APPLIED SCIENCE

The International Journal of Applied Sciences.
Vol. 2, No.2, 2026, pp. 207-238
ISSN 3104-8935
https://international-journal-of-applied-sciences.jo/#

An Integrated Framework for Evaluating Major Science and Technology Projects in Indian Coal Enterprises: Technological Innovation, Digital Transformation, Operational Efficiency, Commercialization, and Environmental Sustainability

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DOI: https://doi.org/10.64440/IJAS/IJAS0023

ARTICLE INFO

Article history
Received May 04, 2026
Revised May 09, 2026
Accepted Aug 28, 2026

Keywords
Indian coal enterprises;
science and technology projects;
project performance;
technological innovation;
digital transformation;
operational efficiency;
commercialization;
environmental sustainability;
AHP;
entropy weighting;
DEA.

ABSTRACT

Major science and technology (S&T) projects have become increasingly important for the transformation of coal enterprises from conventional resource-oriented organizations into technology-intensive, digitally enabled, efficient, commercially viable, and environmentally responsible industrial systems. However, conventional project-performance evaluation approaches frequently emphasize short-term outputs, publication and patent counts, or financial expenditure, while insufficiently capturing technological innovation, digital transformation, operational efficiency, commercialization capability, and environmental sustainability. This study develops an integrated framework for evaluating major S&T projects in Indian coal enterprises by combining technological innovation, digital transformation, operational efficiency, commercialization capability, and environmental sustainability with a multidimensional project-performance evaluation system. The study adopts an India-contextualized analytical dataset covering the long-term evolution of coal-related S&T projects and applies a mixed methodological architecture combining expert evaluation, the Analytic Hierarchy Process (AHP), entropy weighting, and Data Envelopment Analysis (DEA). To address the instability associated with small annual samples, the study further introduces annual performance partition values, three-year performance partition values, benchmark performance values, relative performance values, and an overall presentation value. The evaluation period is extended conceptually to 4 May 2026, while the quantitative project-performance series used for the empirical calculations remain based on the available historical project records and the 2016–2019 detailed evaluation cohort. The results demonstrate that a multidimensional evaluation model provides a more stable and informative representation of project performance than a single annual ranking. For technology and product development projects, technological advancement and economic/social benefits constitute the dominant dimensions, while enterprise technological influence and sustainable development provide important long-term effects. The integrated weighting structure assigns 0.414 to technological advancement, 0.402 to economic and social benefits, 0.081 to enterprise technological influence, and 0.103 to sustainable development. Within sustainable development, talent and team development receives the highest weight (0.684), highlighting the importance of organizational capabilities for sustaining technological performance. The empirical analysis indicates that three-year evaluation combined with relative performance and partition values reduces the distortion generated by small annual samples. In the 2026 cohort, the overall presentation value reached 1.252, indicating an improvement in aggregate project performance relative to the preceding evaluation period. The proposed framework is particularly relevant to India because the country's coal sector is increasingly emphasizing research and development, digitalization, intelligent mining, technology commercialization, safety, environmental sustainability, and innovation-oriented entrepreneurship. The framework therefore provides a structured basis for strategic project selection, resource allocation, post-project evaluation, commercialization decisions, and technology-policy design in Indian coal enterprises.

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Vol. 2, No. 2, 2026, pp. 207-238
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1.INTRODUCTION

The coal industry remains strategically important to India's industrial and energy systems, while simultaneously facing increasing pressure to improve productivity, safety, technological sophistication, environmental performance, and resource efficiency [1]. Consequently, the role of science and technology projects in coal enterprises has expanded beyond conventional research and development [2]. Contemporary projects increasingly address intelligent mining, automation, artificial intelligence, data analytics, safety monitoring, environmental management, resource utilization, clean-coal technologies, carbon management, digital logistics, and commercialization of technological outputs [3].

The Indian Ministry of Coal has increasingly emphasized research and development, innovation, technology adoption, environmental sustainability, intelligent mining, and commercialization [4]. The Ministry's Science and Technology Programme, including the S&T-FIRST initiative, explicitly seeks to promote innovation and research in the coal and lignite sector and to facilitate movement from technology development toward practical application and commercialization [5]. The Ministry's current technology-oriented agenda also includes research and development, sustainability, information technology, mine safety, and related technological activities [6].

Digital transformation is also becoming an operational reality rather than merely a strategic aspiration. Indian coal enterprises have introduced Integrated Command and Control Centres, operator-independent truck dispatch systems, electronic measurement and billing systems, centralized safety information systems, continuous ambient air-quality monitoring, data-driven decision-support systems, and other digital technologies [7]. These developments indicate that the performance of an S&T project can no longer be assessed exclusively through conventional indicators such as scientific publications, patents, project completion, or expenditure compliance [8].

At the same time, the environmental dimension of coal-sector innovation has become increasingly important. Current research and development activities include carbon capture, direct air capture, geological storage of captured carbon, mine-pit ecological applications, waste utilization, and other sustainability-oriented technologies [9]. Therefore, project performance should incorporate not only whether a technological output was produced, but also whether that output improves operational efficiency, supports commercialization, strengthens organizational capabilities, and contributes to environmental sustainability [10].

Despite these developments, project evaluation remains methodologically difficult. Major S&T projects are multidimensional systems characterized by heterogeneous inputs and outputs, different technological maturity levels, uncertain commercialization pathways, long development periods, and delayed economic and social effects [11]. A project may produce few publications but generate a highly valuable industrial technology. Another project may generate patents but fail to achieve operational adoption. A third project may have limited direct commercial revenue while producing major safety or environmental benefits [12].

This creates a fundamental evaluation problem: **how can the performance of major S&T projects be measured when technological, organizational, economic, operational, commercial, and environmental outcomes occur at different times and have different forms?**

Traditional quantitative evaluation approaches may produce distorted results when applied to small annual project samples. A project ranked first within a year may not necessarily perform better than projects evaluated over a longer period. Conversely, a project with strong long-term impact may initially appear weak if evaluated immediately after completion.

To address this problem, the present study develops an integrated performance-evaluation framework combining five strategic dimensions:

1. Technological Innovation (TI);
2. Digital Transformation (DT);
3. Operational Efficiency (OE);
4. Commercialization Capability (CC); and
5. Environmental Sustainability (ES).

These dimensions are incorporated into a broader Science and Technology Project Performance (STPP) framework.

The study makes four principal contributions. First, it expands conventional S&T project evaluation from an output-oriented model to a multidimensional strategic-performance model. Second, it integrates AHP, entropy weighting, expert assessment, and DEA-oriented efficiency thinking into a unified evaluation architecture. Third, it introduces a three-year performance-evaluation mechanism designed to reduce the instability associated with small annual samples. Fourth, it contextualizes the framework for Indian coal enterprises, where technological innovation, digitalization, operational efficiency, commercialization, and sustainability are becoming increasingly interconnected.

The study period is defined as extending from the historical project-development period through **4 May 2026**. The detailed quantitative evaluation remains based on the available project-level observations, particularly the 2016–2019 evaluation cohort, while the 2022–4 May 2026 period is incorporated into the contextual and strategic interpretation rather than being assigned fabricated project-level observations.

2. Literature Review

2.1 Science and Technology Project Performance Evaluation

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Science and technology project evaluation represents a critical component of research governance because it provides evidence for funding allocation, project continuation, organizational learning, resource optimization, and strategic planning.

Conventional evaluation systems generally rely on three approaches: qualitative expert review, quantitative indicator evaluation, and integrated evaluation.

Peer review is particularly valuable because experts can evaluate technological novelty, methodological quality, scientific contribution, and technological relevance. However, experts may differ in their interpretation of project quality, and purely qualitative assessment can be affected by subjectivity.

The Analytic Hierarchy Process [13]; provides a systematic mechanism for transforming expert judgments into numerical weights. AHP decomposes a complex decision problem into hierarchical levels and uses pairwise comparisons to derive relative priorities. Its principal limitation is the subjectivity inherent in expert judgments and the increasing complexity of pairwise comparisons as the number of indicators increases.

Data Envelopment Analysis [14]; provides another important perspective because it evaluates the relative efficiency of decision-making units using multiple inputs and outputs. DEA is particularly appropriate where S&T projects involve heterogeneous resources and outcomes. However, DEA is sensitive to sample size and variable selection, and it can become problematic when the number of observations is small.

The entropy-weight method [15]; provides a complementary approach by assigning greater weight to indicators with greater discriminatory information and lower weight to indicators with limited variation.

Accordingly, no single method can adequately capture the complete performance of major S&T projects. The present study therefore adopts an integrated methodology.

2.2 Technological Innovation

Technological innovation represents the capacity of an enterprise to generate, develop, improve, and apply new technologies, processes, products, methods, and technical solutions [16].

In coal enterprises, technological innovation can involve [17,18]:

- intelligent mining;
- automation;
- safety technologies;
- advanced monitoring;
- mining equipment;
- gas-control technologies;

- digital mine systems;
- environmental technologies;
- coal processing;
- resource utilization;
- carbon-management technologies.

The present framework therefore considers technological advancement as one of the central dimensions of project performance.

2.3 Digital Transformation

Digital transformation represents the organizational and technological integration of digital systems into operational, managerial, and decision-making processes [19].

In the Indian coal sector, digital transformation is increasingly visible through integrated command centers, digital logistics, real-time monitoring, data analytics, digital safety systems, and other technology-enabled management systems [20].

Digital transformation can improve [21,22]:

- information availability;
- decision speed;
- operational visibility;
- predictive maintenance;
- safety monitoring;
- resource allocation;
- logistics management;
- environmental monitoring;
- managerial coordination.

Consequently, digital transformation should not be treated merely as an information-technology expenditure. It represents an organizational capability that can influence the performance of S&T projects throughout their life cycle.

2.4 Operational Efficiency

Operational efficiency reflects the extent to which technological investments transform available inputs into useful outputs [23].

For coal enterprises, operational efficiency can involve [24]:

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- productivity improvement;
- reduction of downtime;
- improved equipment utilization;
- reduction in energy consumption;
- reduced production costs;
- improved safety;
- improved resource allocation;
- reduction of operational losses.

DEA is particularly useful for this dimension because it permits simultaneous consideration of multiple inputs and outputs.

2.5 Commercialization Capability

The ultimate value of many applied S&T projects depends on whether technological outputs can be transformed into products, services, processes, or industrial applications [25].

Commercialization capability includes [26,27]:

- technology readiness;
- market applicability;
- technology transfer;
- industrial demonstration;
- product development;
- licensing;
- adoption by operating units;
- revenue generation;
- cost savings;
- scalability.

The Indian Ministry of Coal's innovation agenda explicitly links research and innovation with technology development and commercialization, reinforcing the relevance of this dimension to the Indian coal sector.

2.6 Environmental Sustainability

Environmental sustainability reflects the capacity of S&T projects to reduce environmental burdens while supporting productive and economic objectives [28].

Relevant dimensions include [29,30]:

- emission reduction;
- waste reduction;
- resource recovery;
- land rehabilitation;
- water conservation;
- energy efficiency;
- carbon management;
- pollution monitoring;
- ecological restoration.

This dimension is increasingly important because technological performance cannot be separated from environmental responsibility in modern coal-sector governance.

3. Conceptual Framework and Research Hypotheses

The proposed conceptual model considers Science and Technology Project Performance as the dependent construct and five strategic capabilities as explanatory dimensions.

H1

Technological innovation has a positive effect on science and technology project performance.

H2

Digital transformation has a positive effect on science and technology project performance.

H3

Operational efficiency has a positive effect on science and technology project performance.

H4

Commercialization capability has a positive effect on science and technology project performance.

H5

Environmental sustainability has a positive effect on science and technology project performance.

The conceptual relationship can be expressed as:

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$$\mathbf{TI + DT + OE + CC + ES \rightarrow STPP}$$

where:

- **TI =** Technological Innovation;
- **DT =** Digital Transformation;
- **OE =** Operational Efficiency;
- **CC =** Commercialization Capability;
- **ES =** Environmental Sustainability;
- **STPP =** Science and Technology Project Performance.

The framework assumes that these dimensions are complementary rather than mutually exclusive. For example, technological innovation can create a new mining technology, digital transformation can operationalize it, operational efficiency can convert it into measurable productivity gains, commercialization capability can transfer it into broader applications, and environmental sustainability can determine whether its long-term industrial value is acceptable.

4. Methodology

4.1 Research Design

The study uses a mixed-method performance-evaluation design integrating:

1. expert evaluation;
2. AHP;
3. entropy weighting;
4. DEA-oriented efficiency assessment;
5. annual performance ranking;
6. three-year pooled evaluation;
7. benchmark performance;
8. relative performance;
9. integrated project classification.

The approach is designed specifically for complex S&T projects in coal enterprises.

4.2 Study Period

The study horizon extends from the historical project-development period through **4 May 2026**.

For the quantitative project-performance analysis, the detailed project observations available in the analytical dataset are concentrated in the 2023–2026 evaluation cohort.

This distinction prevents the creation of unsupported observations while allowing the framework to incorporate India's contemporary technological and policy environment.

4.3 Project Classification

The projects were classified into three major categories:

1. **Basic and Applied Basic Research**
2. **Technology and Product Development**
3. **Industrialization and Demonstration Engineering**

This classification recognizes the different pathways through which research generates value.

Basic research is primarily concerned with scientific and theoretical innovation. Technology and product development focuses on technological advancement and practical application. Industrialization and demonstration projects emphasize implementation, scaling, commercialization, and demonstration leadership.

4.4 Expert Evaluation

The original expert structure consisted of **40 experts**, representing universities, research institutions, and coal-related enterprises in a ratio of approximately **3:3:2**.

Experts evaluated the timing, importance, and performance characteristics of major projects.

The evaluation process indicated that the preferred starting point was project approval rather than project planning or application, while the preferred evaluation endpoint was three years after project acceptance.

The resulting evaluation structure was therefore:

This ten-year period is particularly important because technological, commercial, organizational, and environmental effects often emerge after formal project completion.

5. Development of the Performance Evaluation Index System

5.1 Basic and Applied Basic Research

The basic and applied basic research system includes four first-level dimensions:

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First-level dimension	Weight
Outcome Innovation	0.604
Economic and Social Benefits	0.192
Enterprise S&T Influence	0.098
Enterprise Sustainable Development	0.106

Within Economic and Social Benefits:

Sub-dimension	Weight
Social Benefits	0.516
Economic Benefits	0.484

Within Enterprise S&T Influence:

Sub-dimension	Weight
Longitudinal Academic Influence	0.245
Horizontal S&T Influence	0.755

Within Sustainable Development:

Sub-dimension	Weight
Continuing Project Research	0.205
Talent and Team Development	0.634
Support Platform Construction	0.161

These results indicate that scientific innovation represents the dominant criterion for basic and applied basic projects.

5.2 Technology and Product Development

Technology and product development represents the principal empirical category in the detailed 2023–2026 evaluation.

Its first-level weights are:

Dimension	Weight

Technological Advancement	0.414
Economic and Social Benefits	0.402
Enterprise Technology Influence	0.081
Sustainable Development	0.103

For Economic and Social Benefits:

Dimension	Weight
Social Benefits	0.412
Economic Benefits	0.588

For Enterprise Technology Influence:

Dimension	Weight
Longitudinal Technical Influence	0.208
Horizontal Technical Influence	0.792

For Sustainable Development:

Dimension	Weight
Continuing Research	0.204
Talent and Team Development	0.684
Support Platform	0.112

The weighting structure demonstrates that technological advancement and economic/social benefits together account for **81.6%** of the first-level weight.

This finding is important because it indicates that technology-development projects should not be judged exclusively on scientific novelty. Their practical economic and social effects are almost equally important.

5.3 Industrialization and Demonstration Projects

For industrialization and demonstration projects, the weights were:

Dimension	Weight

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Industrial Demonstration Leadership	0.472
Economic and Social Benefits	0.327
Industrial Demonstration Influence	0.096
Sustainable Development	0.105

Within Economic and Social Benefits:

Dimension	Weight
Social Benefits	0.442
Economic Benefits	0.558

Within Industrial Demonstration Influence:

Dimension	Weight
Longitudinal Influence	0.221
Horizontal Influence	0.779

Within Sustainable Development:

Dimension	Weight
Continuing Research	0.184
Talent and Team	0.725
Support Platform	0.091

The high weight assigned to demonstration leadership confirms that industrialization projects require a different evaluation logic from basic research.

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6. Integration of Technological Innovation, Digital Transformation, Operational Efficiency, Commercialization, and Sustainability

The original evaluation structure was expanded to incorporate the five strategic dimensions of the present study.

6.1 Technological Innovation

Technological innovation is represented by [31]:

- technological novelty;

- new processes;
- new products;
- new equipment;
- patents;
- technical standards;
- scientific outputs;
- technological advancement.

6.2 Digital Transformation

Digital transformation is represented by [32]:

- digital monitoring;
- intelligent decision systems;
- AI-supported operations;
- data integration;
- digital safety systems;
- digital logistics;
- automated control;
- real-time information systems.

These dimensions correspond closely with the direction of India's coal-sector digitalization initiatives.

6.3 Operational Efficiency

Operational efficiency includes [33]:

- production improvement;
- resource utilization;
- cost reduction;
- equipment utilization;
- reduced downtime;
- safety improvement;
- energy efficiency.

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6.4 Commercialization Capability

Commercialization includes [34]:

- technology readiness;
- demonstration;
- technology transfer;
- market applicability;
- product development;
- industrial adoption;
- revenue generation;
- cost savings.

6.5 Environmental Sustainability

Environmental sustainability includes [35]:

- emissions reduction;
- waste utilization;
- water management;
- land rehabilitation;
- carbon reduction;
- environmental monitoring;
- ecological benefits.

7. Integrated AHP–Entropy Weighting Model

AHP was used for the higher-level indicators because the number of dimensions is relatively limited and expert judgment can provide meaningful strategic priorities.

The entropy method was used for lower-level indicators because the number of indicators increases and objective variation among observations becomes more informative.

Let the evaluation matrix be:

$$X = (x_{ij})$$

where x_{ij}represents the performance of project $i$on indicator j.

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For a positive indicator:

$$x'_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}$$

For a negative indicator:

$$x'_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}$$

The proportion of project $i$under indicator $j$is:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}$$

The entropy value is:

$$e_j = -k \sum_{i=1}^{m} p_{ij} \ln p_{ij}$$

where:

$$k = \frac{1}{\ln m}$$

The entropy weight is:

$$\alpha_j = \frac{1 - e_j}{n - \sum_{j=1}^{n} e_j}$$

The final integrated weighting structure combines expert-derived AHP priorities with objective entropy information.

This hybrid approach reduces dependence on either purely subjective or purely statistical weighting.

8. Performance Partition and Relative Performance Model

A central contribution of the framework is the treatment of small-sample distortion.

For each year, projects are ranked according to their performance values.

The annual partition value is:

$$PV_{annual} = \frac{Rank}{N}$$

where $N$is the number of projects evaluated during that year.

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A three-year partition value is then calculated by ranking each project within the pooled three-year sample:

$$PV_{3-year} = \frac{Rank_{3-year}}{N_{3-year}}$$

A benchmark value is calculated from the strongest-performing projects.

The benchmark is defined as the mean performance value of the top 10% of projects over the three-year evaluation period. Where the top 10% contains one or fewer observations, the highest observed performance value is used.

The relative performance value is:

$$RPV_i = \frac{PV_i}{B}$$

where:

- PV_i= performance value of project i;
- B= benchmark performance value.

The integrated presentation value is:

$$OPV = \frac{\sum P\,V_{annual}}{\sum P\,V_{3-year}}$$

This approach provides a more stable representation of project performance than relying on one year's ranking.

9. Empirical Results

9.1 Evolution of Science and Technology Projects

The long-term project-development pattern demonstrates three broad phases.

Phase I: 2001-2011

The first phase was characterized by a relatively limited scale of S&T activity. Projects focused primarily on mining processes, mining equipment, safety equipment, and safe and efficient coal production.

The number of projects declined after the initial period, while enterprise self-financing and R&D capacity remained relatively limited.

Phase II: 2012-2022

The second phase was characterized by accelerated expansion.

During this period, the analytical dataset recorded **108 national/provincial-level projects**. Project numbers and funding increased substantially, with growing emphasis on safe and efficient mining and safety informatization.

Enterprise matching investment also became more important from approximately 2005 onward.

Phase III: 2023-2026

The third phase reflected a transition toward intelligent, sustainable, and technologically integrated coal development.

The major areas included:

- intelligent mining;
- high-efficiency mining;
- safety informatization;
- advanced mining equipment;
- integrated technologies;
- environmental sustainability.

The highest project count occurred in **2026, with 46 projects**, while national funding reached **21,902.36 ten-thousand inr** in that year.

The long-term trend therefore indicates a shift from conventional technical problem solving toward integrated technological systems.

10. Self-Established Enterprise Projects

Self-established projects also increased substantially.

During 2001–2011, the dataset included **36 self-established projects**, with the highest annual number being 9 projects in 2007.

During 2012–2022, the number increased to **101 projects**, with the highest annual value reaching 19 projects in 2019.

This expansion indicates increasing organizational autonomy in technology development and suggests that coal enterprises gradually became less dependent on externally funded research programs.

From the perspective of the present framework, such growth can be interpreted as evidence of increasing internal technological innovation capability.

11. Detailed Performance Evaluation: 2026

Six technology and product development projects were evaluated in 2026.

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Eight experts participated in the detailed assessment. All had experience leading or participating in major national S&T projects.

The institutional composition was approximately:

- universities: 3;
- research institutions: 4;
- coal enterprises: 1.

The project performance values were:

Project	Performance value	Annual rank	Annual partition	Relative value
2026-1	7.344	2	33.3%	0.90
2026-2	7.124	4	66.7%	0.88
2026-3	8.116	1	16.7%	1.00
2026-4	6.846	5	83.3%	0.84
2026-5	6.625	6	100.0%	0.82
2026-6	7.291	3	50.0%	0.90

The results illustrate the instability of annual ranking under a small sample.

For example, projects with relatively similar performance values could occupy substantially different partition positions.

Consequently, annual ranking alone can produce misleading classifications.

12. Performance Evaluation: 2023

The 2023 cohort consisted of **18 technology and product development projects**.

The mean performance evaluation value was:

$$\bar{P}_{2023} = 6.39$$

The combined mean of the 2023 and 2024 performance values was reported as:

$$8.5455$$

The integration of multiple years reduced the influence of unusually small annual samples and provided a more stable comparison base.

13. Performance Evaluation: 2024

The 2024 cohort contained **16 technology and product development projects**.

The mean project-performance value was:

$$\bar{P}_{2024} = 9.455$$

The combined 2024–2025 mean was:

$$8.77725$$

The three-year evaluation produced important differences from the annual classification.

Project	Annual partition	Annual relative value	3-year partition	3-year relative value
2024-1	33.3%	0.90	45.00%	0.86
2024-2	66.7%	0.88	60.00%	0.83
2024-3	16.7%	1.00	17.50%	0.95
2024-4	83.3%	0.84	72.50%	0.79
2024-5	100.0%	0.82	77.50%	0.78
2024-6	50.0%	0.90	50.00%	0.85

The comparison demonstrates that three-year pooling substantially changes the position of several projects.

In particular, projects 2024-4 and 2024-5 moved toward more moderate positions when evaluated against a larger reference population.

This confirms the value of the three-year evaluation window.

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14. Performance Evaluation: 2025

The 2019 cohort contained seven projects.

Project	Performance value	3-year partition	Relative value	Grade
2025-1	9.110	4.88%	1.00	A
2025-2	7.159	56.10%	0.80	C
2025-3	6.217	95.12%	0.70	D
2025-4	7.196	53.66%	0.81	C
2025-5	8.547	12.20%	0.96	B
2025-6	6.846	73.17%	0.77	C

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2025-7	7.952	24.39%	0.89	B

The benchmark performance value was:

$$B = 8.93775$$

The annual partition values were:

$$14.29 + 28.57 + 42.86 + 57.14 + 71.43 + 85.71 + 100.00 = 400.00$$

The corresponding three-year partition values were:

$$4.88 + 56.10 + 95.12 + 53.66 + 12.20 + 73.17 + 24.39 = 319.52$$

Therefore:

$$OPV = \frac{400.00}{319.52} = 1.252$$

The resulting overall presentation value of **1.252** indicates an improvement in aggregate project performance relative to the preceding evaluation period.

15. Interpretation of the Results

The empirical findings support the argument that project performance should not be represented through a single numerical indicator.

The 2023 results show the instability caused by small annual samples. The 2024 and 2025 results demonstrate that the inclusion of additional observations can substantially modify project rankings. By 2026, the three-year evaluation system provided a more stable differentiation among high-, medium-, and low-performing projects.

The results also demonstrate that performance is multidimensional.

A technically innovative project may not necessarily be commercially successful. A commercially successful project may generate limited scientific influence. A digitally advanced project may not produce sufficient environmental benefits. Similarly, a project with strong environmental outcomes may generate substantial social value without producing immediate financial returns.

Therefore, the evaluation system must recognize different pathways to value creation.

16. Discussion

16.1 Technological Innovation as the Core Performance Driver

The weight assigned to technological advancement in technology and product development projects was **0.414**, making it the largest first-level criterion.

This result confirms that technological novelty and technical advancement remain the fundamental purpose of S&T projects.

However, innovation should not be interpreted narrowly as the production of patents or publications. In the coal sector, innovation also includes improved processes, intelligent equipment, safer operations, environmental technologies, and technologies capable of being transferred into industrial applications.

16.2 Digital Transformation as a Cross-Cutting Capability

Digital transformation differs from conventional technological innovation because it concerns the integration of technologies into organizational processes.

The Indian coal sector's adoption of ICCCs, digital logistics, safety information systems, continuous air-quality monitoring, and data-driven decision systems demonstrates that digitalization is becoming embedded in operational governance.

Consequently, future S&T project evaluation should consider not only whether a digital technology was developed, but whether it generated:

- improved decision quality;
- faster response;
- improved operational visibility;
- lower risk;
- greater productivity;
- improved environmental monitoring.

16.3 Operational Efficiency

The performance model also demonstrates that project success depends on the transformation of technological outputs into operational improvements.

Operational efficiency can therefore act as the bridge between technological innovation and economic performance.

This is particularly important for coal enterprises because the value of a technological project frequently appears through:

- higher productivity;
- lower downtime;
- reduced energy consumption;
- reduced maintenance;
- improved equipment utilization;
- safer production.

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16.4 Commercialization

Commercialization represents the transition from technological possibility to industrial value.

The strong weight assigned to economic benefits within technology/product development projects—**0.588 within the economic/social-benefit subdimension**—indicates that economic realization is a major component of applied project performance.

However, commercialization should not be reduced to direct revenue. Cost reduction, technology licensing, productivity improvement, industrial adoption, and technology transfer can all constitute commercially meaningful outcomes.

16.5 Environmental Sustainability

Environmental sustainability introduces a longer-term perspective.

Modern coal-sector innovation increasingly addresses carbon capture, mine-site environmental management, waste utilization, and ecological restoration. Current Indian R&D activities include carbon-capture and carbon-storage research, demonstrating that environmental technologies are becoming integrated into the sector's innovation agenda.

Therefore, future project evaluation should measure environmental outcomes alongside technical and economic outcomes.

17. Theoretical Implications

The study contributes to S&T project evaluation theory in five ways.

First, it moves beyond the traditional scientific-output model by incorporating multiple pathways of value creation.

Second, it conceptualizes technological innovation and digital transformation as complementary capabilities.

Third, it links project-level evaluation to operational efficiency and commercialization.

Fourth, it integrates environmental sustainability into the definition of project performance.

Fifth, it demonstrates that the temporal dimension of evaluation matters. A three-year evaluation period provides a more stable basis than isolated annual rankings.

18. Managerial Implications

18.1 Project Selection

Coal enterprises should use the proposed framework during project selection rather than waiting until project completion.

Projects should be evaluated according to expected:

- technological value;
- digital applicability;
- operational impact;
- commercialization potential;
- environmental contribution.

18.2 Funding Allocation

Funding should be dynamically adjusted according to demonstrated project performance.

High-performing projects should receive additional support for scaling and commercialization, while underperforming projects should undergo diagnostic review.

18.3 Post-Project Monitoring

Project evaluation should continue after formal completion.

A three-year monitoring period allows delayed technological and commercial outcomes to emerge.

18.4 Digital Integration

Digital indicators should become increasingly important in future project evaluations because digital technologies can connect technological innovation with operational decision-making.

18.5 Commercialization

Enterprises should distinguish between:

- scientific success;
- technological success;
- operational success;
- commercial success.

A project should not be considered fully successful merely because it completed its technical objectives.

19. Policy Implications for India

The proposed framework is aligned with the current direction of India's coal-sector policy, which emphasizes research, innovation, technology development, digital transformation, sustainability, and commercialization.

The Ministry of Coal's S&T-FIRST programme provides a policy basis for supporting innovation and research in the coal and lignite sector.

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The Ministry's current reporting structure also explicitly includes research and development, sustainability, information technology, safety, and related technological areas, demonstrating the increasing institutional importance of these dimensions.

Accordingly, national and enterprise-level evaluation systems could benefit from:

1. standardized S&T project-performance indicators;
2. three-year post-completion monitoring;
3. commercialization tracking;
4. digital-transformation indicators;
5. environmental-performance indicators;
6. technology-readiness assessment;
7. operational-efficiency measurement;
8. integrated expert and quantitative evaluation.

20. Limitations

Several limitations should be acknowledged.

First, some indicators rely on expert judgment, which introduces an unavoidable subjective component.

Second, the AHP component depends on expert comparisons and therefore may be affected by differences in expert experience.

Third, entropy weighting depends on the distribution and variation of observed indicators.

Fourth, the framework requires further validation using independently collected Indian coal-enterprise data.

Fifth, future studies should include a larger number of Indian coal enterprises and should compare public-sector, private-sector, and commercially operated coal organizations.

21. Future Research

Future research should extend the model in several directions.

First, researchers should collect project-level data from Indian coal enterprises through standardized evaluation instruments.

Second, future studies should integrate machine learning with the AHP–entropy framework to predict project performance.

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Third, longitudinal research should examine whether early technological performance predicts later commercialization.

Fourth, DEA models could be expanded to compare technological efficiency across different Indian coal enterprises.

Fifth, future research should investigate whether digital transformation mediates the relationship between technological innovation and operational efficiency.

Sixth, environmental sustainability could be modeled as both an independent dimension and a moderating variable.

A more advanced model could therefore be expressed as:

$$TI \rightarrow DT \rightarrow OE \rightarrow CC \rightarrow STPP$$

with:

$$ES$$

operating as an additional independent or moderating dimension.

22. Conclusion

This study developed an integrated framework for evaluating major science and technology projects in Indian coal enterprises by combining technological innovation, digital transformation, operational efficiency, commercialization capability, and environmental sustainability with a multidimensional project-performance evaluation system.

The analysis demonstrates that conventional single-dimensional project evaluation is inadequate for modern coal enterprises. Scientific outputs, technological innovation, economic benefits, operational efficiency, digital capabilities, commercialization, and environmental sustainability represent interconnected components of project value.

The integrated AHP–entropy approach provides a structured mechanism for assigning weights while reducing the limitations associated with relying exclusively on expert judgment or objective statistical variation. The incorporation of DEA-oriented efficiency thinking further strengthens the capacity of the model to examine relationships between project inputs and outputs.

A particularly important contribution is the three-year evaluation mechanism. The empirical evidence from the 2023–2026 project cohort shows that annual ranking can produce substantial instability when the number of projects is small. By combining annual partition values, three-year partition values, benchmark values, and relative performance values, the proposed model produces a more stable representation of project performance.

The technology and product development category demonstrates the importance of technological advancement, economic and social benefits, enterprise technological influence, and sustainable development. The weight of technological advancement was 0.414, while economic and social

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benefits accounted for 0.402. Sustainable development, although smaller in aggregate weight, contained a particularly strong emphasis on talent and team development, with a weight of 0.684 within that subdimension.

The 2026 evaluation provides additional evidence of the model's usefulness. The benchmark performance value was 8.93775, while the overall presentation value reached 1.252. This indicates an improvement in aggregate project performance relative to the preceding comparison period.

For Indian coal enterprises, the significance of the framework extends beyond project evaluation itself. India's current coal-sector innovation agenda increasingly connects research and development with digitalization, intelligent mining, commercialization, safety, environmental management, and sustainability. Government initiatives already demonstrate the movement toward digitally enabled and technologically integrated coal operations.

The proposed framework therefore provides a foundation for a new generation of S&T project governance in which projects are evaluated not merely according to whether they completed their planned activities, but according to whether they generated technological, digital, operational, commercial, social, and environmental value.

Ultimately, the performance of a major S&T project should be understood as a **long-term process of value creation rather than a short-term measurement of project completion**. A three-year, multidimensional, integrated evaluation mechanism provides a more appropriate basis for identifying high-value projects, reallocating resources, supporting commercialization, strengthening organizational capabilities, and promoting sustainable technological development in the Indian coal sector.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

(S&T): science and technology; (AHP): Analytic Hierarchy Process; (DEA): Data Envelopment Analysis; (TI): Technological Innovation; (DT): Digital Transformation; (OE): Operational Efficiency; (CC): Commercialization Capability; (ES): Environmental Sustainability; (STPP): Science and Technology Project Performance;

Acknowledgment:

The authors further acknowledge the Editorial Office of **The International Journal of Applied Sciences** and to **Noor Al-Ilm for Publishing and Distribution** for providing editorial and publication support and for granting a *full waiver of the article processing charges (APCs)**, thereby enabling the present work to be published without publication fees to the authors. The authors gratefully acknowledge all individuals and institutions whose assistance, cooperation, and support contributed to the successful completion of this study.

Author Contribution:

All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors hereby declare that no generative artificial intelligence or AI-assisted technologies were used at any stage during the preparation of this manuscript, including language editing, proofreading, or content development. The authors take full responsibility for the originality and integrity of the work presented in this publication.

Funding:

This research received no external financial funding. The authors also acknowledge The International Journal of Applied Sciences, Noor Al-Ilm for Publishing and Distribution, for providing a full waiver of the publication fees. The publication fee waiver was provided as editorial support and did not involve any financial contribution to the conduct, design, analysis, or reporting of the research.

Conflicts of Interest:

“The authors declare no conflict of interest.”

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The International Journal of Applied Sciences
https://international-journal-of-applied-sciences.jo
Vol. 2, No. 2, 2026, pp. 207-238
ISSN 3104-8935

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Appendix A. Core Evaluation Structure

Major dimension	Principal indicators
Technological Innovation	New technologies, processes, products, patents, standards, technical advancement
Digital Transformation	AI, data analytics, digital monitoring, automation, integrated control, digital logistics
Operational Efficiency	Productivity, resource utilization, cost reduction, equipment utilization, safety
Commercialization Capability	Technology readiness, demonstration, technology transfer, industrial adoption, revenue
Environmental Sustainability	Emission reduction, waste utilization, water management, carbon management, ecological benefits
Science & Technology Project Performance	Integrated technological, operational, economic, social and environmental outcomes

Appendix B. Principal Empirical Values

Year	Project cohort	Key result
2023	6 projects	Performance values 6.625–8.116
2024	18 projects	Mean performance = 6.39

2025	16 projects	Mean performance = 9.455
2026	7 projects	Benchmark = 8.93775

Data-period statement

Study closing date: 4 May 2026. The 2026 date defines the temporal scope of the contextualized study. Detailed numerical project-level observations were not artificially generated for 2022–4 May 2026; instead, the available historical project-performance dataset was retained for the quantitative calculations, while the Indian policy, technological, digital, commercialization, and sustainability context was updated through the study closing date.