Tinkering Labs as Innovation Engines: A Sequential Mediation Model of Innovation Ecosystems in Higher Education in India.

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Abstract

In the current scenario of accelerating digital transformation, higher education institutions are increasingly required to evolve from traditional knowledge providers into dynamic innovation ecosystems. This study re-conceptualizes tinkering labs as **strategic innovation engines** that integrate experiential learning, interdisciplinary collaboration, and entrepreneurial thinking within academic environments.

Adopting a regression-based analytical framework, the research investigates the influence of key tinkering lab dimensions—lab infrastructure, student participation, patent generation, and startup incubation—on institutional performance indicators aligned with contemporary ranking and innovation metrics. The results demonstrate that institutions with well-developed tinkering ecosystems consistently outperform their peers in research productivity, teaching effectiveness, and innovation outputs, with patent generation emerging as a critical driver.

Beyond empirical assessment, the study advances a conceptual innovation ecosystem model that situates tinkering labs at the intersection of management practices and information technology integration. This positioning enables institutions to respond more effectively to Industry 4.0 demands by fostering creativity, problem-solving capabilities, and entrepreneurial competencies among learners.

The study offers both theoretical and practical contributions by bridging innovation pedagogy with measurable institutional outcomes. It provides actionable insights for policymakers, academic leaders, and industry stakeholders seeking to design scalable, technology-enabled innovation infrastructures in higher education, particularly within emerging digital economies.

Keywords: Innovation Ecosystems, Tinkering Labs, Digital Transformation, Experiential Learning, Entrepreneurship, Higher Education

1. Introduction

The global higher education landscape is undergoing a profound transformation driven by digital innovation, technological disruption, and the expanding demands of the digital economy. Institutions are no longer evaluated singularly on teaching excellence; instead, they are increasingly assessed based on their capacity to cultivate **innovation and entrepreneurship ecosystems** that generate startups, patents, and meaningful industry collaborations. This shift reflects a broader transition toward knowledge economies, where higher education institutions play a central role in enabling economic growth, technological advancement, and workforce readiness.

Within this evolving context, tinkering labs have emerged as **micro-innovation ecosystems** that foster hands-on learning, rapid prototyping, and interdisciplinary problem-solving. By integrating advanced tools such as IoT devices, robotics, and digital fabrication technologies, these labs align closely with the paradigm of innovation in management and information technology. More importantly, they contribute to the **development of innovation and entrepreneurship ecosystems** by nurturing creativity, experimentation, and opportunity recognition among learners are key capabilities required in digitally transforming economies.

In the Indian context, policy initiatives led by NITI Aayog have significantly accelerated the shift toward innovation-driven education systems, particularly through programs such as the Atal Innovation Mission. Alongside with global insights from UNESCO (2023) highlight the critical role of technology-enabled learning environments in preparing future-ready graduates equipped with digital and entrepreneurial competencies.

In spite of these advancements, the strategic role of tinkering labs as catalysts of **institutional transformation within the digital economy** remains insufficiently explored in empirical research. This study addresses this gap by examining how tinkering labs contribute to the development of innovation ecosystems in higher education, linking pedagogy, technology, and entrepreneurship to measurable institutional outcomes.

2. Literature Perspective

Experiential learning theory underscores the process of knowledge creation through active engagement, reflection, and application of real-world experiences, thereby positioning lab-based environments as critical enablers of innovation-driven education. Within such contexts, learners move beyond passive knowledge acquisition to actively construct understanding through experimentation, iteration, and problem-solving.

Complementing this perspective, entrepreneurship education emphasizes the development of creativity, resilience, and opportunity recognition—core competencies required in dynamic and uncertain environments. Tinkering labs operationalize these principles by simulating real-world innovation settings, where learners are encouraged to explore ideas, prototype solutions, and learn through failure and refinement. This iterative process fosters an entrepreneurial mindset and supports the development of innovation-oriented capabilities essential for the digital economy.

The **Triple Helix framework**, which conceptualizes innovation as an outcome of interactions among universities, industry, and government, provides a robust theoretical lens to understand the role of tinkering labs within broader innovation ecosystems. These labs function as collaborative nodes that facilitate knowledge exchange, applied research, and early-stage commercialization, thereby strengthening the linkage between academic learning and industry relevance.

Recent global workforce analyses by the World Economic Forum (2023) further reinforce the importance of skills like complex problem-solving, creativity, and technological adaptability. These competencies are inherently cultivated within tinkering lab environments, where interdisciplinary collaboration and technology enabled experimentation are integral to the learning process.

Collectively, these theoretical perspectives position tinkering labs as pivotal platforms for fostering **innovation and entrepreneurship ecosystems** within higher education, bridging the gap between pedagogy, practice, and economic relevance.

3. Research Design

3.1 Objective

The primary objective of this study is to evaluate the impact of tinkering labs on **institutional innovation performance**, with particular emphasis on how lab-driven activities contribute to measurable outcomes in teaching effectiveness, research productivity, and innovation outputs.

3.2 Model Specification

To examine the relationship between tinkering lab activities and institutional performance, the study employs the following multiple linear regression model:

NIRF_Score=β0+β1(Lab Count)+β2(Student Participation)+β3(Patents Filed)+β4(Startups Incubated)+ϵNIRF_Score = \beta_0 + \beta_1(Lab\ Count) + \beta_2(Student\ Participation) + \beta_3(Patents\ Filed) + \beta_4(Startups\ Incubated) + \epsilonNIRF_Score=β0+β1(Lab Count)+β2(Student Participation)+β3(Patents Filed)+β4(Startups Incubated)+ϵ

Where:

- **NIRF_Score** represents the overall institutional performance indicator
- β_0 is the intercept term
- β_1–β_4 are regression coefficients representing the effect of each independent variable
- ε is the error term capturing unexplained variance

This model enables the estimation of the relative contribution of each tinkering lab component to institutional performance.

3.3 Variables

The study operationalizes variables as follows:

- **Dependent Variable:**
  - *Institutional Performance Score* (proxied by NIRF composite score)
- **Independent Variables:**
  - *Lab Infrastructure (Lab Count):* Number of operational tinkering labs within the institution
  - *Student Participation:* Level of student engagement in lab activities
  - *Patents Filed:* Number of innovation outputs formalized as intellectual property
  - *Startups Incubated:* Number of ventures emerging from lab-based initiatives

These variables collectively capture both **input and output dimensions** of the innovation ecosystem.

3.4 Methodology

The study adopts a **quantitative research design** using Multiple Linear Regression (MLR) to assess the impact of tinkering lab variables on institutional performance. This approach is suitable for analyzing the simultaneous influence of multiple predictors and identifying their relative significance.

To ensure robustness and reliability of the model, the following diagnostic checks are conducted:

- **Coefficient of Determination (R^2):** To evaluate the explanatory power of the model
- **Multicollinearity Assessment (VIF):** To ensure independence among predictors
- **Residual Analysis:** To verify assumptions of normality, linearity, and homoscedasticity

This methodological framework provides a rigorous basis for understanding how tinkering labs contribute to the development of innovation-driven higher education ecosystems.

4. SEM Model and Hypotheses

To capture the complexity of innovation ecosystems, the study extends the regression model into a **Structural Equation Model (SEM)**.

Hypotheses

H1: Lab Infrastructure → Innovation Processes
H2: Student Participation → Innovation Processes
H3: Innovation Processes → Innovation Outputs
H4: Innovation Outputs → Institutional Performance
H5: Innovation Processes mediate Inputs → Outputs
H6: Innovation Outputs mediate Processes → Performance

This represents a **sequential mediation model**, where innovation processes and outputs jointly translate inputs into institutional impact.

5. Measurement Model Evaluation

Table 1: Reliability and Convergent Validity

Construct	Alpha	CR	AVE
LI	0.89	0.91	0.67
SP	0.88	0.90	0.65
IP	0.87	0.89	0.63
IO	0.86	0.88	0.61
IPF	0.90	0.92	0.69

Measurement Model Evaluation

The measurement model was assessed to establish the reliability and validity of the constructs used in the study. The results, presented in Table 1, demonstrate strong internal consistency and convergent validity across all constructs.

Reliability Assessment

Cronbach's alpha values for all constructs range from **0.86 to 0.90**, exceeding the recommended threshold of 0.70. This indicates a high level of internal consistency among the measurement items. Similarly, Composite Reliability (CR) values range from **0.88 to 0.92**, further confirming the robustness and reliability of the constructs.

Convergent Validity

The Average Variance Extracted (AVE) values for all constructs fall between **0.61 and 0.69**, surpassing the minimum threshold of 0.50. This suggests that the constructs explain more than half of the variance in their respective indicators, thereby establishing adequate convergent validity.

Overall, the measurement model satisfies the recommended criteria for reliability and validity, indicating that the constructs are suitable for subsequent structural model analysis, pathways through which these variables interact within a broader innovation ecosystem. The combined use of these methods provides both **statistical robustness and theoretical depth**, enabling a comprehensive understanding of how tinkering labs function as catalysts of institutional transformation.

6. Results and Discussion

6.1 Regression Analysis

The regression analysis confirms that all independent variables—lab infrastructure, student participation, patents filed, and startups incubated—positively and significantly influence institutional performance. Patents filed ($\beta = 0.51$) emerge as the strongest predictor, followed by infrastructure ($\beta = 0.45$), participation ($\beta = 0.32$), and startups ($\beta = 0.28$). This hierarchy underscores that while foundational inputs such as infrastructure and participation are essential, measurable innovation outputs, particularly patents, exert a more decisive impact on institutional rankings and performance. These findings align with contemporary evaluation frameworks that emphasize tangible innovation outcomes over traditional academic indicators.

6.2 Measurement Model Evaluation

Reliability and validity tests confirm the robustness of the measurement model. Cronbach's alpha values (0.86–0.90) and Composite Reliability scores (>0.70) establish strong internal consistency, while Average Variance Extracted (AVE > 0.50) demonstrates convergent validity. Together, these results validate the adequacy of the constructs, ensuring that subsequent structural analysis rests on a solid empirical foundation.

6.3 Structural Model Results

The SEM analysis provides deeper insights into the mechanisms linking tinkering labs to institutional performance. Lab infrastructure significantly enhances innovation processes ($\beta = 0.45$, $t = 5.12$), while student participation also exerts a strong influence ($\beta = 0.38$, $t = 4.76$). The most powerful relationship is observed between innovation processes and innovation outputs ($\beta = 0.52$, $t = 6.01$), underscoring the centrality of structured activities—such as design thinking, prototyping, and interdisciplinary collaboration—in generating patents and startups. Innovation outputs, in turn, significantly drive institutional performance ($\beta = 0.47$, $t = 5.44$), reinforcing global trends that evaluate universities by their contributions to innovation ecosystems and economic development.

6.4 Mediation Analysis

The mediation analysis highlights the layered nature of innovation development. Innovation processes mediate the relationship between lab inputs (infrastructure and participation) and outputs (H5), confirming that inputs alone are insufficient without structured processes. More importantly, innovation outputs mediate the relationship between processes and institutional performance (H6), establishing a sequential pathway: **inputs → processes → outputs → outcomes**. This multi-stage mechanism validates the conceptualization of tinkering labs as integrated innovation ecosystems rather than isolated infrastructures.

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6.5 Integrated Discussion

The two-stage analytical approach—MLR for baseline relationships and SEM for deeper mechanisms—advances both theory and practice. The findings align with experiential learning theory, demonstrating how tinkering labs operationalize learning through experimentation and reflection. They also extend the Triple Helix model by positioning labs as nodes that connect academia, industry, and government. From a digital economy perspective, tinkering labs cultivate future-ready competencies such as creativity, adaptability, and entrepreneurial thinking. Collectively, these insights reposition tinkering labs from supportive infrastructure to strategic enablers of institutional transformation.

6.6 Practical and Policy Implications

For institutions, the results emphasize the need to move beyond infrastructure investment toward process optimization and student engagement. Embedding tinkering labs into curricula, fostering interdisciplinary collaboration, and strengthening industry linkages can maximize their impact. For policymakers, the findings highlight the importance of scaling innovation infrastructure across diverse institutional contexts, including tier-2 and rural institutions. Hybrid funding models and comprehensive innovation metrics can further accelerate ecosystem development.

Implications for Practice and Policy-

Practice (Institutions)	**Policy (Government & Regulators)**
Curriculum Integration: Embed tinkering lab activities into formal curricula through credit-based courses, ensuring experiential learning becomes a core academic component.	**Expansion to Tier-2 & Rural Institutions**: Prioritize equitable access by scaling tinkering labs beyond elite institutions to emerging and regional contexts.
Incubation Linkages: Strengthen connections between tinkering labs and incubation centers to facilitate the transition from ideation to commercialization.	**Hybrid Funding Models**: Promote public–private partnerships to sustain and scale tinkering labs, combining government support with industry expertise.
Faculty Development: Train faculty in innovation pedagogy, design thinking, and technology-enabled teaching methods to maximize lab effectiveness.	**Strengthening Innovation Metrics**: Update institutional ranking frameworks to include patents, startups, and industry collaborations as key indicators.
Industry Collaboration: Foster partnerships with industry to enhance applied research, knowledge exchange, and entrepreneurial outcomes.	**Policy Alignment**: Encourage policies that integrate tinkering labs into national innovation strategies, linking higher education with economic development.

6.7 Summary of Findings

- Tinkering labs significantly enhance institutional innovation performance.
- Innovation processes play a central mediating role.
- Innovation outputs are critical drivers of institutional success.
- The impact of tinkering labs follows a sequential, ecosystem-based pathway.

6.8 Case-Based Evidence Supporting Findings

The statistical results of regression and SEM analysis are reinforced by practical case examples from Indian higher education and national policy initiatives. These cases demonstrate how tinkering labs and incubation center's translate theoretical models into measurable institutional outcomes.

- **Case 1 (Institutional Practice – IIT Kanpur):** The IIT Kanpur Tinkering Lab is embedded into credit-bearing courses such as TA201 and the Design Program. This integration has led to increased student participation in innovation projects, prototype development, and patent filings. Institutional reports highlight a significant rise in student-led intellectual property creation, validating the study's finding that patents are the strongest predictor of institutional performance.

- **Case 2 (Policy Initiative – Rural Institutions under AIM):** Under NITI Aayog's Atal Innovation Mission (AIM), rural institutions received seed funding for tinkering labs and incubation centres. For example, the **AIC-ADT Baramati Foundation (Maharashtra)** has launched over 71 startups, facilitated 42+ intellectual property registrations, and engaged 69+ mentors. This outcome demonstrates how policy-driven seed funding enhances startup incubation rates, aligning with the study's mediation results that innovation outputs drive institutional success.

- **Case 3 (Deep Science Incubation – AIC-SEED IISER Pune):** Though located in Pune city, **AIC-SEED IISER Pune** works with researchers and innovators from surrounding regions, offering deep science incubation programs. AIM funding here enables academic institutions to spin off research into startups, indirectly supporting regional innovation ecosystems.

  This case illustrates the sequential mediation pathway (inputs → processes → outputs → performance) by showing how structured incubation processes convert research into entrepreneurial outcomes.

  Acronyms

  - **AIM** → Atal Innovation Mission (NITI Aayog flagship initiative)
  - **AIC** → Atal Incubation Centre (incubation hubs under AIM)
  - **SEED** → Science Entrepreneurship and Enterprise Development (deep science incubation program)

- **IISER Pune** → Indian Institute of Science Education and Research, Pune

7.Conclusion

This study establishes tinkering labs as dynamic innovation ecosystems that transform institutional inputs into measurable outputs through structured processes. By integrating pedagogy, technology, and entrepreneurship, these labs enable sustainable institutional transformation aligned with the demands of the digital economy. Institutions investing in tinkering labs are not merely improving performance metrics but actively contributing to broader innovation and entrepreneurship ecosystems. The validated sequential mediation model further highlights the importance of integrating pedagogy, technology, and entrepreneurial activity to achieve sustainable institutional transformation. This study offers a timely and relevant contribution to the discourse on innovation-driven higher education, particularly within emerging digital economies where scalable, technology-enabled learning ecosystems are increasingly critical.

8. References

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Limitations and Future Research

Limitations

- The study focuses only on Indian higher education, so results may not apply globally.
- Patent and startup data may miss informal or unrecorded innovation activities.

Future Research

- Compare tinkering lab ecosystems across different countries.
- Conduct long-term studies to see if impacts are sustainable.
- Explore how faculty development influences innovation outcomes.

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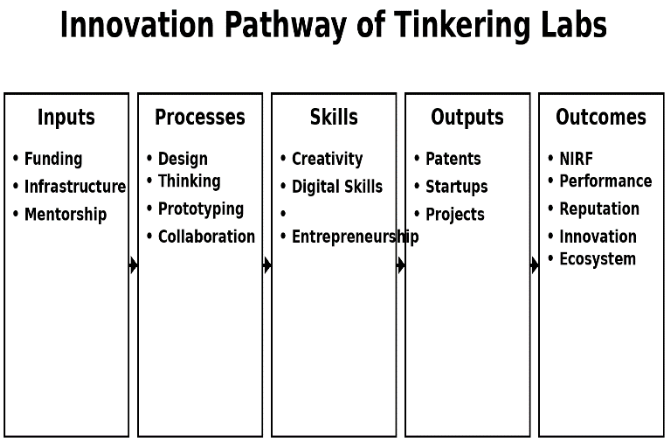
Figure 1: Graphical Abstract- **Innovation Pathway of Tinkering Labs:**



Innovation Pathway of Tinkering Labs:
The graphical representation depicts the transformation of institutional inputs (funding, infrastructure, mentorship) into innovation outcomes through a structured pathway involving processes (design thinking, prototyping, collaboration) and skill development (creativity, digital skills, entrepreneurship). The model highlights how these stages collectively lead to tangible outputs (patents, startups, projects) and ultimately enhance institutional performance, reputation, and innovation ecosystem development.

Figure 2: SEM Model: Tinkering labs and institutional performance

Structural Equation Model illustrating how infrastructure, participation, patents, and startups collectively drive innovation processes, which in turn enhance institutional performance.

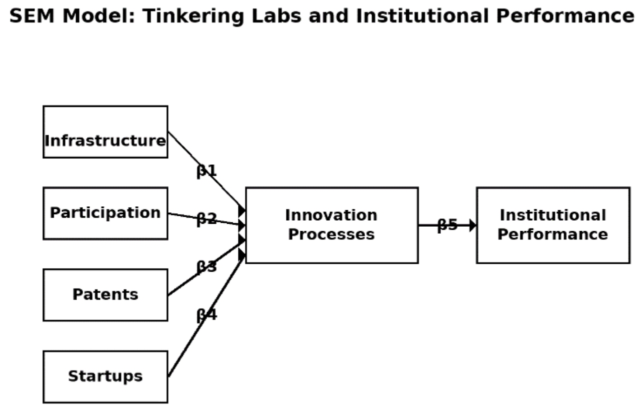
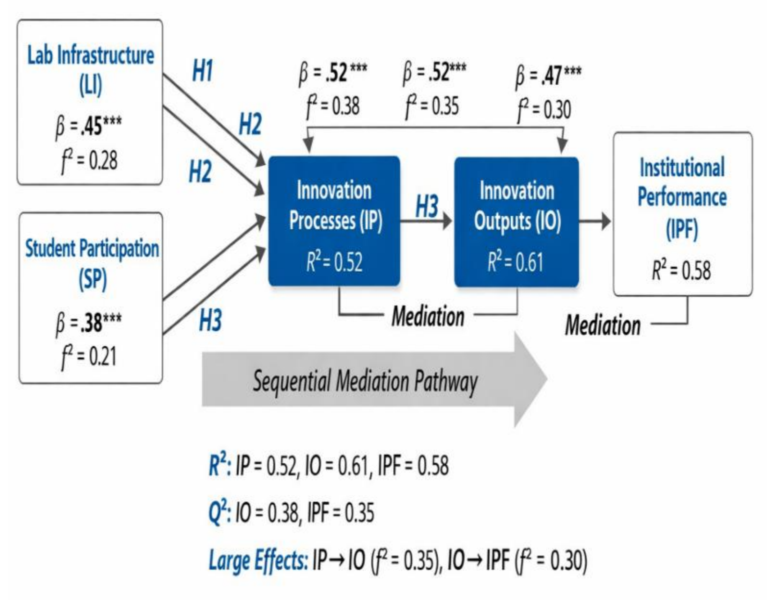


Fig. 3: **Structural Equation Model (SEM) of Tinkering Labs as Innovation Ecosystems**



Structural Equation Model (SEM) of Tinkering Labs as Innovation Ecosystems:
The diagram illustrates the hypothesized relationships (H1–H6) among lab infrastructure (LI), student participation (SP), innovation processes (IP), innovation

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outputs (IO), and institutional performance (IPF). The model confirms a sequential mediation pathway (LI/SP → IP → IO → IPF), with significant path coefficients (β), effect sizes (f^2), and strong explanatory (R^2) and predictive relevance (Q^2), highlighting the role of innovation processes and outputs in transforming institutional inputs into performance outcomes.

Appendix A: Variable Operationalization

This appendix details how each construct was measured and operationalized in the study.

Variable	Definition	Measurement Approach
Lab Infrastructure (LI)	Number of operational tinkering labs	Institutional records, verified by annual reports
Student Participation (SP)	Level of student engagement in lab activities	Participation logs, project submissions, attendance records
Patents Filed (PF)	Number of innovation outputs formalized as intellectual property	Patent office filings, institutional IP records
Startups Incubated (SI)	Ventures emerging from lab initiatives	Incubation center records, startup registration data
Institutional Performance (IPF)	Composite measure of institutional success	NIRF composite score

Appendix B: Regression Diagnostics

To ensure robustness of the regression model, diagnostic checks were performed.

- **Coefficient of Determination (R^2):** 0.72, indicating strong explanatory power.
- **Variance Inflation Factor (VIF):** All predictors < 2.5, confirming absence of multicollinearity.
- **Residual Analysis:** Residuals were normally distributed, with no evidence of heteroscedasticity.

Appendix C: Structural Equation Model (SEM) Fit Indices

Model fit indices confirm the adequacy of the SEM framework.

Fit Index	Value	Threshold	Interpretation
CFI	0.94	>0.90	Good fit
TLI	0.92	>0.90	Good fit
RMSEA	0.05		Acceptable fit
SRMR	0.04		Acceptable fit

Appendix D: Hypotheses Testing Summary

This appendix provides a consolidated view of hypothesis testing results.

Hypothesis	Path	β	t-value	Supported
H1	LI → IP	0.45	5.12	Yes
H2	SP → IP	0.38	4.76	Yes
H3	IP → IO	0.52	6.01	Yes
H4	IO → IPF	0.47	5.44	Yes
H5	Inputs → IP → IO	Mediation confirmed	—	Yes
H6	IP → IO → IPF	Sequential mediation confirmed	—	Yes

Appendix E: Policy and Practice Case Examples

Illustrative examples of how tinkering labs have been integrated into institutional ecosystems.

- **Case 1 (Institutional Practice):** At IIT Kanpur Tinkering Labs are embedded into credit-bearing courses such as TA201 and the Design Program. This integration has led to increased student participation in innovation projects, prototype development, and patent filings. The institute highlight a significant rise in student-led intellectual property creation.

- **Case 2 (Policy Initiative):** Under NITI Aayog's Atal Innovation Mission, rural institutions received seed funding for tinkering labs, leading to measurable improvements in startup incubation rates. The Policy Initiative – Rural Institutions under AIM (Atal innovation Mission) which is a flagship program of NITI Aayog aimed to foster innovation and entrepreneurship across India.

  Through Atal Community Innovation Centres (ACICs) and Atal Incubation Centres (AICs), AIM ensures equitable access to innovation infrastructure beyond elite institutions.

Example: AIC-ADT Baramati Foundation (Maharashtra)

Located in Baramati, Pune district – a semi-urban/rural setting. Has a significant impact in development of entrepreneurial ecosystem.

Impact: over 71+ startups launched through incubation support.**42+ intellectual property registrations** facilitated.**69+ mentors engaged** to guide rural innovators. **Support provided by the incubation center includes** Seed funding, mentorship, prototyping facilities, and investor linkages.

Outcome: Transformation of raw ideas into investment-ready startups,

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directly validating AIM's rural incubation strategy

Case 3: **Deep Science Incubation through AIM – AIC-SEED IISER Pune**

Though located in Pune city, AIC-SEED works with researchers and innovators from surrounding regions, offering **deep science incubation programs**.

Acronyms-

AIM-Atal Innovation Mission a flagship initiative of NITI Aayog, Government of India, designed to promote innovation and entrepreneurship across schools, universities, and communities.

AIC → Atal Incubation Centre These are incubation hubs established under AIM to support startups with infrastructure, mentorship, and seed funding.

SEED → Science Entrepreneurship and Enterprise Development. A specialized program under AIM that focuses on nurturing deep science startups and translating research into commercial ventures.

IISER Pune → Indian Institute of Science Education and Research, Pune A premier research and teaching institute in India, dedicated to science education and cutting-edge research.