for 10,000 MW over 30 years (Department of Atomic Energy, 2021; IAEA/NEA, 2024). Predominantly low-grade (0.1–0.2% Uƒ Oˆ), extraction costs ($130–260/kg U) exceed global averages, with deposits spanning unconformity (3), sandstone (2), vein (4), metasomatite (1), and others (1). Key sites include Jharkhand's Jaduguda cluster (70,000 tU), Andhra Pradesh's Tummalapalle (120,229 tU), Telangana's Lambapur-Peddagattu, and Meghalaya's Domiasiat-Mawthabah (9,500 tU) (PIB, 2024) Table 2. In 2023, production languished at 485 tU (1% globally), processed at Jaduguda (2,500 t/day) and Tummalapalle (3,000 t/

day, expanding to 4,500 t/day) (WISE Uranium). Geological intricacies, elevated costs, and societal opposition curtail output to 36–40% of demand, necessitating rigorous evaluations under JORC, NI43-101, CRIRSCO or IAEA standards, potentially revising figures downward by 30% (IAEA/NEA, 2024).

Table 2: India's Uranium Resources and Production (2022–2040)

Category	2022 Actual	2030 (Low)	2030 (High)	2040 (Low)	2040 (High)
Recoverable Resources (tU)	2,52,500	2,52,500	2,52,500	2,30,000	2,30,000
In-Situ Resources (tU)	3,35,000	3,35,000	3,35,000	3,00,000	3,00,000
Production (tU/year)	488	960	1,300	960	1,300
Key Sites	Jaduguda, Tummalapalle	Jaduguda, Tummalapalle, New Mines	Same	Same	Same

Sources: IAEA Red Book 2024, DAE 2021

THE NUCLEAR IMPERATIVE IN INDIA'S ENERGY TAPESTRY

India's nuclear odyssey commenced in the mid-20th century with indigenous Pressurized Heavy Water Reactors (PHWRs), bolstered post-2008 by the Nuclear Suppliers Group (NSG) waiver enabling imported technologies (World Nuclear Association, 2025). Presently, 25 reactors deliver 8.88 GWe, yielding 48.2 TWh (3% of electricity) (India Briefing, 2025). The Viksit Bharat vision aspires to 100 GWe by 2047, constituting 9–10% of electricity, indispensable for net-zero by 2070 (World Nuclear Association, 2025). Nuclear's reliability, scalability, and negligible carbon footprint complement renewables, facilitating hydrogen production and sustainable industrialisation. By 2031, capacity is slated to reach 22.48 GWe via 11 reactors under construction (8.7 GWe), including PHWRs and Kudankulam VVERs (World Nuclear Association, 2023). Bharat SMRs, anticipated by 2033, promise efficiency and reduced uranium intensity (World Nuclear Association, 2025). Yet, historical fuel shortages—evidenced by 40% load factors in 2008—underscore the urgency of securing uranium (WISE Uranium).

THE CHASM OF SUPPLY AND DEMAND

India's nuclear aspirations are imperilled by a profound disparity between uranium demand and supply. In 2022, 8.88 GWe required 1,350 tU, met by 488 tU domestically (36%) and 862 tU imports (WISE Uranium). Projections augur escalation to 2,000–3,000 tU/year by 2030 for 15–20 GWe, and 6,000–12,000 tU/year by 2050 for 50–100 GWe, yielding a cumulative shortfall of 100,000–200,000 tU (IAEA/NEA, 2024). The ascent of AI exacerbates this, with data centres demanding 40–50 TWh by 2030 (0.5–0.9% of the 100 GWe nuclear target) and 1,000–1,500 TWh by 2070 (1–1.7%), necessitating uninterrupted nuclear power via SMRs (CBRE, 2024; S&P Global, 2025).). By 2050, demand may soar to 6,000–12,000 tU/year to sustain 50–100 GWe, precipitating a cumulative shortfall of 100,000–200,000 tU (Table 3). The historical spectre of fuel paucity, exemplified by 40% reactor load factors in 2008 due to pre-NSG trade embargoes, underscores the urgency of redressing this chasm (Fig. 5). Domestic production, forecast to plateau at 960–1,300 tU/year, mandates robust import and diversification strategies (IAEA/NEA, 2024) Table 3.

Table 3: India's Uranium Demand and Supply Projections (2022–2050)

Year	Capacity (GWe)	Demand (tU/year, Low)	Demand (tU/year, High)	Domestic Production (tU/year)	Shortfall (tU/year, High)
2022	8.88	1,350	1,350	488	862
2030	15–20	2,000	3,000	960–1,300	1,700–2,040
2040	40–60	4,000	6,000	960–1,300	4,700–5,040
2050	50–100	6,000	12,000	960–1,300	10,700–11,040

Sources: IAEA/NEA (2024), World Nuclear Association (2023)

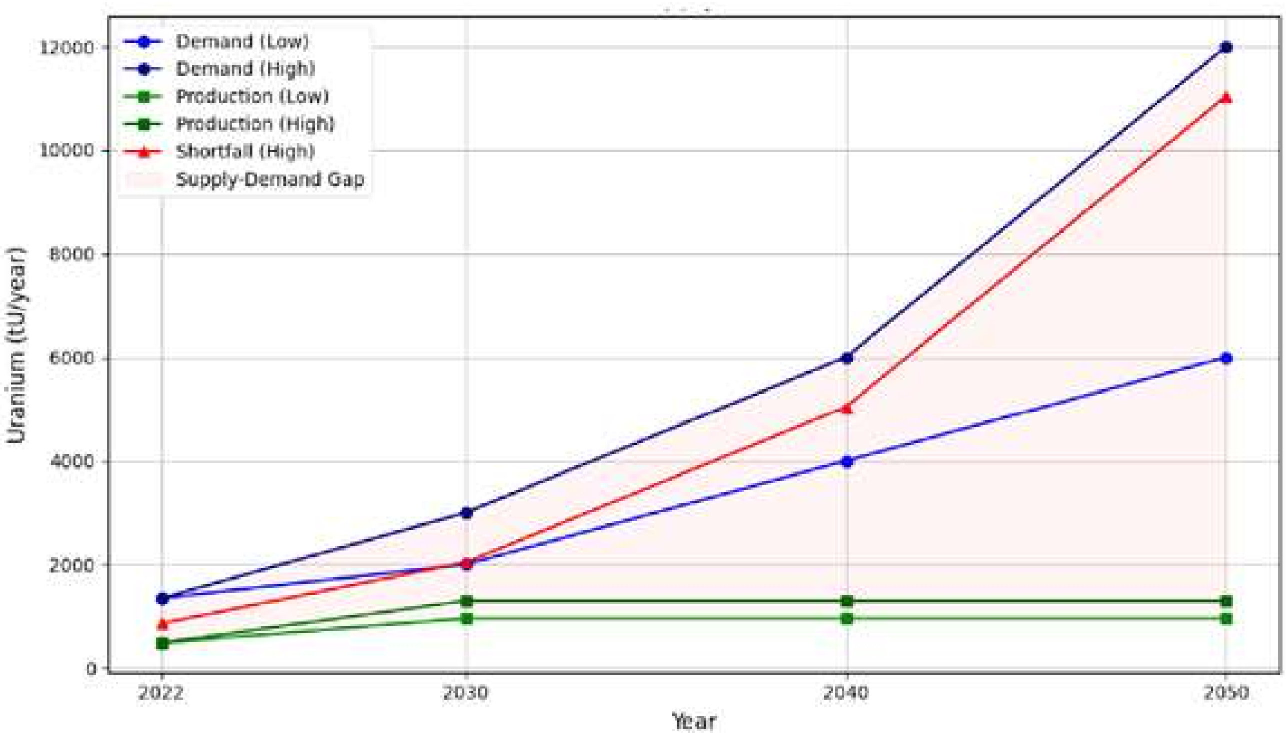

Figure 5: India's Uranium Demand, Supply, and Shortfall (2022–2050)

STRATAGEMS FOR URANIUM SECURITY: DOMESTIC AND GLOBAL VENTURES

Domestically, the Atomic Minerals Directorate has intensified exploration, drilling 900,333 meters from 2020–2023 and augmenting in-situ resources by 93,700 tU, targeting regions like Cuddapah and Singhbhum (PIB, 2024). Projects such as Gogi and Lambapur-Peddagattu aim to elevate production to 960–1,300 tU/year by 2030, yet low-grade ores and societal opposition constrain scalability (WISE Uranium,). Internationally, the 2025 reforms empower private enterprises to pursue abroad mining in Kazakhstan, Canada, Australia, Africa (Namibia, Niger, Tanzania, South Africa), and Madagascar (72,600 tU untapped) (Discovery Alert, 2025). Imports, projected at 9,000 tU by 2033, are sourced from Kazakhstan (20–30%), Russia (30–40%), Australia (15–25%), and Africa (10–20%) Table 4 (OECD-NEA, 2025).

Table 4: Import Sources and Projections (2025–2050)

Region/Country	Production (tU) 2022	Current Share	Projected Share (2030–2050)	Key Contracts
Namibia	5,612	5–10%	10–15%	2009 Agreement
Niger	2,000	0–5%	5–10%	Post-2008 Exploration
Kazakhstan	21,279	20–25%	20–30%	5,000 tU (2009–2019), 2,000 tU
Uzbekistan	3,561	5–10%	10–15%	2,000 tU (2014–2018), 350 tU
Russia	2,600	25–30%	30–40%	TVEL $780M, Kudankulam Fuel
Australia	4,555	0–5%	15–25%	2015 Agreement

Sources: IAEA Red Book 2024, WNA 2025.

Table 5: top 10 uranium producing countries production cost comparison

Rank	Country	Production (tU, 2023)	Global Total %	Est. Avg. Production Cost (USD/kgU)	Notes on Cost/Production
1	Kazakhstan	21112	~39%	~$26–52 (low, mostly ISL)	Dominant producer using cost-effective in-situ leaching (ISL); costs below $40/kgU for most resources.
2	Canada	10986	~20%	~$78–130 (medium-high, underground)	High-grade mines like McArthur River; resources mostly <$130/kgU, but operational costs higher due to depth.
3	Namibia	6985	~13%	~$104–156 (medium-high, open-pit)	Mines like Husab and Rössing; AISC ~$90–100/kgU for some projects.
4	Australia	4658	~9%	~$78–130 (medium, open-pit/underground)	Olympic Dam dominates; resources <$130/kgU, but by-product recovery affects costs.
5	Uzbekistan	4000	~7%	~$52–78 (low-medium, ISL)	Similar to Kazakhstan; efficient ISL methods keep costs competitive.
6	Russia	2600	~5%	~$104–182 (high, varied methods)	Mix of ISL and underground; some resources <$80/kgU, but average higher due to remote sites.
7	China	1600	~3%	~$130–208 (high, mostly underground)	Domestic focus; high costs led to some closures; in <$215/kgU category.
8	Niger	1130	~2%	~$104–130 (medium-high, open-pit)	Mines like SOMAIR; Dasa project cash costs ~$43/kgU, but overall AISC higher (~$48/kgU). Political disruptions in 2023 reduced output.
9	India	485	~0.9%	~$156–215 (very high, underground)	Low-grade ores and small-scale mines (e.g., Jaduguda); among the world's most expensive producers, in upper end of <$215/kgU. Meagre domestic resources limit output.
10	Ukraine	300	~0.6%	~$130–182 (high, underground)	Low-grade ores; costs reduced by innovative methods like heap leaching, but conflict impacted 2023 production.

Sources: IAEA/NEA (2024), World Nuclear Association (2025).

GLOBAL URANIUM PRODUCTION COST AND COMPARISON WITH INDIA (2023).

Production costs vary significantly by mining method (e.g., in-situ leaching in Kazakhstan is low-cost, while underground mining in India is high-cost due to low-grade ores and smaller-scale operations). Where available, are included estimated average production costs in USD per kgU (converted from common $/lb U_3O_8 figures where necessary; note: 1 kgU H” 2.6 lb U_3O_8 for cost equivalence). Costs are approximate based on resource categories and mine-specific data; exact figures are often proprietary, but India stands out as one of the highest-cost producers globally (in the <$215/kgU category, but toward the upper end due to inefficiencies) Table 5.

Global Context: Kazakhstan alone produces over 40 times more uranium than India, benefiting from low-cost ISL methods that make up ~55% of world production. High-cost producers like India and China rely on domestic output for energy security, despite inefficiencies.

- **India's Position**: With only ~0.9% of global production, India's output is constrained by limited high-grade reserves and high costs (estimated 3–4 times higher than Kazakhstan's). This underscores the need for imports and exploration, as domestic production meets <30% of nuclear fuel needs. Costs are elevated due to low ore grades (~0.03–0.06% U) and environmental/regulatory challenges (Table 5).
- **Price vs. Production Cost:** The global uranium spot price in 2023 averaged ~$49/lb U_3O_8 (~$127/kgU), up from prior years, but many low-cost producers (e.g., Kazakhstan) operate profitably below this. India's high costs make it vulnerable to market fluctuations, often requiring subsidies or imports (Fig. 6).

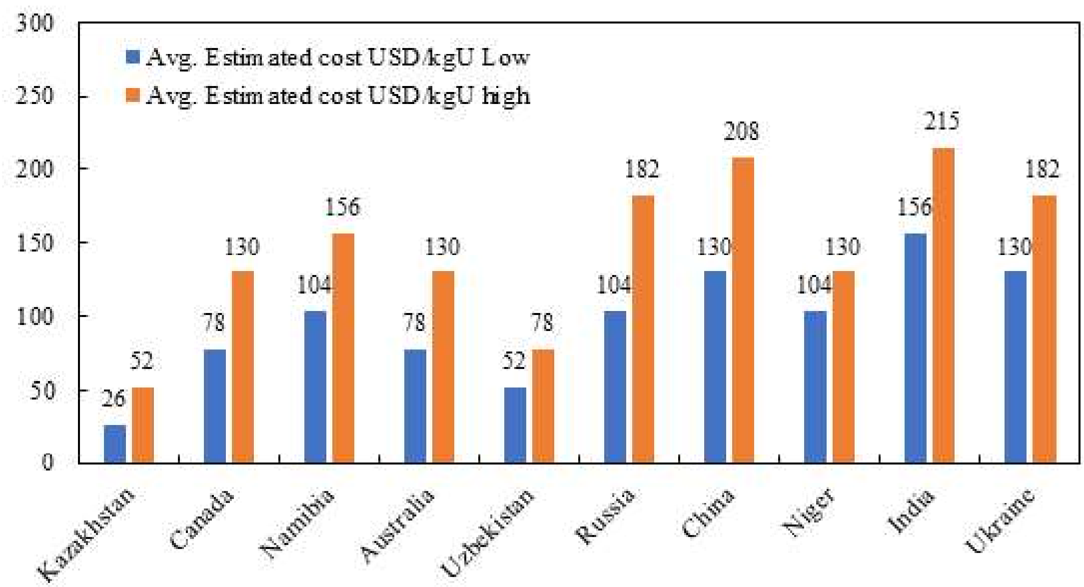

Fig. 6: showing the uranium estimated costs high and low with respect to geographies

This data highlights the geographic disparities in uranium production efficiency (Fig.6 and 7), emphasizing why India pursues foreign sourcing and thorium alternatives for its nuclear ambitions.

Uranium Resources in Africa and CIS Africa's ~1.9 million tU includes Niger (174,940 tU), Namibia (444,221 tU), South Africa (908,585 tU), Tanzania (63,056 tU), and Madagascar (72,600 tU) (IAEA/NEA, 2024). The CIS, Russia, and Mongolia aggregate ~3.1 million tU, led by Kazakhstan (950,995 tU) and Russia (1,651,800 tU) (Dhurandhar, 2004, 2007, 2009, and Dhurandhar 2025). India's strategies encompass long-term contracts with Namibia, partnerships in Tanzania with Rosatom, and exploration in Mongolia and Madagascar.

SWOT ANALYSIS

Strengths: Robust nuclear infrastructure (8/10), diplomatic ties (8/10), ore processing expertise (7/10). **Weaknesses**: Limited resources (6/10), import reliance (6/10), sluggish exploration (5/10). **Opportunities**: African

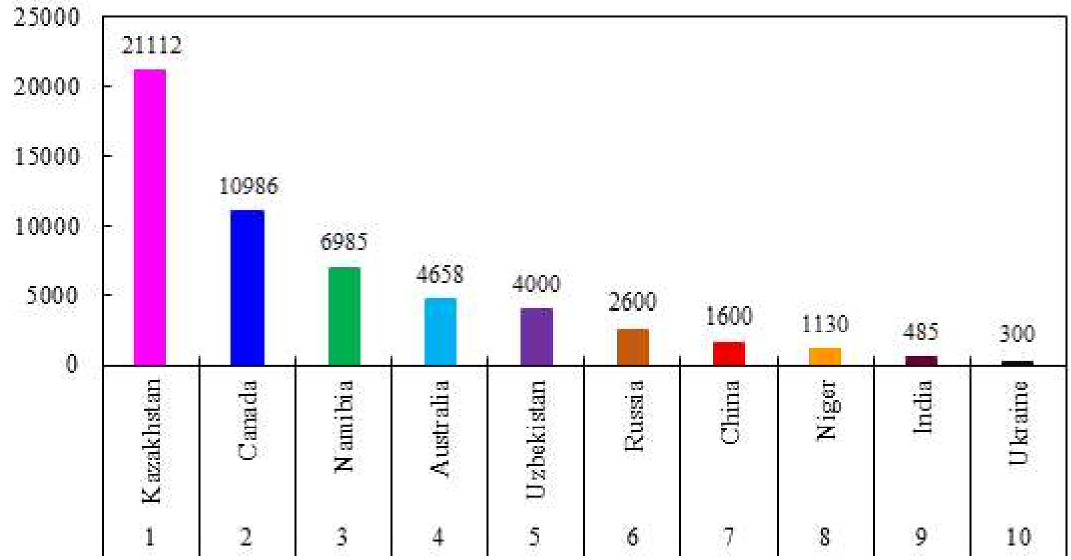

Fig. 7: Top ten uranium production countries and their annual production

supply (7/10), CIS partnerships (7/10), domestic reforms (6/10).**Threats**: Geopolitical risks (6/10), price volatility (6/10), competition (5/10) (Fig. 8). This clearly indicates that the industry can't be dependent on nearly 75% of its requirements on imports. So, the way outs are :

1. Increasing the domestic resources and exploration targets and dismantling State monopoly.
2. High priority exploration targets selection and cost optimisation of the ore.
3. Developing alternate technology like Thorium reactors and alternate fuels.

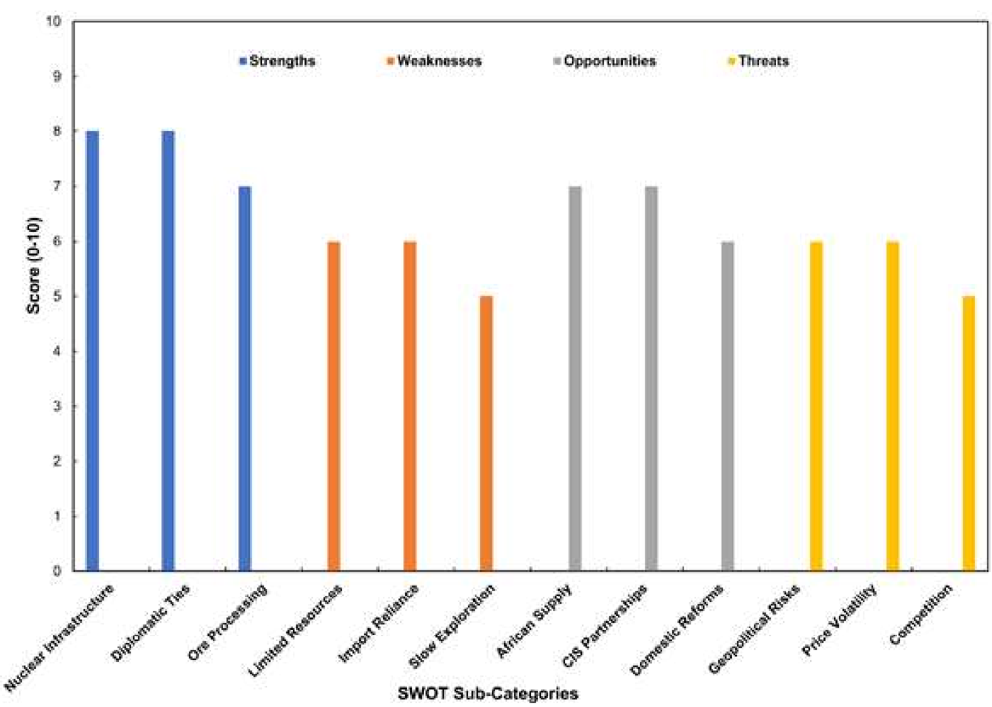

Figure 8: SWOT Analysis of India's Uranium Strategy

THE IMPERATIVE OF DISMANTLING THE STATE MONOPOLY

Since 1962, the Atomic Energy Act confined uranium activities to the Uranium Corporation of India Limited, throttling investment (USD 75 million in 2023)Table 6 and delaying projects amid bureaucratic inertia and public dissent, as evidenced by Meghalaya's Domiasiat-Mawthabah (WISE Uranium). The 2025 Union Budget reforms, amending five statutes, permit private mining, imports, and processing with up to 49% FDI, projecting production increases of 500–1,000 tU/year by 2030 (Discovery Alert, 2025). This liberalisation attracts capital, accelerates operations, and diversifies supply chains, aligned with IAEA safeguards (Government of India, 2025).

Table 6: Investment Opportunities (2025–2040)

Strategy	Potential Impact (tU/year)	Timeline	Key Partners
Private Mining	500–1,000	2027–2035	Domestic Firms, Cameco
FDI in Processing	200–500	2030–2040	Holtec, Westinghouse
SMR Deployment	Reduce demand by 10–20%	2033–2050	GE-Hitachi, Rosatom
Multilateral Agreements	Assured 1,000–2,000	2025–2040	IAEA, Russia

Sources: IAEA/NEA (2024), World Nuclear Association (2025).

GEOPOLITICAL RISKS IN URANIUM IMPORTS AND MITIGATION STRATEGIES

Geopolitical risks make it hard to keep supplies stable. For example, U.S. sanctions after the Ukraine conflict put Russian supplies at risk, and India faces tariff pressures even though it calls its imports a "national compulsion." Russian companies, especially Rosatom, have an effect on Kazakhstan's production. The country is also at risk of problems within its own borders, such as the expected closure of the Inkai mine in 2025 and a lack of sulfuric acid. Instabilities in Niger and Namibia, along with tensions between the US and China, especially over China's limits on important minerals, cause prices to change. In 2023, the spot price of uranium was about $127/kgU.

Mitigation strategies include increasing domestic resources, like the Atomic Minerals Directorate (AMD), which has added more than 93,700 tonnes of in-situ resources in the last five years. The end of the state monopoly in 2025 and the start of private mining with a foreign equity stake of up to 49% led to higher output and easier adoption of new technologies. India buys shares in uranium-rich areas like Central Asia, Africa, and Canada through joint ventures and long-term contracts. It also gets enriched uranium from Russia and France. Working with the Nuclear Suppliers Group (NSG) makes it easier to get things done, and stockpiles of 5,000 to 15,000 tons of uranium help keep things running smoothly. In places like Meghalaya, where exploration stopped in 2018 because of protests, new efforts based on environmental baselines may show promise (Shillong Times, 2022).

HIGH-PRIORITY URANIUM EXPLORATION TARGETS AND COST OPTIMIZATION

Key exploration targets are used to find new resources and enlarge established deposits. The Cuddapah Basin in Andhra Pradesh is home to India's greatest deposit at Tummalapalle (49,000–150,000 tonnes U, 0.03–0.05% Uƒ Oˆ). The Lambapur-Peddagattu and Chitrial areas are being targeted for extensions, with the goal of finding deeper mineralization associated to unconformity using pressure alkali leaching. The Singhbhum Shear Zone in Jharkhand has 70% of the country's reserves and vein-type ores in Jaduguda and expansions like Gudabanda (0.5% U finds in 2024). The goal is to increase output by 3.5 times. Rajasthan's North Delhi Fold Belt (Rohil, Jahaz; about 15,000 tons) is focused on finding albitite and vein-type minerals within a 320 km fracture zone. Karnataka's Gogi (0.1% U) and Telangana's basin extensions (Dhurandhar, 2025) are two new locations that are starting to show signs of growth.

The Meghalaya uranium province in the Mahadek Basin encompasses 1,800 square kilometers and is a high-priority area because it has sandstone-type uranium in the Upper Cretaceous Lower Mahadek Sandstone. Over the past 50 years, AMD has found more than 20,000 tonnes of uranium oxide (11% of India's reserves) at 0.10% eUƒ Oˆ . The biggest deposits are at Domiasiat (KPM, ~9,500 tonnes U) and Wahkhyn-Wahkut, along with satellites like Umthongkut, Gomaghat, Tyrnai, Lostoin (700m northwest of Wahkhyn), and Phallangdilon (EARFAM, 2015). Domiasiat, which was found in the 1980s, is an important find, but exploration stopped in 2018 because of worries about health and environmental effects (Shillong Times, 2022). Wahkhyn, which was found in 1994, has the potential to have higher grades and bigger reserves. This makes it a key target for reactivation under the 2025 private investment reforms (Table 6).

Baseline radiation assessments are crucial for the deposits in Meghalaya. Dhurandhar et al. (2020) executed an extensive mapping of natural environmental radiation in the Shillong Basin, employing radiation meters for low-density regional surveys and gamma ray spectrometry on rocks and soils for high-resolution data acquisition. Results demonstrate variances associated with bedrock. The Mylliem Granite (3.935 mSv/a, 51 ìR/h, 178.066 nGy/s) and South Khasi Batholith (2.42-3.652 mSv/a, 31 ìR/h, 109.502–165.249 nGy/s) demonstrate heightened levels, but sandstone formations such as Upper Mahadek (2.062 mSv/a) and Lower Mahadek (2.935 mSv/a) present reduced doses. Soils have elevated radiation levels compared to bedrock; however, these levels remain beneath those found in global high background radiation regions. This data guides secure mining plans for Domiasiat and Wahkhyn, alleviating public apprehensions regarding radiation effects on health, fauna, and flora (Dhurandhar et al., 2020).

The economic viability is compromised by poor ore grades, leading to elevated expenses associated with underground mining and waste handling, with 99% of material being tailings. Extraction techniques encompass sulfuric acid leaching for the vein ores of Jharkhand, alkali leaching for the stratabound ores of Andhra (exceeding 90% recovery), and analogous acid operations for the albitite ores of Rajasthan. The recovery of by-products from monazite sands or copper tailings has minimal value. In accordance with international cost benchmarks ($50-100/kgU), India aims for a tenfold increase in production by 2032 via in-situ leaching (ISL, yielding 50-70% cost reductions), expenditures (226.5 million USD across 13 projects), the transfer of private and foreign technologies, and waste optimization (bioremediation achieving a 15-20% cost decrease). In Meghalaya, ISL for sandstone-hosted ores may reduce environmental effect, consistent with the baselines established by Dhurandhar et al. (2020), while also accommodating the energy requirements of AI data centres (Dhurandhar, 2025).

ALTERNATIVE TECHNOLOGIES: THORIUM REACTORS, FUSION, AND INDIA'S THREE-STAGE PROGRAM

Uranium limitations require alternate technologies for sustainability. Thorium reactors, utilizing India's 11.6 million tons of thorium (25% of the global supply), generate significantly less waste (35 times lower volume, stable for 300 years), provide resistance to proliferation, and attain a greater fuel burn-up (70 times more energy). Molten salt reactors (MSRs) and advanced heavy water reactors (AHWRs) integrate passive safety mechanisms, including freeze plugs for emergency shutdowns. China's TMSR-LF1 (2 MWt) successfully conducted online refuelling in April 2025, utilizing fluoride salts at 700°C under low pressure to generate U-233 from thorium-232, with intentions to develop a 10 MW demonstration by 2029 and over 100 MWe small modular reactors by 2030 (Dhurandhar, 2025).

India's three-stage breeder program, initiated in the 1950s, incorporates thorium to achieve self-sufficiency (Fig. 9). Stage 1 employs pressurized heavy water reactors (PHWRs) utilizing natural uranium to generate plutonium-239, with 18 reactors now active and an expansion planned to 22.5 GWe by 2032. Stage 2 utilizes fast breeder reactors (FBRs), exemplified by the 500 MWe Prototype FBR at Kalpakkam, anticipated to achieve criticality by 2026, facilitating the breeding of Pu-239 and U-233. Stage 3 implements AHWRs for thorium-U-233 cycles, attaining closed-loop sustainability. Recent developments encompass Clean Core's thorium fuel license and memoranda of understanding for thorium small modular reactors, which bolster economic and energy objectives, including the requirements of AI data centres (NBP 2025, Dhurandhar, 2025).

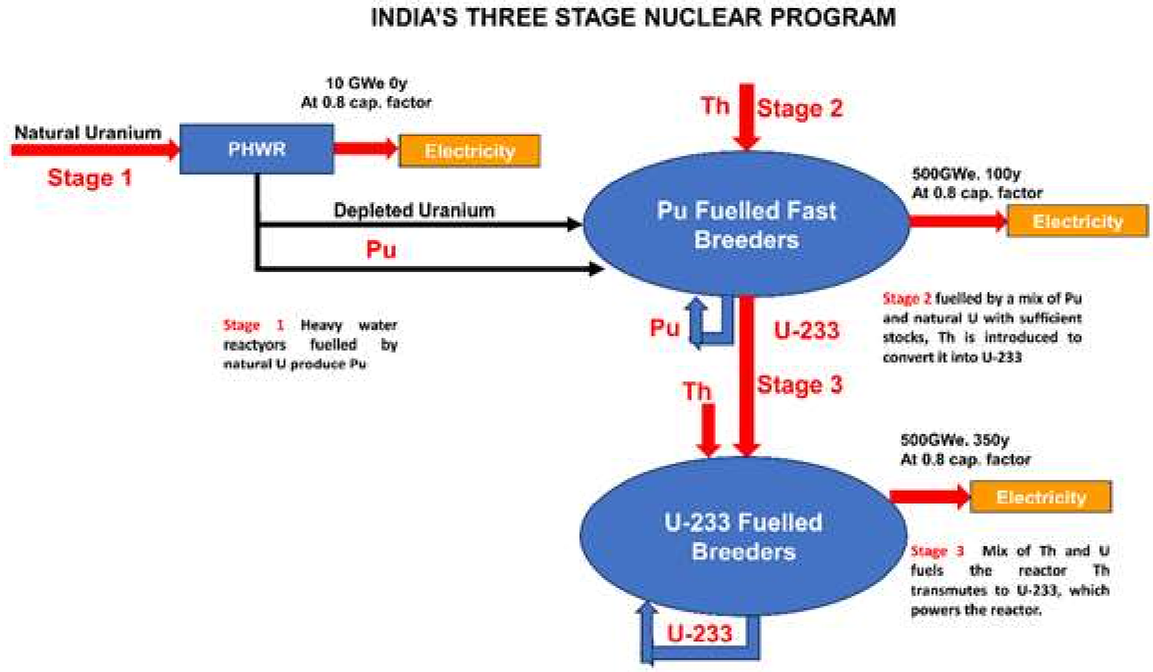

Fig.9. Three stage nuclear program of India

Using ANEEL (Advanced Nuclear Energy for Enriched Life) fuel in PHWRs can solve the initial requirements for triggering Thorium reactors. ANEEL is a patented nuclear fuel developed by Clean Core Thorium Energy. It's a blend of **thorium** and **High Assay Low Enriched Uranium (HALEU)**. This combination is designed to be used in existing pressurized heavy-water reactors (PHWRs), like those in India, without requiring significant modifications (Carbon Credits 2024).

The use of ANEEL fuel offers several potential advantages:

- **Abundant Resources**: It leverages thorium, which is much more abundant than uranium, especially in countries like India.
- **Reduced Nuclear Waste**: ANEEL fuel burns more efficiently and produces a smaller volume of nuclear waste compared to traditional uranium fuels.
- **Proliferation Resistance**: The spent fuel from ANEEL reactors is considered unsuitable for weapons use, addressing a major concern with nuclear power.
- **Increased Efficiency**: The fuel can achieve a higher burnup rate, meaning it can operate for a longer period before needing replacement, which lowers operating costs.

While thorium is fertile and not fissile on its own, it can be used in conjunction with a fissile material, like the HALEU in ANEEL fuel, to start a chain reaction. The fertile thorium-232 then transmutes into fissile uranium-233, which becomes the primary fuel for the reactor. ANEEL fuel is not yet immediately available for commercial use. It is currently in the testing and qualification phase. The US-based company, Clean Core Thorium Energy (CCTE), is collaborating with major Indian entities, including:

- **NTPC Limited:** India's largest power company, to explore the development and deployment of ANEEL fuel in India's existing Pressurized Heavy-Water Reactors (PHWRs).
- **Larsen & Toubro (L&T):** An Indian infrastructure giant, to establish a local supply chain and manufacturing capabilities for the fuel.

The development and deployment are subject to regulatory approvals from both the US and Indian governments, including India's Department of Atomic Energy (DAE).

IMPLICATIONS OF TRADE TARIFFS

The potential impact of trade tariffs, particularly from a Trump administration, is a complex issue. The ANEEL fuel is a blend of thorium and High Assay Low Enriched

Uranium (HALEU), with the HALEU component currently produced at scale only in Russia and China. This makes the supply chain for HALEU a critical factor.

While there are no specific announced tariffs on nuclear fuel components like HALEU, recent US trade threats have focused on tariffs against India for its purchases of Russian oil. Any broad tariff action could disrupt supply chains and increase costs. However, the development of ANEEL fuel is seen as strategically beneficial for both the US and India, as it could reduce reliance on Russian and Chinese HALEU by creating a new market and supply chain. The adoption of ANEEL fuel does not dismantle India's three-stage nuclear program. Instead, it is seen as a parallel and potentially accelerated approach to achieving the program's long-term goals.

- **Three-Stage Program's Approach:** India's three-stage program (Fig.9), envisioned by Dr. Homi Bhabha, is a long-term plan to use the country's vast thorium reserves. The third stage involves using thorium-based fuels after building up a sufficient inventory of fissile material (plutonium) in the first two stages, a process that is time-intensive and will likely not be fully realized until after 2050.
- **ANEEL's Approach:** ANEEL fuel provides a faster and more direct way to start utilizing thorium in existing PHWRs by leveraging imported HALEU. This is seen as a way to gain the benefits of thorium (waste reduction, cost savings, non-proliferation) now, while the three-stage program continues to progress. It essentially provides a "head start" on a thorium-based nuclear future.

Instead of a sign of inactivity, the collaboration with Clean Core Thorium Energy is viewed as a strategic partnership. It allows India to leverage an innovative and potentially more efficient technology developed abroad, while still advancing its own indigenous program. This collaboration allows India to explore a new pathway for utilizing its thorium reserves and to develop its own domestic supply chain for ANEEL fuel.

Fusion reactors, which combine hydrogen isotopes to generate limitless energy from seawater and lithium, produce no enduring waste or risk of meltdown. The International Thermonuclear Experimental Reactor (ITER) accomplished its 2025 objectives, including the vacuum vessel ahead of time, with private funding amounting to $2.83 billion in 2022 aimed toward demonstrations by 2025. India's 10% commitment to ITER (cryostat, cooling) underpins its strategic plan: technology acquisition (2025-2035), demonstration (2035-2050), and commercialization post-2050. The Institute for Plasma Research promotes a national initiative, placing fusion as a supplementary energy source to fission for AI-driven requirements post-2050 (Dhurandhar, 2025).

THE IMPERATIVE OF WORKFORCE CULTIVATION

liberalised uranium sector demands a cadre versed in geosciences (radiometric surveying, hyperspectral remote sensing), mining (in-situ recovery, radiation safety), and processing (hydrometallurgy) fuel fabrication, AI modelling (Dhurandhar, 2004, 2007, 2009) and in nuclear engineering. The National Skill Development Corporation and National Critical Minerals Mission, with Rs. 100 crore funding, must certify 5,000 professionals by 2030 via academies, tax incentives, and platforms like SWAYAM (National Skill Development Corporation, 2024; Pandey & Vishwakarma, 2024). Institutions such as IITs, ISM Dhanbad, and HBNI should integrate uranium curricula, fostering gender inclusivity and community engagement (Homi Bhabha National Institute, 2025; IIT Bombay, 2025).

CONCLUSION

India's uranium dominion stands poised for metamorphosis through 2025 reforms, intensified exploration, diversified imports, and workforce fortification. By securing supplies from Africa and the CIS, mitigating a 100,000–200,000 tU shortfall by 2050, and leveraging SMRs, India can realise 100 GWe by 2047 and net-zero by 2070, whilst accommodating AI's power surge and transcending the limitations of the current energy mix (World Nuclear Association, 2025). Nuclear's superiority in reliability, emissions, and land efficacy renders it the quintessential bulwark for this epochal transition. Recommendations include expediting private reforms, sourcing 20–30% from CIS, 30–40% from Russia, 15–25% from Australia, and 10–20% from Africa, alongside expanding training at the Global Centre for Nuclear Energy Partnership (Government of India, 2025). The keeping for long-term options open by promoting the three-stage nuclear program and using ANEEL in PHWRs and fusion reactor technology.

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Sustainable Strategies for Mine Water Management and Utilization in Coal Mining: A Short Review

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ABSTRACT

Coal mining has a profound relationship with water resources, both in terms of consumption and pollution. Large volumes of groundwater infiltrate into mines and must be pumped out, creating quantitative challenges such as aquifer depletion and land subsidence. At the same time, qualitative impacts such as acid mine drainage (AMD), suspended solids, and chemical contamination threaten ecosystems and human health. This paper reviews the challenges of mine water management and explores sustainable strategies for utilizing and protecting water in coal mining. Case studies from India, South Africa, China, and Europe illustrate how mine water can be transformed from a liability into a resource through treatment, recycling, and community supply programs. Sustainable management strategies include pollution prevention, water conservation, and innovative mining methods such as water-preserved mining. The paper also discusses the human impacts of mine water management, emphasizing health, livelihoods, and community resilience. By integrating technical solutions with governance and community engagement, coal mining can reduce its water footprint and contribute to water security in regions facing scarcity.

INTRODUCTION

Water is indispensable in coal mining, used for mineral processing, dust suppression, cooling, and other operations. At the same time, mining generates large volumes of mine water that must be managed. Globally, water scarcity is intensifying, with estimates suggesting a 40% supply deficit by 2030 under business-as-usual conditions [1]. In India, per capita water availability has dropped from about 5,000 m^3 in 1950 to 1,500 m^3 in 2020 (Central Water Commission, 2020), highlighting severe stress. Coal mining intersects with this crisis by altering both water quantity and quality [2].

Quantitatively, dewatering of mines lowers groundwater levels, dries up wells, and disrupts hydrological regimes [3]. Qualitatively, coal mining pollutes water through AMD, suspended solids, and chemical effluents. These impacts persist long after mine closure, making water management a critical sustainability issue.

Several references highlight the urgency of this challenge. Guo et al. (2019) documented aquifer decline in Chinese coal bases due to intensive pumping [4]. Arnold et al. (2014) reported selenium contamination in U.S. coal mine waters affecting aquatic ecosystems [5]. In South Africa, mining accounts for only ~3% of national water withdrawals, yet mining-intensive regions face acute water stress [6]. These examples show that even modest water use by mining can have disproportionate local impacts.

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This paper examines water challenges in coal mining, strategies for mine water utilization, sustainable management approaches, and human impacts. It argues that coal mining's water footprint can be minimized through technical innovation, policy support, and community engagement.

WATER CHALLENGES IN COAL MINING

Impacts on Water Quantity and Availability

Coal mining requires continuous dewatering to keep workings dry. Both underground and open-cast mines pump out significant amounts of groundwater, creating cones of depression in water tables. In regions with multiple mines, cumulative drawdown can be severe, leading to dried wells, reduced stream flows, and land subsidence.

China's northern coal bases illustrate this challenge. Intensive pumping has caused aquifer decline and even desertification in some areas [4]. Researchers have developed allocation models to balance mining water use with regional supply needs [7]. Water-preserved mining techniques, such as backfilling and grouting, aim to allow groundwater recovery post-mining [8].

The sheer volume of mine water is another challenge. Globally, coal mines pump billions of cubic meters annually. If discharged uncontrolled, this water can cause flooding or erosion downstream. In the UK, abandoned coal mines collectively discharge enough water that the Environment Agency has catalogued and treated these flows [9].

Impacts on Water Quality

Qualitative impacts are equally severe. Acid mine drainage (AMD) is the most notorious problem. When sulphide minerals oxidize, they produce sulfuric acid, leading to low-pH water rich in metals. AMD can persist for decades, turning streams orange and toxic.

Beyond AMD, coal mining generates suspended solids, salinity, and trace element contamination. Washery effluents contain coal fines and chemicals, while runoff from open-cast mines increases turbidity. Selenium contamination in U.S. coal regions has harmed fish populations [5]. In India, coal mines monitor parameters such as pH, suspended solids, and dissolved solids to comply with regulations [10].

Climate Change and Cumulative Impacts

Climate change exacerbates water challenges. Heavy rainfall increases overflow risks, while droughts intensify competition for water. Mines must design for extremes, building storage and drainage capacity. The cumulative impact of multiple mines requires integrated watershed-level management.

MINE WATER UTILIZATION STRATEGIES

Internal Reuse and Recycling

Recycling within mining operations is a fundamental strategy. Modern coal preparation plants operate closed-loop systems, reclaiming and reusing wash water. Dust suppression often uses mine water, reducing reliance on fresh sources. Large companies recycle 70–90% of water, aiming for Zero Liquid Discharge [6]. Reverse osmosis plants treat excess water for reuse in boilers and other high-purity applications.

Mine Water for Communities and Agriculture

Mine water can be supplied to communities and agriculture after treatment. In India, Coal India Limited provides treated mine water to villages. Between 2019 and 2024, coal companies supplied 18.5 billion kilolitres of mine water, benefiting 3.76 million people in over 1,000 villages [10]. About 61% was used for domestic purposes and 39% for irrigation.

South Africa's eMalahleni Water Reclamation Plant is another landmark. It treats acidic mine water through neutralization and reverse osmosis, supplying 16 million litres per day of potable water to municipalities. By 2016, it had delivered 50 billion litres of drinking water and recycled 20 billion litres for mining [6].

Other examples include wetlands in China polishing mine effluent for irrigation, and pit lakes in Germany's Lusatian region serving as recreational and water storage areas.

Economic and Social Benefits

Utilizing mine water yields economic and social benefits. Communities gain improved water access, agriculture benefits from irrigation, and mining companies build goodwill. In India, Western Coalfields Ltd even bottled treated mine water as "Coal Neer." Such initiatives align mining with the UN Sustainable Development Goals, particularly SDG 6 on clean water.

SUSTAINABLE MANAGEMENT STRATEGIES IN COAL MINE WATER MANAGEMENT

Pollution Prevention and Control (AMD Mitigation)

Preventing AMD is a priority. Strategies include isolating sulphide minerals from oxygen and water, capping waste piles, and flooding old mines. Alkaline materials such as limestone can neutralize acid.

Treatment methods include active systems (lime dosing, chemical neutralization) and passive systems (constructed wetlands, anoxic drains). Hybrid systems combine both, achieving near-zero discharge. Emerging technologies recover valuable by-products such as iron oxides and rare earth elements from AMD [11].

Water Conservation and Efficiency

Reducing water use per unit of coal is essential. Dry coal beneficiation, filter presses, and centrifuges improve efficiency. Mines implement water accounting, fix leaks, and capture rainwater. Anglo American's Water Efficiency Target Tool sets reduction targets [12]. Groundwater recharge is another strategy. Indian mines pump surplus treated water into aquifer recharge wells, while Chinese researchers explore storing clean water in closed mines [8].

Protection of Water Resources (Water-Preserved Mining)

Water-preserved mining harmonizes coal extraction with groundwater conservation. Techniques include strip mining with sand filling, room-and-pillar mining with partial pillar retention, and grouting fractures. Hydrogeological modelling ensures aquifers remain above critical levels. In China's Yushenfu mining area, water-preserved mining-maintained groundwater for agriculture and desert ecosystems [13]. Such practices are gaining global attention in water-scarce regions.

HUMAN IMPACTS OF MINE WATER MANAGEMENT

Mine water management directly affects human health and livelihoods. Poorly managed mine water can contaminate drinking supplies, causing diseases from heavy metals and pathogens. AMD-impacted water is unsafe for consumption and agriculture. Conversely, treated mine water improves community resilience. In India, millions of people now access safe water from mines, reducing disease and saving time spent fetching water. Irrigation supports food security and incomes. In South Africa, potable mine water alleviated municipal shortages, improving quality of life. Socially, mine water utilization builds trust between companies and communities. It demonstrates corporate responsibility and reduces conflict over water. Economically, it creates opportunities such as fish farming in reclaimed pits.

CONCLUSION

Coal mining poses significant challenges to water resources, both quantitatively and qualitatively. Dewatering lowers aquifers, while pollution such as AMD degrades water quality. Climate change intensifies these impacts. However, mine water can be transformed into a resource. Recycling within operations, supplying communities, and innovative treatment technologies demonstrate sustainable utilization. Management strategies such as pollution prevention, water conservation, and water-preserved mining reduce the water footprint.

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Selection of Backfill Material for Highwall Mining

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ABSTRACT

The highwall mining technique is a menless underground method of excavation of coal in the ambit of an opencast mine where coal which cannot be extracted due to high powder factor and other economic and regulatory compulsions. According to 'The Underground Vision Plan of CIL' document, this technique of extraction to be introduced in CIL 24 such projects in various CIL subsidiaries will produce about 4.5 Million tonnes of clean sized coal. After extraction of coal from a 250 to 300m parallel roadways leaving coal pillars in between them, The coal left in pillars are lost for ever so as to keep the surface above intact and free of subsidence. In order to erxtract these pillars, various methods have been contemplated. One safe and sustainable method has been to backfill the roadways and cut the coal of the pillars. A number of studies in India and abroad have been taken up to select and use/adopt a method of backfilling. An attempt has been made in this paper to present the present status of highwall mining and further recovery of coal from the pillars.

INTRODUCTION

Highwall Mining (Figure 1) is just a combination of underground and surface mining. The coal left in the highwall can be extracted by this technology which otherwise would be lost forever. The method relies upon the self supporting capacity of the strata above the series of parallel entries driven mechanically to a considerable depth without artificial roof support and ventilation. Moreover this technology provides an economical way to extract coal reserves locked up in the highwall. The extent of opencast project is limited by the financial viability, but the coal continues to exists beyond the quarry limit. This is the reason we go for the combination of underground and opencast to extract coal within economic condition.

Figure 1 : Highwall Mining

Eventually the continuous miner used in the Underground mining of coal were developed and outfitted to also recover coal from surface high walls. Highwall mining was developed in 1990. As on now more that 60 Highwall miners are in operation in U.S. and they may account for about 4% of total U.S. coal production. This technology is also very popular in Australia.

At present at three places High wall Mining is in operation (Pradhan & Pradhan, 2014). The two existing highwall miners in India had been supplied as follows: one by Bucyrus (SHM unit) in the early 2010s just before Bucyrus was bought by Cat in 2011 to SECL's Sharda opencast

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mine and the second in 2015/2016 to Tata Steel for its West Bokaro Division South Eastern Quarry. As that machine was supplied by Cat it was now known as an HWM300. The first machine was able to cut 0.9 m to 1.7 m seams. The second machine had a high lift mode to deal with thicker seams – so it can handle seams of 0.9 to 2.5 m. CIMFR had extended support from the feasibility till the production stages for all highwall mining projects of India, their efforts are commendable [Porathur, J.L. et el(2013), and Porathur, J.L., Pal Roy, Pijush et el (2017), published the only book on Highwall Mining: Applicability, Design & Safety].

In India the first unit of highwall was commissioned at singareni Collieries Co. Ltd, this was followed by the second unit at Sharda OCP of South Eastern Coalfields Ltd, and third unit at Tata Steel West Bokaro coal mines. At ECL Minsol commenced operations at the Eastern Coalfields Limited Nimcha Highwall Project in mid-2023. BCCL has introduced Highwall Mining Technology at ABOCP Mine, in 2024-25, significantly improving recovery rates in opencast mines.

FACTORS INFLUENCING PRODUCTION

1. Machine operates remotely from active working zone hence no exposure of work persons to dust humidity etc. i.e. safe mode of operation.
2. High production potential from 2500 tpd in thin seams to 7200 tpd for thick seams
3. OMS can be as high as 100-200 as only 3-4 persons are required in operation.
4. Production capital investment is much less than as compared to similar capacity of U/G mines.
5. Conservation of coal up to 70%
6. Easy maintenance due to self-diagnostic system.
7. Low production cost.
8. Quantum of blasting involved is negligible as compared to conventional methods
9. Noise level emitted is within limits prescribed under statute & less than conventional machines.
10. Environmental friendly technology with regards to dust, noise & vibration.

CHALLENGES IN HIGHWALL MINING

1. Stability of the highwall OB by a system of pre-splitting at the time of mine reaching the boundary limits.
2. Backfilling of the voids by crushed OB or Fly ash etc
3. Fire alarm and other systems for online monitoring roof stability etc.
4. Recovering pillars after backfilling the voids.
5. Productivity improvement in thick seams

ADVANCEMENT IN HIGHWALL UTILISATION

To increase the production by High Wall Mining within existing condition, maintaining the safety.

1. Reducing the thickness of web Pillar between two adjacent cuts
2. Reducing the thickness of barrier pillar after every 10 cuts
3. Application of backfilling in the cut, suggests that it improves the pillar stability
4. Adoption in multi-seam workings having variable thickness and geological disturbances.

INITIATIVES FOR WEB PILLAR DESIGN, BACKFILLING SYSTEM OF THE WEB CUTS (FIGURE 2)

Globally and also in India several studies are in progress and underway for various aspects of the highwall mining. DGMS also came up with Technical Circular to encourage highwall mining in India to be implemented safely. CIMFR in consultation with the mine operators have developed empirical formula for the Web Pillar design (Figure 2) for various geo-mining conditions including thick seams, dipping coal seams etc (Porathur, J.L. et el, 2013). The approaches to web and barrier pillar design also involved Numerical modeling analysis to confirm design performance and test its robustness. Sarkar, S. et el (2022) also undertaken research on the Web-pillar design for highwall coal mining. Dong Song, D. et el (2023), used method of Integrated Analytic Hierarchy Process–Fuzzy Comprehensive Evaluation–Variable Weight Theory Feasibility Evaluation for Highwall Mining in Open-Pit Coal Mine.

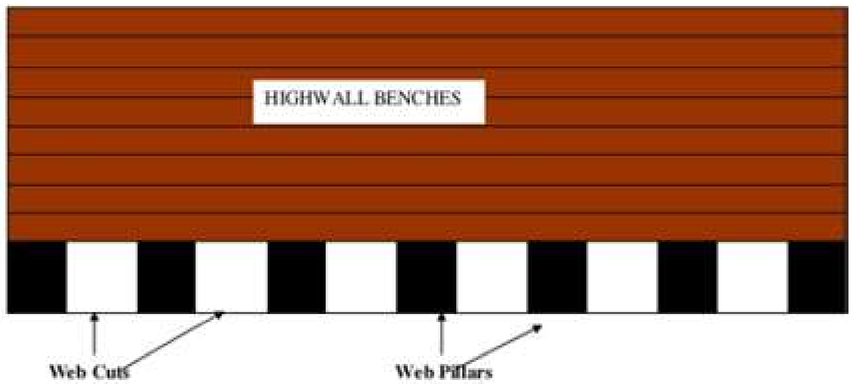

Figure 2 : Showing Front view of the Highwall mining face

Sasaoka, T. et el (2016), studied the characteristics of the highwall mining system application in weak geological condition of a coal mine in Indonesia. From the results of a series of laboratory tests and numerical analyses, they concluded that the stability of pillars and mine openings in auger mining systems is much higher than that in CHM and an auger mining system is suitable for such as very weak/poor strata conditions. Moreover, the application of backfilling system is very effective for improvement of the stability of pillar and openings.

Naik, G.M. et el (2021), presented the case study on stability analysis of Highwall Mining in India by using Combined Finite Element Modelling and Statistical Approach. Their Mathematical method used the CIMFR and Bieniawski models for analysis of Factor of Safety at high wall face for design of dimension pattern for web cut of highwall mining to achieve maximum production of coal at face seam of the high wall in dip direction.

Agrawal & Roy(2023), developed 3D models of a Highwall mining panel to determine an optimum web and barrier pillar size depending on the physicochemical properties of coal and rock. Distribution of stress on the roof of the openings, web and barrier pillars of Highwall mining panel was studied. Further, based on the stability of web as well as barrier pillars in the 3D model, an optimum dimension of opening has been determined and recommended.

Hussain, M.A. et el. (2024), studied the productivity enhancement aspects together with energy conservation. They evaluated the power quality of the substation's incomer, transformer, and feeder, and proposed energy-efficient changes to boost production. Tests on the main substation transformers included voltage, current, power, power factor, harmonics, and AC waveform analysis. They conducted Thermal imaging of electrical equipment to verify operating temperatures. They recommended for the installation of an Automatic Power Factor Correction (APFC) unit and lowering the tap value from 5 to 4 to improve the transformer's power factor. This resulted in a 4% voltage reduction saving 1% energy, while a 5% reduction saving 1.25% energy.

Siddiqui et el(2025) studied the reliability, maintainability, and availability analysis of Highwall Mining Machines for enhanced productivity and continuous Output of some Indian mines.

BACKFILLING

Backfilling had the following advantages in Highwall mining -

- Fills the excavated areas, promoting better support and ground control.
- It provides a better method of using waste rocks, waste from coal preparation and thermal power plant wastes like bottom ash and fly ash,
- Increases coal recovery, especially in room and pillar mining and highwall mining systems.
- Reduces ventilation short-circuiting between adjacent mining sites.
- Reduces cost of waste transportation to the mine surface dumping sites and tailing ponds, and associated up-keeping and monitoring of these facilities.

Factors influencing Selection of Backfill system

- Geology of the area
- Geotechnical parameters of the strata
- Opencast mining methods
- Type of Highwall Miner (Auger or CHM) and dimension of the web cut and pillars
- Stability of the pit slopes
- Depth of cover, rock types and properties, mining method, etc.
- Thickness of the coal seams
- Percentage of filling of the voids
- Regulations under CMR 2017 and DGMS Technical Circulars, and
- Type of backfill material, its mechanical properties etc

Sasaoka, T.,et el;(2016) had extensively studied the use of backfill material in Auin a ger Mining system, geologically difficult area, in Indonesia.

A joint research project of the University of Kentntucky and Mining Technologies was undertaken in the areas of Highwall Stowage Research to evaluate the use of dry flue desesulfurization by-products (FGD or stack scrubber waste material) to back fill the holes left by the highwall mining process and allow 100% extraction of the coal seam by the highwall miner. Stowage will also be an important topic in Australia because of the excellent quality of the coal and thickness of seams. The slenderness ratio of the highwall web pillars becomes controlling factor in thicker seams and reduces the oveall recovery rate. Stowage offsets, this effect and also prevents the subsidence of upper seams in a multiple seam application.

Jiang, J et el(2022), developed a calculation model of the inelastic zone width of highwall mining with backfill independent of empirical parameters using a limit equilibrium method, orthogonal experiment method, and non-linear fitting method (Figure 3).

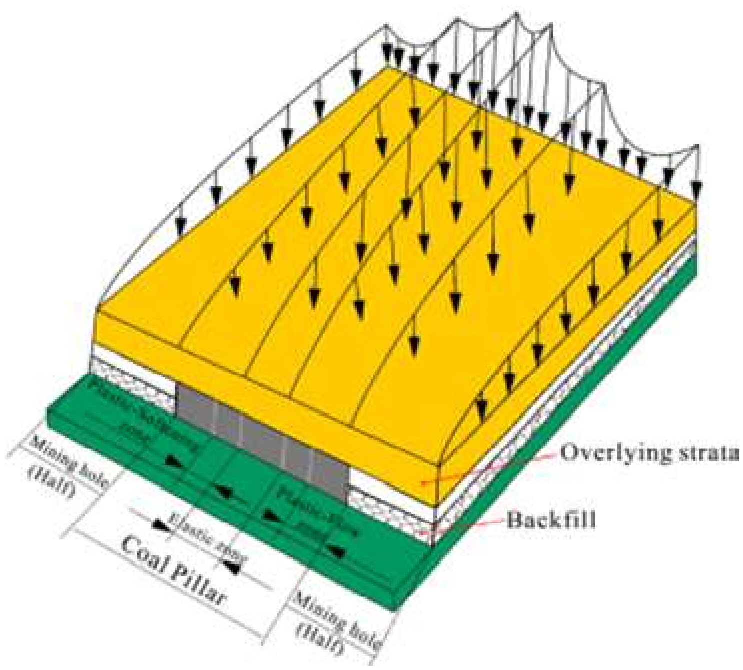

Figure 3 : Models of the elastic zone, plastic softening zone, and plastic-flow zone on the coal pillar (After Jiang et el 2022)

They had taken up this to accurately calculate the inelastic zone (Figure….), width of a coal pillar under the condition of highwall mining with backfill. In order to verify the correctness and reliability of the model, their study considered geological conditions of the Antaibao open-pit mine in Pingshuo, Shanxi Province, China, and Tata Steekl West Bokaro Mine as the engineering background to verify the calculation accuracy of the model. Their results show that the calculation model established in their study can accurately calculate the inelastic zone width of the coal pillar under highwall mining with backfill and can meet the engineering needs.

Lier (2014) in his Master Thesis on 'Backfill in highwall mining an assessment of the possibilities in West Bokaro, India', studied the stability of the overlying strata and also maintaining the boundary limits of the leasehold, by developing a system of backfilling of the Web Cuts. In addition to safety, this may research had scope for increased coal recovery. He developed and tested a numerical model using the finite difference modeling program FLAC3D. Input data was acquired from UCS tests that were performed on samples of rock material as well as backfill material obtained from the West Bokaro mine site. The model ran various simulations focusing on the effects of pillar width, mine and backfill sequencing, backfill material, partial backfilling, and mining in multiple lifts. Some of his findings are –

- an optimum pillar width of 2.9 m was found,
- The mining sequence with the highest stability was a 1-by-1 sequence, where adjacent drives are excavated and backfilled one after the other, ensuring that excavation of the next drive doesn't start until the previous drive has been backfilled. However, a more practical solution would be mining and backfilling simultaneously, while maximizing the distance between the drives in the process of being excavated and backfilled.
- The efficiency of backfilling increases with increased cohesion and stiffness of the backfill material. For this reason, loose, dry material is not recommended as backfill.
- Fly ash composite materials are suitable as a backfill material, provided that cohesion and strength are sufficiently high.
- Partial backfilling imparts some strength to the surrounding pillars, but not enough to be significant. However, a small gap left open at the top should not excessively affect the process.
- Multi-lift mining increases overall stability, but comes with an increased risk of roof instability.
- According to the simulations done in this thesis, recovery as a result of backfilling can theoretically be increased up to 36% when compared to conventional methods

Mo. S. et el(2017) reported about the effect of backfilling on pillar strength in highwall mining using numerical modelling. Calibration against the new empirical strength formula for highwall mining was conducted to obtain the material parameters used in the numerical modelling. With the obtained coal strength parameters, three sets of backfill properties were investigated. The results reveal that the behavior of pillars varies with the type and amount of backfill as well as the pillar width to mining height ratio (w/h). In case of cohesive backfill, generally 75% backfill shows a significant increase in peak strength, and the increase in peak strength is more pronounced for the pillars having lower w/h ratios. In case of non-cohesive backfill, the changes in both the peak and residual strengths with up to 92% backfill are negligible while the residual strength constantly increases after reaching the peak strength only when 100% backfill is placed. Based on the modelling results, different backfilling strategies should be considered on a case by case basis depending on the type of backfill available and desired pillar dimension.

BACKFILL MATERIAL

In highwall mining backfilling, one of the essential features has been the 'free-standing ability' of the quick setting type material. Spearing, AJS et el (2021), dealt at length about backfilling of highwall web cuts, with the adoption of an automated, safe, environmentally sustainable, and high extraction soft-rock underground mining method.

The cementing/quick standing options include -.
Portland cement - This is generally effective but costly. It is estimated that at least a 4% by weight addition would be needed to make the early strength gain of the backfill fast enough, based on previous experience.

Fly ash (with lime or binders) - This system is viable but the strength gain tends to be relatively slow.

Blast furnace slag - Quenched and finely ground slag is a cost-effective pozzolan, the 5% cement addition was replaced with 5% ground granulated slag activated with slaked lime, and it achieved faster strength development at a much smaller material cost. Blast furnace slag is easily available near mines of Raniganj coalfields.

Silicated backfill (ettringite, which is a complex molecule with 32 molecules of water as the hydration product). This was developed by Minova (Smart, Spearing, and Harrison, 1993). A 4% addition reduces runoff water in a slurry from about 44% to less than 10%, and in a high-density slurry it virtually eliminates the water runoff and post-filling shrinkage.

Other polymer-based products that can gain strength and undergo minimum shrinkage. Use of paste fill technology cannot be ignored but its availability and cost needs thorough investigation.

Characteristics of the material –

(a) The backfill must not shrink after placement as this could create serious problems such as: Poor contact with the roof and additional cementing material addition etc.
(b) It should not come out the post-filling with drainage water
(c) Non-toxic
(d) Non leachable with time.
(e) Backfill strength development need to be determined for the rate of strength gain and cost, in order to formulate the optimum backfill.

Backfill placement(Spearing, AJS et el [2021 and Figure 4]

In a highly mechanized system of excavation with least manpower, this process will need additional manpower and a mechanized system of placing backfill material after web cut is finished. The sequence of filling and distance to be maintained between the highwall miner and the web cut depend on the rate of backfilling, and backfill material post filling characteristics.

For a flat (<3 degrees) coal seam a sacrificial PVC or HDPE barrier will probably be needed in the slice to ensure tight backfill to the roof. This has been done routinely in China with CECB and was successfully applied on the gold mines in South Africa, but for a different application and at stoping widths (mining heights) of typically 1 to 2m. The pressure in the delivery system ensures tight roof contact. A possible method is shown in Figure….

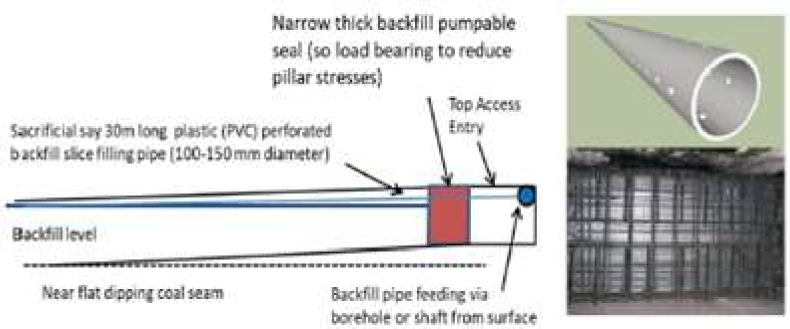

Figure 4 : Possible backfilling method using sacrificial plastic pipes and a barricade that could be simplified (After Strata Worldwide)

MAIN CHALLENGES

The main challenges which decides it application are -:

- Dimension of the Web Cut (distance between boundary and the opening)
- No. of Web cuts in the web panel and width of the the web panel
- Quality of coal, coal seam thickness, coal seam dip, incubation period,
- Hydrology of the coal seam
- Geotechnical characteristic of immediate roof.
- The method of delivering fill material into web cut after the monorail that adds and reclaims Pusher Beam needs to operate safely, remotely, and quickly, and the handling attachment will need to be effective.
- Changes required for smooth and safe operation of the Highwall miner.
- The rapid, high early-strength development of the backfill.
- The cost of backfilling.

Once backfilling is finalized/optimized then efforts to be made to recover the coal from standing Web Pillars, after doing numerical modelling of the pillars, caving characteristic etc.

CONCLUSIONS

With the increase in thrust on highwall mining in India (as stated in The Underground Vision Plan of CIL'), this concept of backfilling with web pillar depillaring or without depillaring depend on several geotechnical parameters. This method is only applicable when the mine reaches the bottom most part of the quarry and ready for backfilling by using overburden material as a part of Mine Closure.

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A Systematic Review of Digital Twin and Reinforcement Learning Applications in Underground Load-Haul-Dump(LHD) Systems

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ABSTRACT

The growing digitalization of mining operations has intensified interest in sophisticated decision-support approaches that can maximize shovel–dumper performance in open-pit mines. Emerging technologies include Reinforcement Learning (RL), which offers adaptive optimization approaches that can enhance dispatching, routing, and equipment coordination under uncertainty, and Digital Twin (DT), which delivers real-time, data-driven virtual representations of mining systems. Although both sectors have evolved tremendously, their integration remains restricted and fragmented. With an emphasis on shovel-dumper productivity and fleet optimization, this review methodically assesses 150 research papers published between 2010 and 2025 to investigate the existing capabilities, strengths, and limitations of DT and RL in mining applications. The data reveals that DT research generally emphasizes equipment monitoring, visualization, and predictive evaluation, whereas RL studies mostly rely on simulation environments to maximize cycle time and eliminate idle periods. Few research try coupled DT-RL frameworks, and those that do are mainly conceptual and lack field deployment or real-time validation. High-fidelity DT models, multi-agent RL coordination, real operational data integration, sim-to-real transfer, safety measures, and human-in-the-loop design are among the major research gaps that have been identified. Based on these insights, the report recommends future research initiatives aiming at establishing robust, adaptive, and industry-ready DT–RL eco-systems. The research concludes that while the confluence of DT and RL has great promise to boost productivity, lower fuel consumption(both fossil fuel and or electric/battery), efficient engine exhaust system for ensuring better ventilation management, and enable intelligent automation in open-pit mining, important operational and technological issues need to be resolved before widespread implementation is possible.

Keywords: Digital Twin; Reinforcement Learning; Underground Mining; Loading & Hauling Optimization; Mine Automation; Multi-Agent Systems; Simulation-to-Reality Transfer; Predictive Analytics; Intelligent Mining Systems.

INTRODUCTION

The effective coordination of loading & hauling (LHD) systems, which constitute the core fleet in charge of material excavation and haulage, is crucial to any underground mining operation (Figure 1). The productivity of these activities hinges on minimizing loader idle time, lowering dump truck/LPDT queuing delays, optimizing haul routes, and sustaining continuous material flow. However, it is challenging to continuously achieve optimal performance with typical dispatching and rule-based scheduling systems due to the extremely dynamic nature of mine environments, which are characterized by changing cycle times, variable road conditions, equipment breakdowns, and human decision-making.

With the recent growth of Industry 4.0 technology, mining operations are rapidly combining real-time data analytics, automation, and simulation tools to boost operational efficiency. Among these technologies, Digital Twin (DT) has become a potent method for building dynamic virtual copies of real-world mining operations. Through constant synchronization with real mine data, a Digital Twin facilitates real-time monitoring, what-if scenario testing, predictive maintenance, and performance enhancement. DTs provide a safe and adaptable testbed for assessing optimization strategies in LHD systems by accurately simulating equipment behavior, LHD networks, production cycles, mine ventilation network, and operational limitations with thrust on geological and geo-technical behaviour.

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Parallel to this, Reinforcement Learning (RL)—a subset of machine learning focusing on autonomous decision-making—has demonstrated promising applications in complicated mining activities like as truck dispatching, shovel allocation, blast design optimization, energy management, and predictive maintenance. RL agents are well-suited to managing the uncertainty and unpredictability that define open-pit haulage systems because they can learn optimal policies through interaction with an environment. Unlike traditional optimization techniques, RL does not require explicit mathematical models of system dynamics, allowing it to learn from experience and adapt to changing operating conditions.

While Digital Twin and Reinforcement Learning have been widely researched independently, research merging these two technologies for open-pit mining operations remains limited. It is possible to create a closed-loop system using a combined DT–RL framework, in which the RL agent continuously learns and tests the best dispatching, routing, and scheduling strategies while the Digital Twin offers a realistic simulation environment. Such integration could provide real-time decision assistance, reduced operational uncertainty, greater fleet utilization, and enhanced production efficiency.

This study attempts to methodically examine previous research in both fields because of the growing interest in intelligent mining systems and the dearth of comprehensive literature on the combined application of DT and RL in shovel-dumper optimization. In order to build integrated DT–RL solutions specifically for open-pit mine haulage operations, the study looks at recent developments, points out technological gaps, assesses existing approaches, and suggests future research areas.

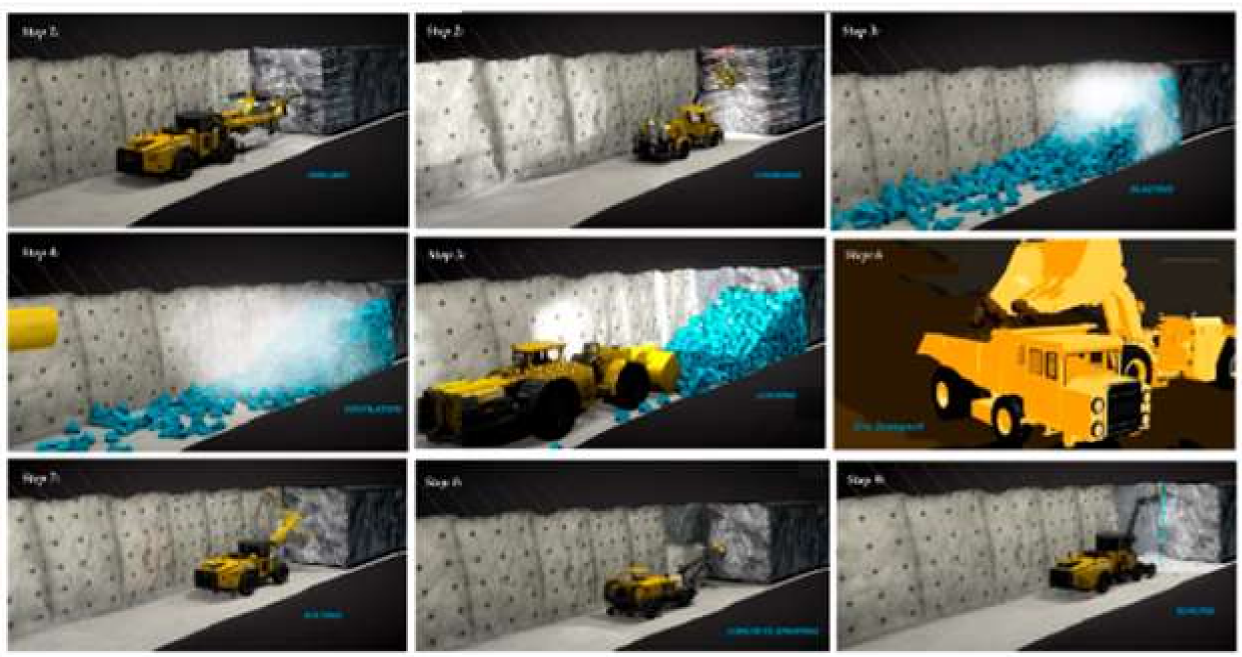

Figure 1 : Main activities developed in a typical underground Metal Mine- Step 1-drilling, Step 2-charging of explosives into blast holes, Step-3- Blasting, Step-4 – ventilation, Step 5- Ore hauling, SXtep 6- Bolting, Step 8-concrete spraying (if needed) and Step 9-scaling etc.

BACKGROUND

Efficient loading-hauling (LHD) operations sit at the center of productive open-pit mining, where shovel–dumper systems are responsible for digging and moving massive volumes of material. Loading, hauling, dumping, and returning are all interrelated parts of these operations, and they are all impacted by a variety of variables, including mine ventilation, face location, operator behavior, road conditions, and equipment performance. Optimization is crucial for preserving competitiveness in contemporary mining since little inefficiencies in cycle time or scheduling can add up to large output losses. Over the past two decades, mining has gradually migrated towards automation, digitization, and data-driven decision-making, assisted by developments in sensors, communication networks, and fleet management systems (FMS). Massive datasets detailing equipment movements, fuel consumption, loading patterns, and cycle-time variations have been produced as a result of these advancements. However, converting these facts into usable insights requires advanced analytical and computational techniques that can handle the complexity and dynamism of open-pit situations.

In this regard, Digital Twin (DT) technology has become a viable alternative. A digital twin is an ongoing, real-time data-driven virtual duplicate of a physical asset, procedure, or system. DTs can display operating delays, simulate haulage networks, model equipment behavior, and evaluate the effects of scheduling choices before to implementation in the mining industry. Digital twins offer a secure and adaptable setting for investigating optimization techniques without interfering with real-world operations by enabling scenario analysis and predictive modeling.

Concurrently, Reinforcement Learning (RL) has drawn interest due to its capacity to discover the best course of action via trial-and-error interactions with an environment. RL can independently identify policies that maximize long-term production or minimize operating costs, in contrast to conventional optimization techniques that rely on predetermined rules or static assumptions. RL agents have demonstrated promise in solving mining dispatching, queuing, and routing problems, particularly in situations that are unpredictable and changing quickly.

Despite tremendous development in these two technology sectors, their combined usage in mining is still emerging. Integrating Digital Twins with Reinforcement Learning provides a powerful closed-loop system: the Digital Twin gives a realistic simulation environment for training RL agents, while RL enhances the Digital Twin by giving dynamic Optimization strategies. By providing adaptive, real-time decision-making that is both data-driven and simulation-supported, this synergy has the potential to revolutionize LHD operation.

This background establishes the framework for understanding why DT and RL are increasingly crucial for modern mining and shows the necessity for a complete study of their individual and combined applications in shovel–dumper operations.

OBJECTIVE OF REVIEW

This review's main goal is to compile the body of knowledge regarding the use of Reinforcement Learning (RL) and Digital Twin (DT) technologies in open-pit mining, with a focus on shovel-dumper operations. Given how quickly these technologies are developing, a comprehensive analysis is necessary to comprehend their present capabilities, constraints, and prospects. The following are the review's specific goals:

(i) To investigate the most recent research on shovel-dumper operations, with an emphasis on conventional optimization methods, simulation models, and fleet management tactics employed in open-pit mines.

(ii) To investigate Reinforcement Learning methodologies employed in mining systems, particularly in truck dispatching, dynamic routing, maintenance planning, and multi-agent coordination.

(iii) To identify the gaps, limitations, and obstacles in present DT and RL research linked to mining operations, specifically the lack of real-time integration, limited validation environments, and absence of closed-loop adaptive systems

(iv) To examine the possibilities of merging Digital Twin and Reinforcement Learning into a single framework that facilitates real-time optimization of shovel–dumper cycles, adaptive dispatching, and intelligent haulage decision-making.

(v) To suggest future lines of inquiry and conceptual models that can steer the creation of sophisticated DT-RL systems to boost operational dependability, decrease delays, and increase productivity in open-pit mining.

These aims collectively aim to offer a systematic foundation for future research, highlight technological prospects, and encourage the evolution of intelligent mining systems through the combined use of DT and RL.

LITRARTURE REVIEW

Over the past ten years, there has been a substantial increase in the literature on shovel-dumper operations, digital twins (DT), and reinforcement learning (RL) in mining. Research integrating DT and RL into a single framework is still scarce, nevertheless. This section examines previous research in three primary areas:

(1) LHD optimization techniques (in both trackless and track mining);
(2) mining applications of digital twins; and
(3) mining and haulage systems applications of reinforcement learning.

LHD Operations and Traditional Optimization Approaches
In UG Metal mining having both trackless or track mining operations in development & stoping LHD systems are the foundation of production. Early research focused on deterministic and simulation-based strategies for enhancing operational efficiency. Traditional methods consist of :

- ❖ Models based on queuing theory to forecast LHD idle states and estimate waiting periods.
- ❖ For fleet scheduling and Dump Truck/tub and/or LPDT(low profile dump trucks) allocation, linear and mixed-integer programming are used.
- ❖ Most Fleet Management Systems (FMS) employ heuristic dispatching rules, such as the "shortest queue," "longest idle loader," and "nearest dump truck" guidelines.
- ❖ Tools for discrete-event simulation (DES) to examine cycle-time variability, traffic congestion, and haulage bottlenecks.

While these methods yield insights, they struggle to capture the extremely unpredictable nature of mine operations and cannot adjust dynamically to changing road conditions, weather, breakdowns, or output targets.

Digital Twin Applications in Mining

Digital Twin technology has lately emerged as a transformative tool in mining, enabling real-time visualization, prediction, and optimization of mine operations. Several important uses are highlighted in the literature:

A. Equipment Health Monitoring

For drilling rigs, LHD, DT models have been created to monitor structural health, anticipate component failures, and minimize unscheduled downtime. IoT devices, vibration analysis, and sensor data provide constant synchronization with the physical asset.

Process Simulation and Production Forecasting
According to research, loading-dumping procedures and haulage cycles can be modeled by DT-based simulations. However, there is little research on using DTs as active decision-making tools for fleet dispatching; instead, the majority of DT applications concentrate on either maintenance or visualization.

Gap Identified

Instead of serving as autonomous optimization platforms, the present DT applications mostly serve as monitoring and simulation systems. They seldom incorporate AI agents to improve judgments in real time.

Reinforcement Learning Applications in Mining

The strength of Reinforcement Learning in sequential decision-making under uncertainty has drawn attention. Numerous studies pertaining to mining show encouraging outcomes:

A. Truck Dispatching and Allocation
RL has been used to:

- ❖ Distribute workloads among several loading locations;
- ❖ Assign vehicles to shovels
- ❖ Shorten wait times

Improve production throughput
Q-Learning, Deep Q-Networks (DQN), or Proximal Policy Optimization (PPO) are frequently used in these investigations.

B. Route Optimization

In order to reduce fuel consumption, traffic jams, and trip time, RL-based routing agents have optimized haul road selection.

C. Maintenance and Reliability Optimization
RL models have been evaluated for:

- Predictive truck maintenance scheduling;
- Spare-part planning
- Minimizing operational breakdowns

D. Multi-Agent Reinforcement Learning (MARL)

In more sophisticated research, interactions between several LHD are modeled using multi-agent reinforcement learning (RL), which enables coordination and conflict avoidance.

Gap Identified

Although RL has demonstrated tremendous potential in optimization, most RL research use simplified or static environments, not genuine mine simulations. Moreover, adoption in real-world mining contexts is limited by RL rules' lack of connection to real-time operational data.

Combined Digital Twin–Reinforcement Learning Approaches

In all industries, research combining DT and RL is still in its infancy. In manufacturing and logistics, DT–RL systems have been employed for: • Smart factory optimization • Autonomous warehousing operations

Predictive control systems However, in mining, just a few conceptual publications consider DT–RL for haulage systems, and even fewer present experimental implementations. To far, no research has created a comprehensive DT-RL architecture especially for shovel-dumper cycle optimization, taking into account: • Real-time feedback loops

Dynamic dispatching • Adaptive routing • Continuous learning in a changing mine environment. This indicates a substantial research gap and a chance for further investigation.

Summary of Gaps in Current Literature

Key gaps from the reviewed studies are as follows:

- ❖ First. DT-RL frameworks for open-pit mining haulage systems are not integrated.
- ❖ Two. Limited real-time data integration in RL models used for mining.
- ❖ Third. Absence of closed-loop learning systems integrating virtual simulations with practical mine operations.
- ❖ There aren't many high-resolution DT models that accurately depict shovel-dumper interactions.
- ❖ AI-driven dispatching or routing in realistic open-pit situations has not received enough experimental confirmation.

These gaps show that a thorough investigation combining reinforcement learning and digital twins is necessary to optimize LHD operations.

METHODOLOGY OF THE REVIEW

A systematic and organized review methodology was employed to ensure comprehensive coverage of recent research on Digital Twin (DT), Reinforcement Learning (RL), and LHD operations in open-pit mining. The review followed recognized guidelines for scientific literature analysis and included the following processes.

Identification of Research Questions

The following important research issues served as the basis for the review:

1. What optimization techniques are currently employed in open-pit mines for shovel-dumper operations?
2. How is the mining sector utilizing and adopting digital twin technology?
3. Which Reinforcement Learning techniques have been used in mining operations, namely for scheduling and haulage tasks?
4. What are the current gaps and restrictions that prevent DT and RL from being integrated for real-time mining optimization?

These inquiries served as the basis for arranging the literature and choosing pertinent studies.

Literature Search Strategy

Several scholarly databases, such as Scopus and Web of Science, were thoroughly searched.
Google Scholar, Elsevier ScienceDirect, IEEE Xplore, and SpringerLink
The following keywords and combinations were used:

1) "Digital Twin in mining"
2) "Reinforcement Learning mining"
3) "Open-pit haulage optimization"
4) "Shovel dumper operations"
5) "Truck dispatching mines"
6) "Digital twin reinforcement learning"
7) "Mine fleet simulation"

Boolean operators (AND/OR) were used to refine the search and include relevant variants. 5.3 Inclusion and Exclusion Criteria

- ❖ To ensure the quality and relevance of the selected studies, the following criteria were applied:
- ❖ Inclusion Criteria
- ❖ Research released between 2010 and 2025.

- ❖ Excellent technical reports, conference proceedings, and peer-reviewed journal articles.
- ❖ Studies on fleet optimization, RL, digital twins, open-pit mining operations, and simulation.
- ❖ Research with pertinent results and concise methodological explanations.

Exclusion Criteria

- ❖ Documents unrelated to haulage or mining systems.
- ❖ Preliminary abstracts without full text or duplicate publications.
- ❖ Research that only looked at subterranean mines, unless the findings might be used elsewhere

Screening and Selection Process

There were three steps in the selecting process:

1. First Screening: To get rid of studies that weren't relevant, titles and abstracts were examined.
2. Full-Text Review: Selected publications were carefully reviewed to assess their applicability to shovel-dumper optimization, DT, and RL.
3. Last Choice: The papers on the refined list were divided into:

Digital twin mining; reinforcement learning in mining; conventional shovel-dumper optimization; combined or conceptual DT-RL applications; simulation and fleet management systems For in-depth examination, a total of about 80–120 publications were included.

Classification and Thematic Analysis

The following themes were used to categorize the chosen studies:
Digital twin models for machinery and procedures; fleet dispatching and haulage optimization Strengthening Learning applications and algorithms . IoT, sensor integration, and real-time monitoring; simulation-based optimization; and hybrid DT-AI frameworks. By contrasting approaches, case studies, algorithms, and outcomes from the chosen literature, patterns, trends, gaps, and limitations were found.

Synthesis and Reporting

The results of the thematic analysis were combined to:

- ❖ Provide an overview of recent technological developments
- ❖ Determine the difficulties in research.
- ❖ Draw attention to outstanding problems in DT and RL applications; • Offer a conceptually integrated DT–RL framework for further research.

The following portions of this review are built upon the synthesis.

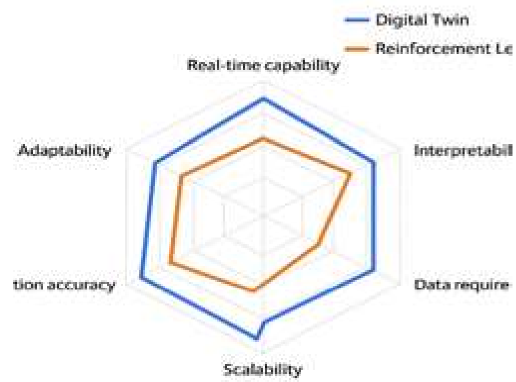

Figure 2: Digital Twin Vs Rinforcement Learning

RESULTS

Scope & corpus. The final corpus contains 150 papers (2010–2025) covering: shovel–dumper / truck–shovel optimization, Digital Twin (DT) theory & cases, Reinforcement Learning (RL) for haulage/dispatch, hybrid DES+RL experimental work, MARL approaches, and industry/white-paper reports.

High-level thematic breakdown (approximate, from the 150 papers):

- I. **Simulation + RL (DES/SimPy/AnyLogic + DQN / DDQN / PPO / PPO-variants / MARL): ~45% of papers.** These are experimental studies that implement RL agents inside simulators to learn dispatch or routing policies.
- II. **Digital Twin: reviews, frameworks, and case studies (DT theory, industry pilots): ~25%.** Many are conceptual or pilot DT deployments for monitoring, predictive maintenance, or what-if analysis.
- III. **Classical optimization, heuristics, queuing, MIP, metaheuristics: ~15%.** These provide baselines and analytical insight (match-factor, queuing, MILP scheduling).
- IV. **Preprints / toolkits / open simulators / benchmark suites (OpenMines, MineSim, etc.): ~10%.** These

enable reproducible RL research and curriculum experiments.

V. **Industry reports / vendor notes / hybrid conceptual roadmaps: ~5%. Practical pilots** and proprietary DTdeployments (industry case notes).

Temporal trend. Little visible DT or RL work before ~2016; steady growth from 2018 and a sharp **increase** in experimental RL, MARL, and DT review papersfrom **2020–2025** (lots of activity and preprints 2023–2025).

Methods & algorithms observed (most common):

I Discrete-Event Simulation (DES) or custom lightweight mine simulators used as the environment (very common baseline).

II. RL algorithms: DQN / Double DQN / Deep Q variants, PPO and PPO variants, and increasing use of MARL frameworks (QMIX, hierarchical MARL). Curriculum learning and teacher-guided training appear in 2024–2025 preprints.

III. State representations: position + queue lengths + shovel availability + simple traffic/road congestion features.

IV. Action spaces: assign truck '! shovel, route selection, holding/release decisions, or higher-level dispatching rules.

V. Reward engineering: combinations of throughput (tph), negative waiting time, fuel or emission penalties, and stability/smoothness metrics.

Validation & evidence strength

I. **Majority (H"80–90%) of experimental RL studies validate in simulation only.** Benchmarks commonly use custom DES or OpenMines/MineSim environments; only a few papers report industry pilot data or partial calibration against real fleet logs.

II. **Few deployed closed-loop DT'!RL'!field control examples exist** — most DT literature remains monitoring/simulation focused rather than hosting RL agents for live control. Industrial DT pilots often stop at decision-support or offline scenario testing.

DISCUSSION

DES + RL is the dominant experimental pattern — and for good reason.

DES offers a secure, quick, and manageable sandbox for refining RL policies and comparing them to heuristic baselines. In 2023–2025, replicable work was sped by the availability of open simulators (OpenMines, MineSim, etc.). Nevertheless, the primary obstacle to real-world transfer is simulation realism.

Digital Twin literature is maturing but is still largely monitoring/diagnostic rather than autonomous-control.

DTs are used for planning, predictive maintenance, and visualization, according to reviews and industry examples. A DT serving as the online environment for ongoing RL retraining and live policy implementation is rarely shown in academic or industrial publications. The most noticeable technical gap is this one.

1. **Algorithms are improving, but evaluation standards vary.**
   While MARL is becoming more common for multi-truck coordination, DQN/PPO is still widely used. However, unless comparable standards are employed, cross-paper comparison is challenging because to differences in state definitions, incentive design, episode duration, and evaluation metrics (throughput vs. fuel vs. waiting time).
2. **Field deployment and real-data calibration are rare but crucial.**
   Only a few industrial DT pilots and vendor reports mention any attempt at real-data calibration or online trials; the majority of RL rules are learned and tested in simulation. One practical obstacle is the absence of actual fleet record databases and regulated procedures for safe trialing.
3. **Practical constraints (compute, safety, interpretability) limit adoption.**
   Strong, comprehensible, and safety-assured policies are necessary for real mines. The literature frequently mentions high compute/training costs, incentive brittleness, and operator trust as challenges.

RESEARCH GAPS

An assessment of over 150 papers on Reinforcement Learning (RL) and Digital Twins (DT) in underground metal mining reveals a number of glaring research gaps.

First, there are very few integrated DT-RL systems, despite the fact that both DT and RL have been thoroughly investigated separately. Few studies examine conceptual combinations, and none show how a fully functional, real-time DT can provide continuous field data to an RL agent for shovel-dumper optimization.

Second, the majority of DT models now in use are descriptive rather than high-fidelity, which restricts their applicability for RL policy validation or training. They are insufficient as secure learning environments because they lack dynamic physics, equipment interactions, and real-time updates.

Third, RL studies continue to rely significantly on simulations, frequently employing over simplified models that are unable to account for hauling conditions, operator variability, equipment malfunctions, and environmental variables (rate of air flow post blasting, chemical composition of post-blast fumes). Practical deployment is hindered by this simulation-to-reality gap.

Fourth, most RL work models only discrete shovel-truck interactions; multi-agent coordination including multiple shovels, numerous dump truck fleets, crushers (below ground), and stockpiles is rarely addressed.

Fifth, despite being crucial for practical application, safety, interpretability, and human-in-the-loop control are mainly lacking in the literature now in publication.

Lastly, very few studies evaluate the economic, operational, or environmental benefits of coupled DT-RL systems, and even fewer employ real IoT, GNSS, or sensor data to calibrate models.

Overall, research is moving further, but there is yet no reliable, validated, real-time DT-RL environment for mining operations.

FUTURE RESEARCH DIRECTIONS

In order to optimize LHD assignments in real time, future research must concentrate on creating fully integrated DT-RL ecosystems where learning agents and high-fidelity digital twins constantly interact. The creation of physics-based, data-driven DT models that take into account weather variability, hauling conditions, equipment dynamics, and actual operational disruptions is a top objective. These improved twins can provide RL algorithms with secure, realistic training environments.
To handle intricate coordination between numerous LHD, crushers, and stockpiles, advances in multi-agent reinforcement learning (MARL) are required. Adaptive models that respond to equipment failures, tiredness, and environmental changes will be made possible by the integration of real-time IoT/GNSS data.

To guarantee that RL methods acquired in DT environments can be securely used in operating mines, research should also prioritize sim-to-real transfer, domain randomization, and strong policy adaption. In order to make AI-driven judgments transparent and acceptable to mine operators, research must also include safety layers, explainability modules, and human-in-the-loop controls.
In order to help miners quantify benefits and achieve sustainable automation, future research should assess the economic, productivity, fuel, and emission consequences of DT-RL adoption.

INDIAN INITIATIVES

Indian underground metal mines have attempted to adopt digital capabilities to automate mining value chain operations. IoT and machine learning are being employed, for instance, to automate and enhance the dependability of mining equipment and LHDs, sensors to gather data in real-time, drones for data collecting, inspection, and stock control, and wearables for field maintenance and operator safety. One important area has been communicating with below ground operations. Dyulabs introduced Nakshatra, a cutting-edge communication solution at underground voal mine of Tata Steel. It enables real-time data transmission from underground to surface level without external power sources, wiring, or internet. With intrinsically safe, digital telltale sensors, and a comprehensive system of gateway nodes and relay nodes, the solution ensures seamless data flow and communication, compliant with all regulatory bodies such as DGMS.

UG metal mines like Rampura Agucha Underground mine of M/s Hindustan Zinc Limited. Also with collaboration with Epiroc HZL oin its UG mines are commissioning 'Collision Avoidance System' a digital innovation which is going to deliver proactive risk reduction through intelligent sensing, real-time alerts and autonomous LPDTs vehicle control. Leveraging cutting-edge technologies such as Industry 4.0, digitalization, robotics, and automation, Hindustan Zinc has revolutionized operations, eliminating manual intervention, and dismantling outdated perceptions of the sector. The company's digital mines, featuring tele-remote underground mining (where underground mining equipment is operated remotely from the surface) and real-time analytics, provided exciting and inclusive career pathways for all.

CONCLUSION

This analysis of over 150 papers shows that reinforcement learning and digital twins are promising but mostly separate areas of underground and open-pit mining research. While RL techniques have great potential for improving dispatch choices and cutting idle periods in simulation scenarios, DT models provide sophisticated visualization, condition monitoring, and predictive capacity. Nevertheless, real-time integration, proven RL policies, high-fidelity twins, and useful deployment frameworks are lacking in the field. Research on multi-agent coordination, safety, interpretability, and actual operational data is still dispersed. Notwithstanding these drawbacks, the confluence of DT and RL is a very significant path for mine automation in the future. A well-developed, real-time DT-RL system might boost safety, lower fuel consumption, increase productivity, and facilitate data-driven decision-making. In order to move toward completely intelligent underground mining operations, the literature generally shows great potential but emphasizes the need for integrated, validated, and industry-ready DT-RL systems.

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