MetaResource vol. XX, no. X, pp. 1–XX, 202X
DOI: 10.23919/METAR.2026.000051
Original Article

Integrated backfill planning for sustainable closure of opencast coal mines in India: Case studies and innovative decision support framework

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Received: 28 Feb 2026
Revised: 25 Apr 2026
Accepted: 6 May 2026
Online: xx xxx xxxx

KEYWORDS

optimization,
opencast,
integrated backfill planning decision support framework,
mine planning,
waste management,
mine closure

ABSTRACT

Opencast (OC) mining dominates global coal production, accounting for more than 95% of India's coal output. While this method is highly productive, it results in substantial mining voids, significant overburden, and extensive land disturbance, making closure planning a major techno-economic and environmental challenge. Although backfilling is commonly used as a mitigation method, planning is frequently prioritized by production objectives over closure viability. As finite resources and ecological concerns become more apparent, the mining industry must adopt and practice sustainable mining techniques to protect the environment and manage resources responsibly. This work presents a strategic integrated backfill planning decision support framework (IBP-DSF) for the sustainable closure-oriented planning of OC coal mines. The IBP-DSF integrates block geometry, material availability, depth of pit, hydro-environmental sensitivity, geotechnical stability, and economic feasibility into a dimensionless integrated backfill planning score (IBPS) using normalized indices and weighted aggregation. Based on defined threshold ranges, the IBPS classifies mines into four closure strategies: complete backfilling, partial backfilling with void optimization, engineered voids or controlled water bodies, and external dump dependency. The framework is applied to brownfield and greenfield Indian OC coal mines, supplemented by hypothetical boundary scenarios. Results indicate that complete backfilling is feasible only within a limited operational envelope, whereas partial backfilling and optimized void management provide more practical and sustainable closure solutions under most conditions. The proposed model offers a transparent, transferable, and scalable decision-support tool to guide realistic closure planning, optimize land use, and reduce long-term environmental, financial, and social risks.

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1 Introduction

Coal continues to be the mainstay of the world's energy supply, propelling industrialization, the production of power, and economic expansion. More than three-quarters of the world's electricity is generated by coal, and over 70% of steel comes from coal [1, 2]. Although renewable energy is expanding rapidly, global coal production reached a record 8.77 billion tonnes (Bt) in 2024, supported by an installed mining capacity of nearly 8.9 Bt [3, 4]. In addition, more than 2,270 million tonnes per annum (Mtpa) of new coal mining capacity is currently being developed, mostly in China, India, Australia, Russia, and South Africa [4]. Clearly, coal continues to play a vital role in global energy security and industrial growth for the foreseeable future.

Globally, both the opencast (OC) and underground (UG) methods are used for coal extraction; however, OC mining has become the dominant method of mining coal in the past decade due to its higher productivity, lower unit costs, operational flexibility, and rapid scalability [5, 6]. According to industry production patterns, approximately 60% of the global coal output is accounted for by OC mining, and the rest 40% is accounted for by UG mining [7, 8]. Apart from China, most large coal-producing nations increasingly rely on OC mining for large-scale expansion. From a techno-economic perspective, the development of coal expansion projects via OC methods is therefore expected to account for nearly half of future projects worldwide.

OC coal mining is predominant in India, Indonesia, Australia, Russia, and the United States, while UG coal mining is more prevalent in China due to its deeper and structurally more complex coal reserves. It is clear from this diversity of mining methods that geological setting, seam depth, and techno-economic factors have a great deal of influence over the choice of mining method.

In terms of coal reserves, India will likely be the fifth-largest country worldwide, based on its projected growth trajectory [9]. It is estimated that in the coming five decades, coal will remain an important source of energy for India [10]. There are about 400.72 Bt of coal reserves in the country, primarily in Jharkhand, Odisha, Chhattisgarh, and West Bengal [11]. As a result of increased power generation, steel manufacturing, and infrastructure development, India's coal demand is expected to reach nearly 1.5 Bt by 2029–2030 [12]. To satisfy the heightened demand in the electricity industry, coal production in India is always rising, resulting in increased pressure on OC mines to attain the targets.

Therefore, the Indian coal mining landscape, however, centers heavily on OC mining [13], due to favorable geology and a high bulk demand for coal. The OC mining sector accounts for nearly 95% of production, while UG mining accounts for only a small portion [14]. A host of factors have contributed to the success of OC coal mining in India, including favorable geological characteristics, thick and shallow seams, high production potential, and economies of scale [5, 6]. Ultimately, the aim is to meet the country's growing energy needs and industrial growth. For energy security, manufacturing, industrial expansion, and financial sustainability, coal continues to be a major part of emerging and rapidly growing economies.

It is also important to note that even though surface mining is dominant and has many advantages, it is not without its challenges, such as constraints on the acquisition of land, considerable environmental repercussions, and land use impacts. The excavation of large-scale pits generates enormous amounts of overburden (OB), extensive disturbances to the land, changes to surface and groundwater regimes, fragmentation of habitats, and the formation of external dumps and mine voids [15–17]. Sustainable restoration of land is a serious concern for the coal mining industry because of the effects on ecosystems in the region, land for agriculture, water supplies, and surrounding neighbourhoods [18, 19].

Therefore, backfilling is an essential component of OC mining. Engineering-based backfilling practices with detailed planning and scheduling utilizing analytical models or tools can improve void management, reduce external dumping, improve slope stability, accelerate land reclamation, and mitigate long-term environmental liabilities. Backfilling, once a closure function, is now a strategic operational procedure integral to every mine's life cycle due to expansion-oriented OC mining projects.

Integrated closure planning must be factored into the workflow of OC mine development [9, 20] to support sustainable operation practices. Mining is fundamentally a transient use of land. Mining land has much more prospects for reclamation and repurposing than for long-term industrial development because it can be utilized for commercial purposes, agriculture and fruit-bearing land, forestry, or watercourses. It is possible to repurpose land after the final mine closure, unlike industrial or urban development, which is permanent. Geotechnical stability, environmental safety, socioeconomic acceptability, and absence of long-term adverse impacts on surface water and groundwater are crucial after mining. To achieve this potential, landform repair and backfilling must be executed in a cohesive and scientifically rigorous approach. This ensures sustainability, hydrological protection, environmental conservation, and socioeconomic support [18, 21].

The mine closure plan has traditionally been viewed as an end-of-life compliance obligation instead of an essential component of life-of-mine (LoM) design. This fragmented strategy has resulted in larger ultimate voids, delayed reclamation, over-reliance on foreign or external dumps, and increased closure liabilities [22]. According to reports, the amount of land destroyed by the disposal of coal waste is about 04 hectares (ha) per million tonnes of coal produced. Over 1,400 ha of land is being damaged annually at this rate [23]. Therefore, backfill should be tailored into the calendar programme, pit and dump schedule, and land-use strategies to optimize hauling, maximize productivity, better mine economics, mitigate carbon and environmental footprints, and increase closure performance.

For OC coal mines, several interconnected elements that vary greatly from mine to mine affect the choice of backfilling approach. It is important to take into account geological conditions, pit geometry, hydrogeological sensitivity, environmental constraints, economic feasibility, and life cycle considerations. Relying solely on a single parameter, such as the coal and OB ratio or production metrics, can be insufficient for making backfilling decisions.

The necessity of integrated mine planning strategies that include closure concerns into LoM design has been brought to light by recent research. Nevertheless, there is still a lack of a clear and organized framework that connects these multifaceted factors to closure-oriented backfilling choices in OC coal mines, especially in the Indian setting.

To address this gap, this current study offers an integrated backfill planning decision support framework (IBP-DSF) which allows for a systematic evaluation of backfilling solutions using a set of normalized, multi-criteria indicators. The approach combines essential physical, environmental, and economic characteristics to provide an integrated backfill planning score (IBPS), which is used to categorize potential closure options under different mining scenarios. The proposed approach is applied to various Indian greenfield and brownfield case studies, reinforced by hypothetical boundary cases, to demonstrate its applicability and robustness. The goal is to enable analytical, rational, adaptable, closure-focused, land-use optimality, and location-specific decision-making at the mining facility and planning stages, thereby enabling informed decisions.

2 Concept of integrated backfill planning

Mine planning plays a significant role in making mining profitable and environmentally friendly. Several studies have shown that the sequences of mine production, OB handling, and closure have substantial impacts on both the economy and the environment [24, 25].

OC mining generally involves concurrent extraction and backfilling operations. During this process, mine voids are created by the removal of OB and minerals. A mined-out area, usually a pit, which may remain as a depressed landform even after rehabilitation, is referred to as a "mine void." These voids can vary in form, ranging from shallow depressions in the restored landscape to features resembling the final mine pit geometry. As part of the progressive mine closure, mined-out sections are methodically backfilled with OB material. However, toward the end of mine life, a significant void may remain between the final highwall and the backfilled dump slope. A coordinated and optimal approach is taken to ensure that the mine-out voids are generated and filled on time (Figure 1).

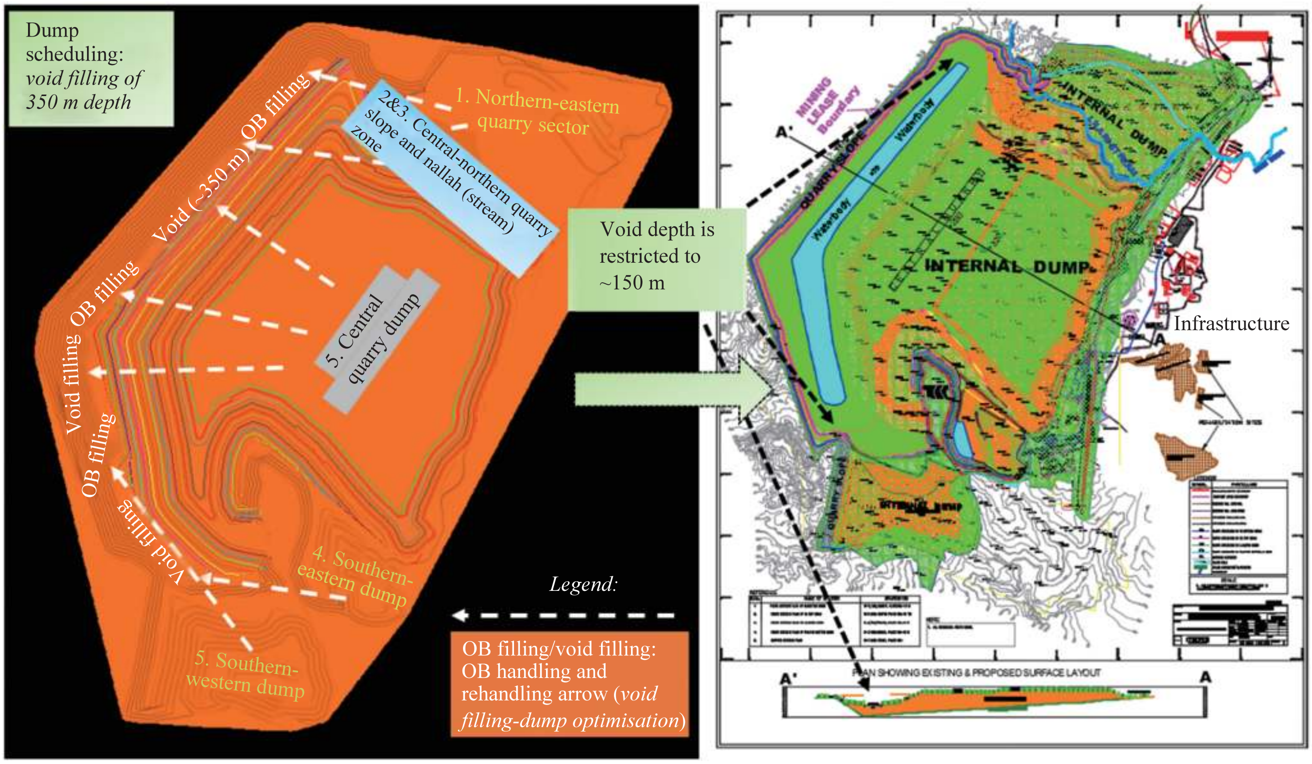

Figure 1 Conceptual void optimization strategy for an open-pit coal mine (maximum depth: 350 m)

In order to optimize mining, pit backfilling, reclamation, and rehabilitation should begin as soon as possible.

An integrated backfilling strategy is a mining planning approach that seamlessly integrates progressive and final backfilling strategies into the production schedule and overall mine life cycle. It is fundamentally important to backfill mining voids so that the following goals can be reached:

(1) Slopes and backfilled areas are stable in terms of geotechnical stability [26–28].

(2) Dump optimization and minimizing the need for external dumping [29–31].

(3) Separation of reactive wastes from groundwater [17, 32].

(4) Restoration of ecosystems and reclamation at an early stage [33, 34].

(5) A cost-optimization approach to mine closure [35–38].

Engineering encapsulation of reactive adverse material is an important environmental safeguard when planning integrated backfills [39]. An encapsulation layer of clay (typically around one meter thick) is used to enclose waste materials within a confined geometry. Since clay is largely impervious, it prevents groundwater from entering the system and leachate from migrating. By incorporating this system into the design and construction process, long-term environmental impacts and costs can be minimized and managed at relatively low post-closure levels.

3 Backfilling methods in OC coal mines

In OC coal mines, backfilling is typically regulated by pit geometry, production sequence, and geo-mining conditions [40–42], as shown in Figure 2.

Backfilling techniques are broadly grouped into three categories: (i) direct replacement and simultaneous backfilling, (ii) around-the-pit backfilling using shovel-dumper systems, and (iii) deferred backfilling with external dump rehandling. These techniques have different operating sequences, material flow, and closure effects. The selection and optimization of these approaches require balancing operational feasibility, cost efficiency, environmental considerations, and long-term closure objectives.

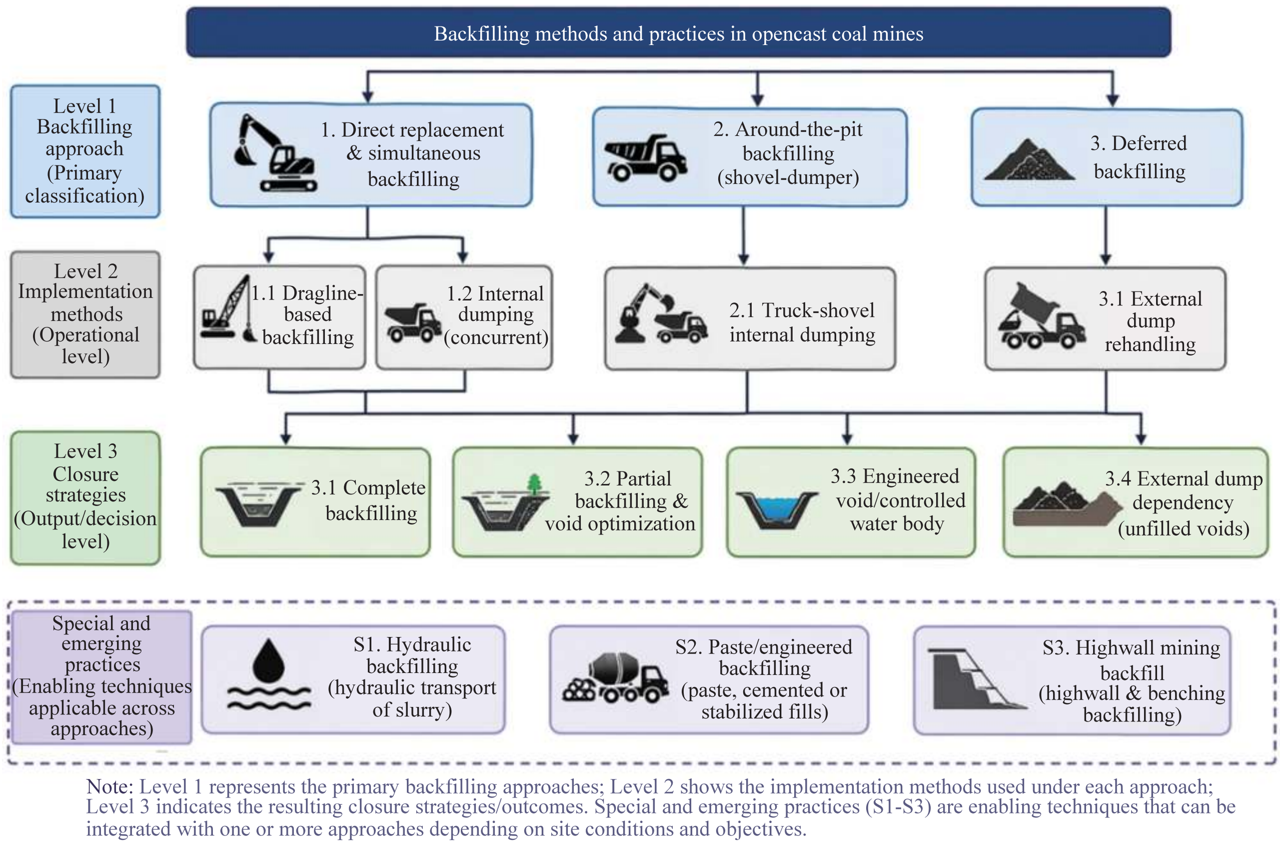

Figure 2 Hierarchical classification of backfilling methodologies in OC coal mines, delineating primary methods, associated implementation techniques, and resultant closure strategies, with particular emphasis on special and emergent practices recognized as cross-cutting techniques usable across various approaches

3.1 Direct replacement and simultaneous backfilling

In direct replacement, OB is immediately placed into adjacent voids, often using draglines and scrapers [43, 44]. Generally, this approach works well in deposits that are shallow to moderately deep, have favorable strip geometry, and have sufficient equipment reach. It encourages early land reclamation, cuts down on rehandling, and minimizes haulage distance. The Jayant OC mine in India is a beneficial example of how dragline-based direct replacement is effective.

Dragline mining projects gradually generate enormous waste dumps that may pose operational and safety challenges for coal loading activities. In situations where the depth of the OB exceeds the digging and casting capacity of one dragline, the entire burden cannot be handled by draglines alone. These conditions require integrated equipment systems, such as tandem draglines (horizontal or vertical configurations) or shovel–dumper–dragline systems (Figure 3).

Typically, shovel–dumpers are used to pre-strip upper layers of OB to excavate them quickly and cast them directly onto the leveled or unleveled dragline dump created onto the decoaled strip area. The removal, preservation, and reapplication of topsoil during reclamation is part of simultaneous backfilling.

With this integrated approach, long-haul OB transportation, which is the most energy-intensive component of surface mining, becomes less efficient. Shovel–dumper-dominated haulage accounts for 70%–80% of all diesel usage and significantly contributes to overall operating costs [44, 46].

3.2 Around-the-pit backfilling (shovel–dumper method)

Around-the-pit backfilling is the process of placing OB into interior voids utilizing truck–shovel combinations, especially in mines with complicated geology, multiple

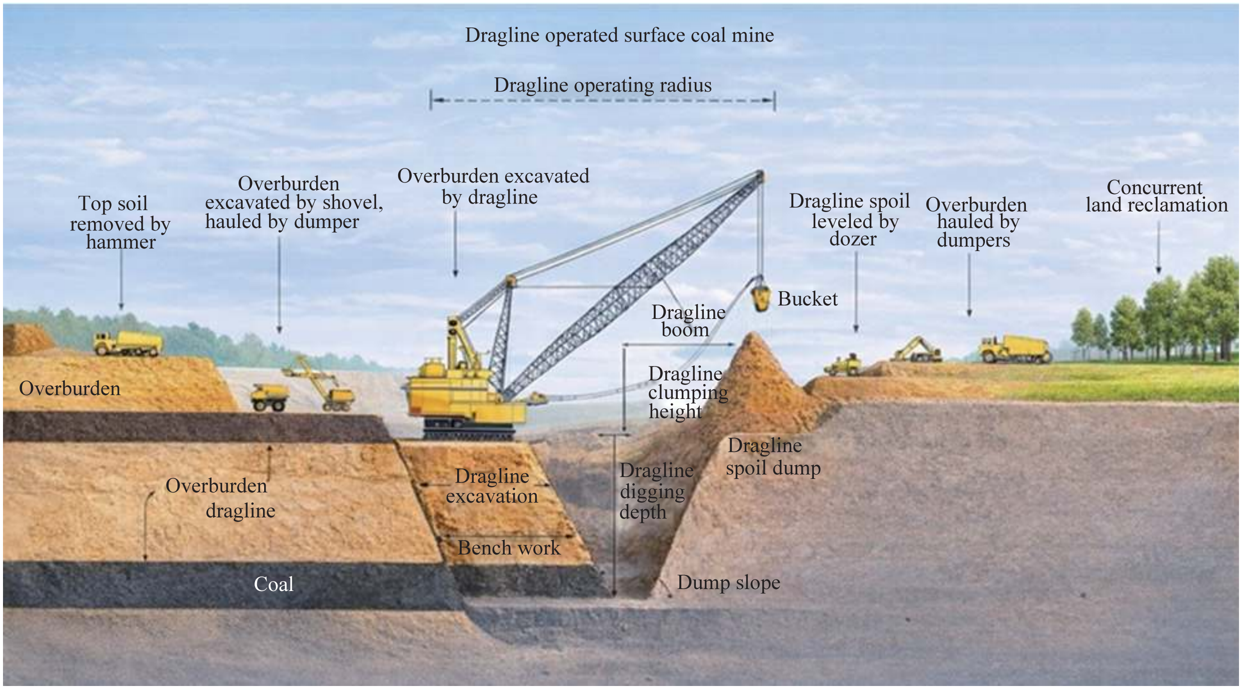

Figure 3 Schematic illustration of the sequence of operations and backfilling in a dragline surface coal mine (modified after [45])

seams, or uneven pit geometry [47]. A mine's perimeter or quarry boundary is excavated to place the OB in internal voids, termed as internal dumping (Figure 4). This approach offers excellent operational flexibility and adaptation to changing mining circumstances. However, it is linked with greater haulage costs, increased fuel consumption, and reliance on haul road conditions as compared to dragline-based systems.

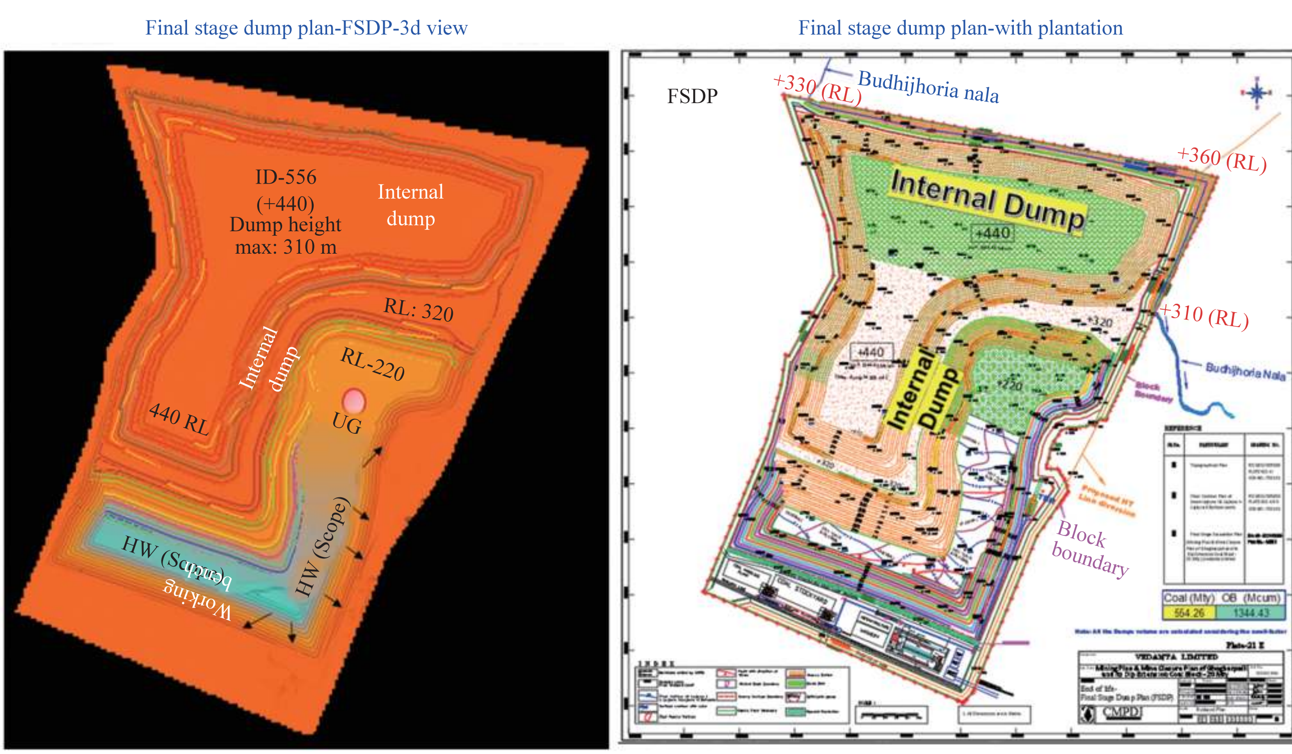

Figure 4 Final-stage dump plan showing internal dumping around-the-pit using shovel–dumper method

3.3 Deferred backfilling

Deferred backfilling is used when quick internal dumping is not an option owing to geometric, geotechnical, or sequencing restrictions. OB is initially disposed of at external or temporary dumps before being reclaimed for mined-out voids (Figure 5). At the initial stage, boundary dumping is permitted if related factors for stability and environmental protection are satisfied.

This strategy allows for early-stage production and flexible planning, but it also requires more material handling, greater expenses, and delayed reclamation. Depending on site circumstances, a portion of the final void may be preserved as an engineered void or water body.

3.4 Special and emerging backfilling practices

In addition to conventional methods, specialist approaches such as hydraulic backfilling, paste or designed backfilling, and highwall mining backfill are employed when specific technical or environmental requirements are satisfied. These techniques are often used when more stability, controlled placement, or environmental detention is required.

A comparative overview of backfilling techniques, including their suitability, benefits, and shortcomings are shown in Table 1.

4 Decision support framework (DSF)

For closure-oriented decision-making, traditional methods frequently rely on a single criterion like stripping ratio (SR) or production-driven considerations, which are inadequate as they do not account for the combined effects of multiple interacting constraints.

To close this gap, IBP-DSF is proposed. The framework adopts a structured multi-criteria approach that integrates key planning parameters into a unified decision structure to delineate viable closure options.

4.1 Concept and architecture of the model

IBP-DSF unifies important economic, environmental, and physical factors into a single multi-criteria evaluation framework. Five primary domains form the fundamentals of IBP-DSF:

(1) Material balance and pit geometry, including void volume, OB availability, and stripping properties.

(2) The maximum depth and its geotechnical consequences are examples of depth-related limitations.

(3) Geotechnical stability reflects rock mass characteristics and dump dynamics.

(4) Hydro-environmental sensitivity, including groundwater interplay and ecological restrictions.

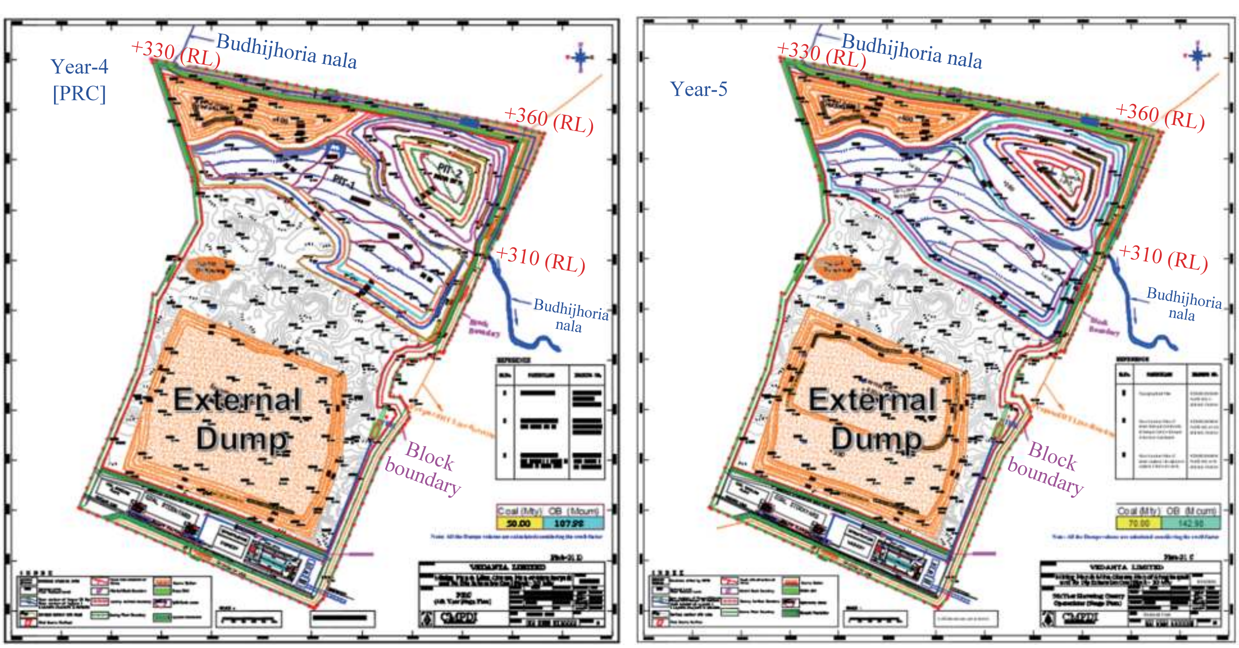

Figure 5 Deferred dump planning, placing temporary external dumps during the initial years

Table 1 Comparative appraisal of OC coal mines' backfilling techniques

Backfilling method	Suitable conditions	Advantages	Limitations
Direct replacement & simultaneous backfilling (dragline-based/concurrent internal dumping)	Deposits with shallow to moderate depths; favorable strip-ratio geometry; sufficient dragline reach, and continual strip mining	Reduces transportation distance; low operational expenses; high productivity; early land reclamation and minimized external waste disposal	Constrained by dragline reach and depth; unsuitable for deep quarries or complex multi-seam scenarios; needs uniform strip geometry
Around-the-pit backfilling (shovel–dumper/truck–shovel internal dumping)	Multi-seam deposits; complicated pit geometry; variable depth conditions; adaptive scheduling	High operational agility; suitable for uneven geometry; adaptable to dynamic mining designs; enables staged internal dumping	Higher haulage expenses; augmented fuel consumption; reliance on haul road conditions; relatively lower efficiency compared to dragline systems
Deferred backfilling (external dump rehandling)	Deeper pits; initial absence of internal void; limited early-stage geometry; staggered mining scenarios	Supports early production; enables strategic planning of the final void; fosters adaptable resource management; facilitates staged closure	Rehandling of OB; higher expenses; increased environmental imprint owing to external disposal; prolonged reclamation
Complete backfilling (closure strategy)	Moderate pit depth; sufficient OB supply; suitable geotechnical and economic circumstances	Eliminates final void; maximizes land restoration; reduces long-term environmental obligation	Often not viable in deep or material-deficient settings; cost-intensive; may be sub-optimal given hydro-environmental restrictions
Partial backfilling with void optimization	Moderate to deep excavation; limited material availability; necessity for equitable closure and economic viability	Practical and generically applicable; optimizes land use; minimizes dump footprint; balances economics and environmental impacts	A residual void exists; necessitates careful design of the ultimate final stage dump and reclamation plan for stability and sustainability
Engineered void/controlled water body	Deep quarries; considerable hydrogeological susceptibility; excess void quantity; environmental limitations	Provides a robust long-term solution that aids groundwater recharging and eliminates excessive material requirements	Needs stringent geotechnical and hydrological management; potentially requires long-term supervision; compliance with regulations
External dump dependency (residual strategy)	Substantial material scarcity; typically, very deep quarries; financial limitations; legacy mining conditions	Reduces rehandling costs; operationally easy in limited settings	Strong environmental effect; continual responsibility; land acquisition issues; decreased closure-related sustainability
Hydraulic backfilling (special practice)	Fine-grained elements; slurry transporting capability; regulated placement settings	Proper compaction; homogeneous fill; appropriate for supervised deployment	Necessitates water management; infrastructure-intensive; uncommon in open-pit coal mines
Paste/engineered backfilling	Requirements for high consistency; regulated settling; environmental isolation (e.g., reactive waste encapsulation)	Superior strength; regulated placement; enhanced environmental performance	Expensive; restricted large-scale OC utilization; material preparation needed
Highwall mining backfill	Remaining coal extraction areas; highwall mining operations; limited or blocked access zones	Enables recovery of additional or blocked reserves; decreases exposed voids locally	Limited application; operational complexities; safety concerns

(5) Economic feasibility, factoring in closure costs and backfilling needs.

Unlike traditional systems that depend on single-parameter indicators or isolated optimization algorithms, IBP-DSF combines these dimensions into a cohesive, dimensionless decision index, allowing for straightforward comparison and consistency among mines with different circumstances. The model does not optimize a single objective but rather provides a realistic closure strategy envelope.

4.2 Index formulation

To quantify the regulating factors, the subsequent dimensionless indices are outlined as follows:

Void filling potential $(\text{VFP}) = \left(\dfrac{\text{OB}}{\text{Pit volume}}\right)$

Backfill adequacy ratio $(\text{BAR}) = \left(\dfrac{\text{OB}}{\text{Coal volume}}\right)$

Depth severity index $(\text{DSI}) = \left(\dfrac{\text{Max depth}}{350}\right)$

Stripping pressure index $(\text{SPI}) = \left(\dfrac{\text{SR}}{5}\right)$

Geotechnical stability index (GSI_m) = Scaled from rock mass rating (RMR)/GSI

Hydro-environmental sensitivity index (HESI) = Site-based categorization (low to high)

The economic backfill viability index (EBVI) is calculated as the closure budget divided by the backfilling cost.

Each index represents a separate aspect of closure viability:

VFP and BAR represent material adequacy;

DSI represents depth-related restrictions;

SPI represents operating pressure;

GSI_m represents stability conditions;

HESI represents environmental restrictions;

EBVI represents economic feasibility.

To ascertain comparability between mines of varying sizes, all indices are transformed to dimensionless normalized metrics.

In the absence of site-specific RMR data for all case studies, geotechnical stability was expressed by a proxy-based categorization representing common interbedded sandstone-shale conditions generally encountered in Indian OC coalfields. The framework was developed using a sample mine-scale stability index (GSI_m = 0.50), which aligns with slope geometry and regional geotechnical practices. This assumption allows for a consistent depiction of stability requirements while ensuring coherence across case studies.

4.3 Mathematical formulation

IBPS is calculated as a weighted aggregate of normalized indices, expressed through Equation (1).

$$\text{IBPS} = \sum_{i=1}^{n} w_i \times X_i^{\text{norm}} \quad (1)$$

where

X_i^{norm}= normalized value of the i^{th} index;

w_i = weight assigned to the i^{th} index;

$\sum w_i$=1.

A linear normalization approach is employed to transform all indices into similar dimensionless values. Weights are allocated based on domain-specific expert judgement, indicating the relative relevance of physical feasibility, geotechnical stability, hydro-environmental sensitivity, and economic feasibility in closure decision-making, and can be adjusted for location-specific variables.

The normalization constants are derived from typical upper-bound operational conditions found in major OC coal mines. DSI is implied to a depth of 350 m, whereas SPI is normalized using a reference SR of 5. While larger depths and SRs may occur in some circumstances, values surpassing these reference limits (DSI > 1 and SPI > 1) signal rising geotechnical and operational restrictions, which may jeopardize backfilling feasibility.

4.4 Criteria for classifying decisions

IBP-DSF employs a classification-based methodology whereby the closure strategy is dictated by IBPS. The following thresholds, as shown in Table 2, are established based on the clustering of case study outcomes and the evaluation of boundary scenarios.

These thresholds establish pragmatic decision boundaries for the selection of closure strategies.

The closure strategy for each case is directly derived from the IBPS value, ensuring a transparent and reproducible decision-making process. Individual indices influence the outcome via weighted aggregation, allowing their collective interaction to determine the final result. The classification-based approach creates a feasible space for closure strategies rather than prescribing a singular optimal solution, thereby enabling site-specific and pragmatic decision-making.

4.5 Decision-making workflow

IBP-DSF adheres to a structured workflow (Figure 6), followed by sequential steps:

Step 1: Input parameters (mine geometry, material availability, depth, geotechnical, hydro-environmental,

Table 2 IBPS-based classification of closure strategies

IBPS range	Closure strategy	Interpretation
IBPS ≥ 0.75	Complete backfilling	Highly favorable conditions with adequate material balance, moderate depth, stable geotechnical conditions, and economic feasibility enabling near-complete void filling and landform restoration
0.55 ≤ IBPS < 0.75	Partial backfilling/ void optimization	Moderately favorable conditions where partial internal dumping combined with optimized void management represents the most practical and sustainable closure approach
0.35 ≤ IBPS < 0.55	Engineered void/controlled water body	Increasing geotechnical, environmental, or economic constraints limit full backfilling, requiring engineered void retention or conversion to controlled water bodies
IBPS < 0.35	External dump dependency	Severe constraints in material availability, depth, environmental sensitivity, or economic feasibility, resulting in strong reliance on external dumping or minimal backfilling

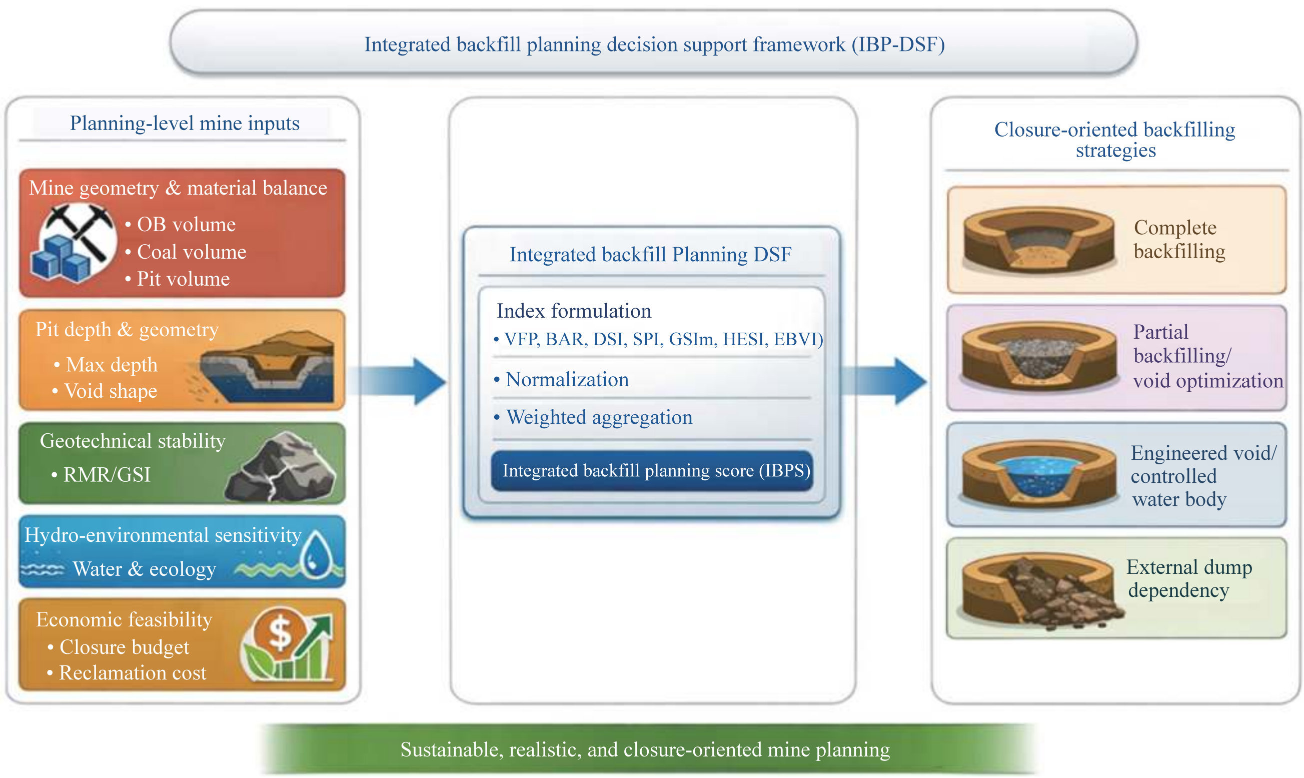

Figure 6 Conceptual workflow of IBP-DSF, illustrating the progression from mine inputs to indices, IBPS, and closure strategies

and economic factors).

Step 2: Conversion to dimensionless indices (VFP, BAR, DSI, SPI, GSI_m, HESI, and EBVI).

Step 3: Normalization and weighted aggregation yield IBPS.

Step 4: Classification of closure strategy.

5 Case studies

The proposed IBP-DSF has been tested on a set of representative brownfield and greenfield OC coal mines in India. The framework was complemented by hypothetical boundary cases to demonstrate its full decision space, as mentioned below:

(1) Brownfield cases are operating mines with partially exhausted reserves and legacy pit geometry that are constrained by historical mining decisions.

(2) Greenfield cases are new or recently approved projects that are capable of allowing closure feasibility to be assessed at an early stage of the planning process.

(3) Hypothetical cases illustrating boundary conditions with serious OB deficiencies, extreme depths,

high hydro-environmental sensitivity, and constrained closure budgets were developed.

In each instance, the input metrics are transformed into dimensionless indices, normalized, and consolidated using a weighted approach to calculate IBPS. The generated IBPS values are then assigned to closure strategies using established classification criteria. As the framework is applied to these cases (Figure 7), the approach provides the following key insights:

(1) The majority of the examined instances had an IBPS score within the range of 0.55 ≤ IBPS < 0.75, showing that partial backfilling with void optimization is the most practical and prevalent closure approach under typical Indian OC mining settings.

(2) Complete backfilling (IBPS ≥ 0.75) is limited to scenarios with advantageous geometry and material balance (VFP and BAR), stable geological circumstances (GSI_m), substantial OB availability, reasonable pit depth (DSI), and appropriate economic feasibility (EBVI).

(3) In situations of deeper depths or limited material supply, closure solutions shift toward artificial voids or controlled water bodies (0.35 ≤ IBPS < 0.55), indicating limitations in geotechnical soundness and hydro-environmental viability.

(4) Where material supply and financial viability are severely limited, an external dump (IBPS < 0.35) reliance arises as a viable, albeit less ecologically sound, closure option.

These findings show that IBP-DSF offers a transparent and consistent framework for assessing closure techniques in a variety of mining circumstances, facilitating a methodical comparison of multi-scenario options and encouraging closure-oriented scheduling that goes beyond traditional production-focused methods.

6 Discussion and solution framework

According to the analysis, no single backfilling method is universally applicable to all OC coal mines. The findings show that the combined effects of different indices determine the viability of backfilling

SI.	Particulars	Symbol	Unit	Brownfield Opencast Projects (BF)			Green-field Opencast Projects (GF)			Hypothetical Opencast Projects (HP)		
				BF: Case Study-1	BF: Case Study-2	BF: Case Study-3	GF: Case-Study-4	GF: Case-Study-5	GF: Case-Study-6	HP:Case Study-7	HP:Case Study-8	HP:Case Study-9
	Input											
1	Overburden Volume	OB	Mm3	4284.490	422.990	229.260	1344.430	613.180	141.400	300.000	150.000	220.000
2	Coal Volume	CV	Mm3	933.810	414.120	160.670	363.400	472.320	158.270	450.000	400.000	700.000
3	Pit Void Volume	PV	Mm3	5218.300	837.110	389.930	1707.830	1085.500	299.670	750.000	550.000	920.000
4	Stripping Ratio	SR	cum/te	3.393	0.722	0.975	2.426	0.798	0.615	0.417	0.233	0.195
5	Maximum Pit Depth	D	m	354.000	247.000	260.000	348.000	215.000	151.000	400.000	600.000	450.000
6	Rock Mass Rating / GSI	RMR	-	50.000	50.000	50.000	50.000	50.000	50.000	40.000	40.000	35.000
7	Hydro-Environmental Sensitivity	HES	0.3/0.6/1.0	0.600	0.600	0.300	0.600	0.600	0.600	1.000	1.000	1.000
8	Closure Budget	CB	₹ Cr	795.890	129.211	127.563	361.290	382.610	143.358	100.000	50.000	60.000
9	Estimated Backfill Cost	BC	₹ Cr	397.945	51.684	51.025	180.645	191.305	71.679	150.000	120.000	150.000
10	Coal tonnage	CT	Mt	1262.860	586.110	235.160	554.260	768.830	229.930	720.000	644.000	1127.000
	Outputs											
	Index	**Symbol**	**Value**	Derived Indices								
1	Void Filling Potential	VFP		0.821	0.505	0.588	0.787	0.565	0.472	0.400	0.273	0.239
2	Backfill Adequacy Ratio	BAR		4.588	1.021	1.427	3.700	1.298	0.893	0.667	0.375	0.314
3	Depth Severity Index	DSI		1.011	0.706	0.743	0.994	0.614	0.431	1.143	1.714	1.286
4	Stripping Pressure Index	SPI		0.679	0.144	0.195	0.485	0.160	0.123	0.083	0.047	0.039
	Index	**Symbol**	**Value**	Geo Env Economic								
5	Geotechnical Stability Index (mine-scale)	GSI_m		0.500	0.500	0.500	0.500	0.500	0.500	0.400	0.400	0.350
6	Hydro-Environmental Sensitivity Index	HESI		0.600	0.600	0.300	0.600	0.600	0.600	1.000	1.000	1.000
7	Economic Backfill Viability Index	EBVI		2.000	2.500	2.500	2.000	2.000	2.000	0.667	0.417	0.400
	Index	**Symbol**		Normalised_Indices								
8	Void Filling Potential	VFP_n		0.821	0.505	0.588	0.787	0.565	0.472	0.400	0.273	0.239
9	Backfill Adequacy Ratio	BAR_n		1.000	0.255	0.357	0.925	0.325	0.223	0.167	0.094	0.079
10	Depth Severity Index	DSI_n		0.989	1.000	1.000	1.000	1.000	1.000	0.875	0.583	0.778
11	Stripping Pressure Index	SPI_n		1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
12	Geotechnical Stability Index (mine-scale)	GSI_n		0.500	0.500	0.500	0.500	0.500	0.500	0.400	0.400	0.350
13	Hydro-Environmental Sensitivity Index	HESI_n		0.400	0.400	0.700	0.400	0.400	0.400	0.000	0.000	0.000
14	Economic Backfill Viability Index	EBVI_n		1.000	1.000	1.000	1.000	1.000	1.000	0.667	0.417	0.400

SI.	Index	Symbol	Weight	Scoring_Model																	
				Normalised Value	Weighted Score	Normalised Value	Weighted Score	Normalised Value	Weighted Score	Normalised Value	Weighted Score	Normalised Value	Weighted Score	Normalised Value	Weighted Score	Normalised Value	Weighted Score	Normalised Value	Weighted Score	Normalised Value	Weighted Score
15	Void Filling Potential	VFP_n	**0.20**	0.821	0.164	0.505	0.101	0.588	0.118	0.787	0.157	0.565	0.113	0.472	0.094	0.400	0.080	0.273	0.055	0.239	0.0478
16	Backfill Adequacy Ratio	BAR_n	**0.15**	1.000	0.150	0.255	0.038	0.357	0.054	0.925	0.139	0.325	0.049	0.223	0.034	0.167	0.025	0.094	0.014	0.079	0.0118
17	Depth Severity Index	DSI_n	**0.10**	0.989	0.099	1.000	0.100	1.000	0.100	1.000	0.100	1.000	0.100	1.000	0.100	0.875	0.088	0.583	0.058	0.778	0.0778
18	Stripping Pressure Index	SPI_n	**0.10**	1.000	0.100	1.000	0.100	1.000	0.100	1.000	0.100	1.000	0.100	1.000	0.100	1.000	0.100	1.000	0.100	1.000	0.1000
19	Geotechnical Stability Index (mine-scale)	GSI_n	**0.15**	0.500	0.075	0.500	0.075	0.500	0.075	0.500	0.075	0.500	0.075	0.500	0.075	0.400	0.060	0.400	0.060	0.350	0.0525
20	Hydro-Environmental Sensitivity Index	HESI_n	**0.15**	0.400	0.060	0.400	0.060	0.700	0.105	0.400	0.060	0.400	0.060	0.400	0.060	0.000	0.000	0.000	0.000	0.000	0.0000
21	Economic Backfill Viability Index	EBVI_n	**0.15**	1.000	0.150	1.000	0.150	1.000	0.150	1.000	0.150	1.000	0.150	1.000	0.150	0.667	0.100	0.417	0.063	0.400	0.0600
22	Total Integrated Backfill Planning Score	IBP_n			0.798		0.624		0.701		0.781		0.647		0.613		0.453		0.349		0.3499

SI.	Index	Symbol		Strategy output								
23	Integrated Backfill Planning Score	IBPS		**0.7981**	**0.6244**	**0.7011**	**0.7812**	**0.6467**	**0.6129**	**0.4525**	**0.3494**	**0.3499**
24	Recommended Backfill Strategy	RBS		Complete Backfilling	Partial Backfilling / Void Optimisation	Partial Backfilling / Void Optimisation	Complete Backfilling	Partial Backfilling / Void Optimisation	Partial Backfilling / Void Optimisation	Engineered Void / Controlled Water Body	External Dump Dependency	External Dump Dependency

Figure 7 IBP-DSF for brownfield, greenfield, and hypothetical OC coal mines (9 case studies). Units: Mt: million tonnes; Mm^3: million cubic meters; m: meters; Cr: crores; cum/te : cubic meters per tonne

in OC coal mines. In large-scale open-pit operations, when complete backfilling is rarely possible under realistic circumstances, the preponderance of partial backfilling throughout the examined examples reflects the normal imbalance between void volume and available OB.

The amount of backfilling is mostly determined by material availability, which is measured by BAR and VFP. Mines with higher values on these indices show better viability for progressive backfilling and landform restoration, whereas material-deficient circumstances limit closure choices and increase reliance on external dumping or engineering solutions.

DSI measures depth-related restrictions, which bring substantial geotechnical and operational limits. As pit depth grows, stability of the slope, compaction, and hauling efficiencies become more severe, necessitating a shift away from total or partial backfilling and toward designed voids or controlled water bodies. The decision-making process is additionally impacted by operational and economic limitations, which are represented by SPI. These forces have an impact on haulage costs, dump stability, and the general viability of backfilling operations. Higher SPI values imply higher operational complexities, necessitating the optimization of backfilling solutions for equitable cost and environmental concerns.

GSI_m and HESI limit closure alternatives, affecting dump stability, groundwater interplay, and ecological concerns. These considerations are particularly important in deep quarries and ecologically sensitive areas.

Economic feasibility, as measured by EBVI, is crucial in establishing the viability of backfilling solutions. Even when physical circumstances are favorable, insufficient financial resources may limit the degree of backfilling, necessitating alternate closure strategies.

The findings unequivocally show that closure planning cannot be accomplished by relying just on single indications like SR. IBP-DSF makes it possible to evaluate closure techniques more practically and convincingly by integrating several aspects into a single framework.

In terms of planning, the framework provides the following advantages:

(1) For greenfield projects (Figure 7), the program allows realistic closure commitments during the approval process. This avoids overpromising in mining, statutory and closure plans. It enhances the legitimacy and practicality of authorized mining and mine closure plans by facilitating the early assessment of feasible backfilling scenarios, associated closure approaches, and prospective progressive and post-closure design and cost implications.

(2) For brownfield projects (Figure 7), it assists in reassessing and optimizing the remaining closure options in light of current conditions rather than assumptions made in the past, enabling planners to improve the backfilling techniques and balance the life of mine decisions with attainable and defendable closure goals.

In summary, IBP-DSF provides a clear and uniform framework for assessing closure methods, allowing planners, governing bodies, authorities, and stakeholders to make more informed decisions.

7 Conclusion

IBP-DSF is a systematic multi-criteria framework for assessing backfilling solutions in OC coal mines. It combines material balance, depth limits, geotechnical conditions, hydro-environmental sensitivity, and financial viability into a single decision index (IBPS).

The framework's application to brownfield, greenfield, and hypothetical cases indicates that complete backfilling is only possible given a narrow set of favorable physical, environmental, and economic conditions. For most mines, partial backfilling with void optimization is the most realistic and long-term closure option, with designed voids or external dump dependence emerging as limitations increase.

According to the research, complete backfilling is often possible when there is a strong void-filling potential (VFP $\gtrsim$ 0.75), modest depth (DSI $\lesssim$ 1), and favorable economic viability (EBVI > 1). On the other hand, practical approaches tend to move toward artificial voids or regulated void retention as depth and hydro-environmental sensitivity increase. The external dump reliance regime is more likely to apply to mines with poor material availability (VFP $\lesssim$ 0.4) and financial limitations. The IBP-DSF's practical applicability bounds under various geo-mining, geometrical, and financial scenarios are defined by these patterns.

The findings demonstrate that closure feasibility necessitates a multi-criteria approach that captures the combined effect of controlling elements rather than being reliably evaluated using single indicators like SR. For OC coal mines in India and similar geological settings across the globe, the proposed IBP-DSF offers an integrated and adaptable decision support tool that complements strategic and comprehensive mine planning and enables informed, evidence-based selection of sustainable closure strategies. It will help the industry to achieve sustainable closure with facts and data. Backfilling strategies should be tailored to site-specific conditions to ensure sustainability throughout the mine's life cycle.

Acknowledgements

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Author Contributions

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Declarations

xxxx.

Conflict of interest

The authors declare that they have no conflict of interests.

Data availability

The relevant data are available from the authors upon reasonable request.

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