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Implementing ATL Tinkering Labs in Rural Schools in India: Challenges and Opportunities.

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Abstract
The Atal Tinkering Labs (ATL) initiative, under the aegis of NITI Aayog, represents a transformative step towards fostering innovation and scientific temper in Indian schools. Though most of the ATL Labs have been tested and are effective in the urban schools, there are some challenges that affect the rural schools for instance ineffective infrastructure, inadequate training and socio-economic issues. However, these schools also have this kind of prospect and future possibilities in closing the innovation divide in rural schools to equip the youths for 21st-century skills. Following a general overview of the research challenges and advantages related to the implementation of ATL Tinkering Labs in rural schools, this review considers policies, stakeholders' roles, and opportunities to foster innovations. A few ideas on how to avoid those pitfalls and how to make sure that ATLs could be as effective as possible in rural settings are provided....
Keywords: ATL Tinkering Labs; Rural Education; Innovation in Schools; STEM Education; Implementation Challenges; Opportunities in Rural Development.

INTRODUCTION

The common global focus on STEM (Science, Technology, Engineering, and Mathematics) education has revealed the need for innovative learning spaces. India with such a diverse pool of human resources can definitely leverage on integrating STEM with the school curriculum. Realizing this potential, the Government of India through NITI Aayog launched the Atal Tinkering Labs (ATL) as part of the intervention process in the direction to develop innovating & creative mindset among students.

These labs offer resources which include 3D printers, robotics kits, microprocessors and sensors for the construction of real solutions by the students. However, the adoption of ATL in rural schools is accompanied by both opportunities and challenges; therefore, requires a critical analysis. The Fig. 1 shows the essence of the Atal Tinkering Labs (ATL) initiative, as envisioned in the context of rural schools. It highlights students collaboratively working on a STEM-based project using ATL resources, such as gears, wheels, and construction tools.

Fig. 1 Rural students collaborating on STEM projects in an Atal Tinkering Lab (ATL).

The ATL initiative under the AIM represents a transformative effort in India to cultivate creativity, critical thinking, and innovation among school students (Ulfah, 2023a), particularly in rural and underserved regions. These ATL labs are modeled as maker spaces to facilitate STEM (Science, Technology, Engineering, Mathematics) understanding through doing with materials, to foster problem solving and deal with entrepreneurship skills (Kanjilal et al., 2021a). With the help of various STEM equipment such as 3D printers, microcontroller kits, and robotics equipment, ATLs wants to make the generation become productive in tackling many challenges in modern-day technology (Phatak & Mane, 2022).

The adoption of ATLs in rural educational institutions poses unique challenges while also offering transformative possibilities. For instance, resource constraints, inadequate teacher training, and the lack of technological know-how among stakeholders are some of the significant barriers (Kumari, 2020). Moreover, the geographical isolation of rural schools often results in logistical and maintenance issues, which further exacerbate inequalities in access to quality STEM education (Dheesha, 2021). Notwithstanding such challenges, the existence of ATLs has resulted in quantifiable improvements in students' engagement and competencies within STEM disciplines, marking a great need for applying solutions to specific local environments (Ulfah, 2023a).

Atal Tinkering Labs are meant for grades 6-12 children focusing on curiosity, creativity and innovation among learners. These labs will be equipped with different kinds of tools, equipment and other structures that would enable students to work towards various STEM projects. The labs are a comfortable environment which basically allows the students to develop skills such as problem-solving, critical and creative thinking, and collaboration. The objective is to create an entrepreneurial spirit and develop innovation at the human development index. From the concept of Atal Tinkering Labs, students are allowed to work on the ideas they have. They offer facilities to get materials such as 3D printers, robotics kits, electronics components, and others as shown in Fig. 2. The labs also give students ‘project advisors,’ or mentors, that help and support the students in their projects.

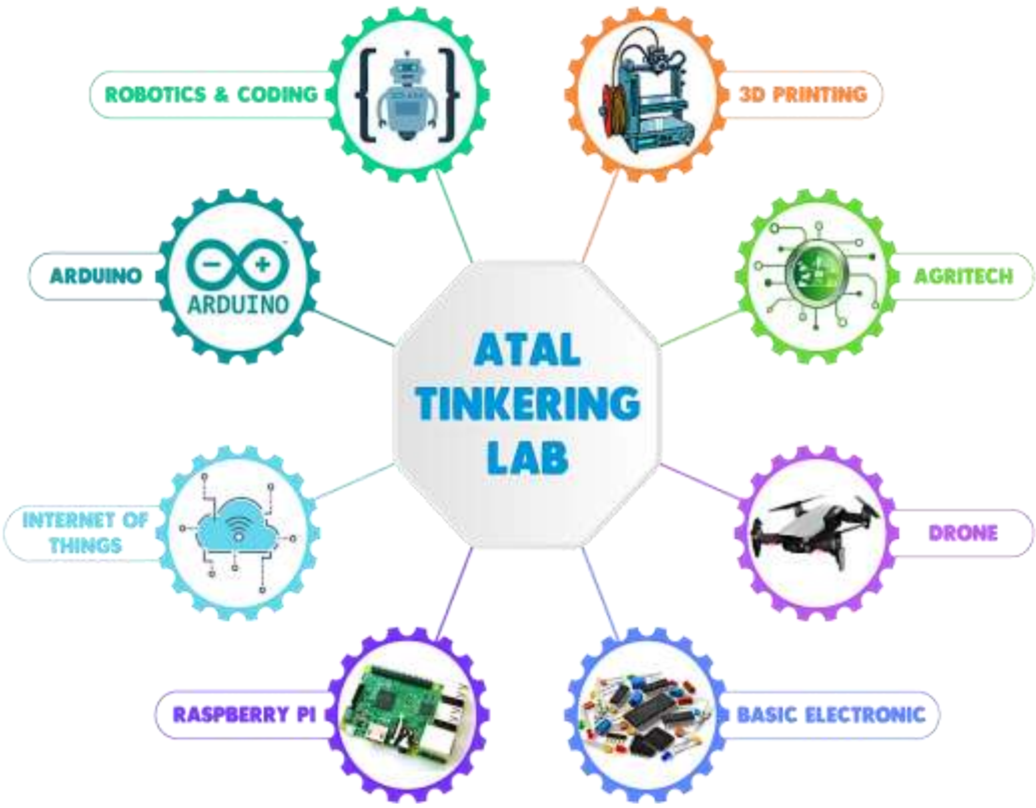

Fig. 2 Basic components of ATAL Tinkering Lab

The curriculum that is followed in Atal Tinkering Labs is liberal and comprehensive and blends Science, Technology, Engineering, and Mathematics. Because it helps the student solve real-life problems and find out the best solutions for such problems. The labs also aim to teach such skills as design thinking, coding, prototyping and problem-solving skills. These labs not only provide students with useful tools but also require them to think like entrepreneurs and to develop their products or services. Atal Tinkering Labs has been designed to develop a generation of innovators, problem solvers and entrepreneurs who can build a New India.

The potential of ATLs to address skill gaps in India's young workforce aligns with the national priorities articulated in the National Education Policy (NEP) 2020. The policy underlines the requirement of experiential learning and innovation-driven education as cornerstones for creating a knowledge-based economy (Osayomwanbo, 2022a). These initiatives are also encouraged by collaboration between schools, communities, and industries, creating a supportive ecosystem for innovation (Manikutty et al., 2024). Thus, providing the rural students with equal chances as their urban counterparts, the ATLs also act as a justice body represented by the educational point of view. This paper aims to explore the two-folded micro-education issues and possibilities of installing ATLs in rural schools. This paper aims at discussing the experiences of the stakeholders and assessing the effectiveness of these labs and then recommends the best strategy for enhancing the labs in different structures. This review systemically synthesises the ATL literature on implementation in Rural India regarding the barriers, policies and recommendation for future research. As discussed, it looks at the stakeholders and addresses the opportunity of ATLs to revolutionize rural education.

Background

On April 9, 2021, the Council of Scientific and Industrial Research (CSIR) decided to adopt 295 Atal Tinkering Labs (ATLs) across the country, with an objective to inculcate scientific research and innovation culture among students. Atal Tinkering Lab are named schools in India under the Atal Innovation Mission of the NITI Ayog with the idea to 'Prepare one million children in India as future ready innovative thinkers'. The aim of the scheme is as follows: To provoke wonder, intrique and inspiration in young learners and to develop in learners dispositions that includes design thinking, computing thinking, learning, physical computing and others. AIM is the flagship institution established by Government of India to promote culture of innovation and entrepreneurship. AIM under NITI Aayog is conceived as an innovation organization for orchestral coordination between different central and state, sectoral ministries; to incentivise the promotion of innovation and entrepreneurship landscaping at higher secondary schools and colleges/ universities/ research institutions, and SME/MSME industry, corporate and government ministerial levels through a public private partnership. The components of the Atal Innovation Mission are given below:

Atal Tinkering Labs
Atal Incubation Centres
Atal New India Challenge
Mentor of Change Program
Atal Community Innovation Centre (CIC)
Atal Research & Innovation for Small Enterprises (ARISE)

The ATL initiative aligns with the objectives of the National Education Policy (NEP) (NEP, 2020), which emphasizes experiential learning, critical thinking, and problem-solving abilities. Despite these progressive goals, the digital divide and lack of resources in rural areas pose significant hurdles. A heat map showing the distribution of ATL Labs across India, highlighting urban and rural areas separately is presented in Fig. 3.

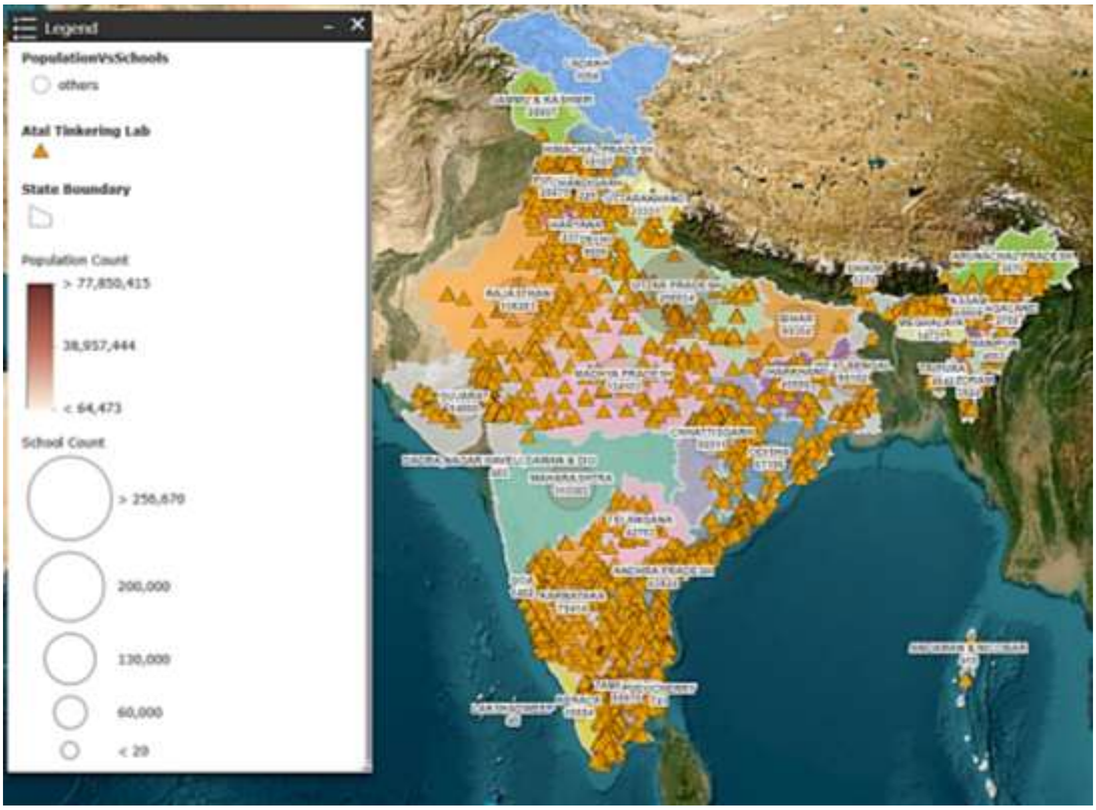

Fig. 3 Map of ATL Lab Distribution in India (*Schools Geo Portal*, 2025)

Who can apply for ATL?

Eligibility Criteria: Atal Tinkering Labs (ATLs) are open to schools that fall under the following categories: Government Schools (Central/State): Currently, schools affiliated with the central or state government are allowed to apply for the establishment of ATLs.

Local Bodies (Municipality/Nagar Nigam): Even schools managed by local bodies like municipalities or Nagar Nigams can also approach setting up an ATL in their school.

Private Trusts/Society: The schools which come under the private trusts or societies are eligible to apply for an ATL in order to enable the institution to engage in innovative approaches and practical learning.

Tribal/Social Welfare Department: Tribal or Social Welfare Departments affiliated institutions are only allowed to participate in the Atal Tinkering Lab scheme.

Target Grades: Atal Tinkering Labs are for students of Grades VI-X and are an innovative method to teach science, technology, engineering, and mathematics (STEM).

Introduction to Tinkering: An Exploration of Concepts and Practices

Tinkering is a concept that has been widely discussed across various disciplines, each providing its unique perspective and interpretation. It is not a casual or haphazard effort but rather a thoughtful activity that encompasses learning, experimenting, and solving problems. The literature already available suggests that tinkering acts as an essential source of ideas and structures for enhancing the skills regarding making, repairing, and creating mental models (Turkle & Papert, 1990). It is defined as a "playful, experimental, iterative style of engagement" in which people repeatedly evaluate their objectives, investigate alternative avenues, and conceive new opportunities (Martinez & Stager, 2013). Furthermore, tinkering has been characterized as a "mindset of solving problems through direct experience, experimentation, and discovery (Martinez & Stager, 2013). Previous researcher (Bevan et al., 2015) further characterize it as the generative mechanism involved in the formulation of personally significant concepts, encountering obstacles in the physical realization of those concepts, maintaining perseverance throughout the process, and achieving breakthroughs upon discovering a solution. These distinct definitions exemplify the intricate and multifaceted essence of tinkering.

Nature of Activities

Tinkering directly connects to a specific set of physical manipulations related to object and tools interactions to reason about ideas (Baker et al., 2015; Godwin et al., 2016). These activities include concept trial where each trial is built to give direction to the next trial of the concept (Jacobsson, 2013; Turkle & Papert, 1990; Wilkinson et al., 2016). Exploratory, more concerned with tried and tested procedures, this is more cyclic than linear in nature. Tools in those activities are not only utilitarian; it means that tools are the means by which people immerse themselves in ideas and gain new insights through the manipulation of objects. It brings about masterly of the contents which planted in students' minds and it helps foster creativity and critical thinking.

Goals

The objectives associated with tinkering are diverse and often change with time. Although some objectives may be defined, many others emerge during the process itself (Berland et al., 2013; Roth, 1996). Generally, the objective is rather open-ended, leaving room for multiple solutions and outcomes (Jonassen, 2000). In contrast, intentional sensemaking is often much more structured and systematic in its approach (Tuminaro & Redish, 2007). The purpose of tinkering goes beyond merely identifying a solution; it encompasses the pursuit of multiple avenues, sometimes even dropping the original idea to seek better options (Quan & Gupta, 2020). This open-ended nature of tinkering fosters experimentation and discovery and, therefore, develops an attitude of iteration rather than precision. It enables learners to learn from their mistakes and adjust their strategies on the fly, a skill that is often unavailable in more formalized environments.

Visible Processes

Tinkering happens when a lot of time is spent in a particular area as a flexible and fluid process within an environment (Quan & Gupta, 2020).This remains to be the feedback from the social as well as the unmaterialized concern that ideas could be made along with changed in the light of presenting barriers along with knowledge. This process is clearly related to the concept of bricolage since resource is assembled from stock of semantically defined parts to build abstract and concrete solutions (Louridas, 1999). This process exemplifies knowledge as a fluid and fungible concept, one that can be adapted based on available materials and intended outcomes. Rigorous, therefore, is not simply a form problem-solving, it is about a disposition that underpins navigating the unknown with the objects to hand and constructing the meaning out of the world (Turkle & Papert, 1990; Vallgårda & Fernaeus, 2015).

Orientation

Tinkering activities are often characterized by a playful orientation, emphasizing the enjoyment of the process rather than the product itself (Bevan et al., 2015; Martinez & Stager, 2013; Vossoughi et al., 2013; Wang et al., 2013). This orientation is not just about being curious or experimental; it involves a holistic sense of how individuals approach the task at hand. The non-restrictive feature enables people to produce original content by always having a certain degree of experimentation without the necessity for gaining high results immediately (Danielak et al., 2014). It also makes tinker as the practice that can be quite different from many activities carried in classrooms where the key emphasis is made on purposeful outcomes and effective procedures (Berland, 2016). Such an approach allows calling tinkering a genuine professional activity allowing for real time interaction and feedback on the action performed (Martinez & Stager, 2013).

Bricolage and Jugaad

Tinkering is similar to other words including bricolage and jugaad, which describe similar processes with nuances. From the literature, bricolage relates the act of building structures based on whatever resources are available and in a creative flexible way (Louridas, 1999). It is, frequently, about making do with what is in front of you, applying your intuition and practical knowledge to find a solution. In contrast, Jugaad encompasses an unconventional, frugal, and frequently creative method of resolving difficulties (Radjou et al., 2012). It is defined by hasty rehashes or jerry-rigged stops on wings-and-prayer budgets. They both relate to the repetition in tinkering as well as creativity and flexibility. However, they differ in their contexts—while bricolage often emphasizes a structured, logical approach, jugaad focuses more on making things work with whatever is available, often in constrained circumstances.

Table 1. Comparison: Tinkering, Bricolage, and Jugaad

Aspect	**Tinkering**	**Bricolage**	**Jugaad**
Goal	Open-ended outcomes	Structure from existing resources	Frugal, quick fixes
Approach	Iterative and experimental	Inductive and deductive	Practical and resource-constrained
Orientation	Playful, learning-focused	Adaptive and experience-driven	Innovative, rule-bending
Key Attribute	Creativity and iteration	Problem-solving through adaptation	Efficiency and ingenuity

Playing is undoubtedly some of one of the most helpful and positive forms of learning and problem solving in the act of creativity, experiment and experience. Nevertheless, it has much in common with bricolage and jugaad while maintaining the main subject matter of open-ended challenges and play orientation. A comparison between tinkering, bricolage and Jugaad has been shown in Table 1.

The perception of tinkering as a mentality and approach presents diverse challenging and opportunities for multiple disciplines, such as education, product design, and engineering. From experience, it indicates that support for exploration, ingenuity, and adaptability open new ways of tackling problems and provide students with better insight on the concepts covered. Analyzing the various views and approaches related to manipulation, we obtain knowledge on how to interact with difficulties as well as envisage and construct useful and significant solutions. It is for this reason that this review seeks to elaborate on these concepts to provide a rich understanding of how tinkering will be used for learning and innovation.

Review of Literature

STEM Education in Rural Areas

STEM (Science, Technology, Engineering, and Mathematics) education plays a critical role in preparing students for a knowledge-based economy. However, studies reveal that rural students often lack exposure to practical STEM learning due to limited infrastructure, inadequate teacher training, and socio-economic barriers (Aslam et al., 2023; Bevan et al., 2015). According to the international recognition, science, technology, engineering and mathematics (STEM) is acknowledged as a significant sector for Innovation, economic growth and development (Amirtham S & Kumar, 2021). So, the introduction into the rural education systems is a great opportunity for bridging the gap between the rural and urban areas of education. However, from the perspective of STEM education pedagogy, there are many challenges and opportunities that rural areas offer (Chaudhari & Nagwanshee, 2019).

STEM education develops for students the skills of critical thinking, problem-solving, and collaboration to excel in the enterprise of the future (Aslam et al., 2023; Mishra & Gupta, 2023b; Osayomwanbo, 2022b). In rural areas, STEM can have additional localized benefits, such as:

Empowering Local Communities: By introducing STEM concepts, students are enabled to address community-specific challenges, such as water scarcity or agricultural inefficiencies, using innovative solutions (Amirtham S & Kumar, 2021).

Bridging the Digital Divide: Access to STEM tools like robotics kits, 3D printers, and coding platforms can bridge the gap between rural and urban education, ensuring equitable opportunities for students (Aashish & Rohit, 2024).

Workforce Development: Preparing rural youth for careers in emerging industries helps diversify local economies, reducing reliance on agriculture as the sole source of livelihood (For & Maguire, 2001).

Atal Tinkering Labs: Concept and Goals

ATL Labs aim to inculcate a hands-on learning approach by encouraging students to design and innovate. NITI Aayog's annual reports ("Niti Aayog Annual Report," 2021) highlight the significant impact of ATL Labs in urban schools, where students have developed low-cost technologies for societal problems (NEP, 2020). However, similar success stories in rural schools remain sparse.

An ATL is an innovation and R&D facility in schools across the country established with the aim of AIM, Government of India (NEP, 2020). The Atal Tinkering labs are intended to develop scientific temper, innovative spirit, scientific curiosity, scientific knowledge, design thinking skills and problem-solving skills among those who attend these labs as shown in Fig. 4. Having functional 3D printers, robotics kits and electronics components, Atal Tinkering Lab enable students to innovate with fun and learning (Osayomwanbo, 2022b). The main idea is to develop the spirit of innovative thinking from childhood and to combine theoretical learning with applications (Berland, 2016). Students not only learn the fundamentals of STEM education in the Atal Tinkering lab but also build the ability to solve problems creatively to face future challenges help develop India's technology potential and contribute to the nation's competitiveness(Mishra & Gupta, 2023b, 2023c). Innovation, problem-solving abilities, and a deep interest in science and technology among students(Bevan et al., 2015; Martinez & Stager, 2013). Equipped with modern tools and technologies like 3D printers, robotics kits, and electronics components, Atal Tinkering Lab provide students with hands-on learning experiences, encouraging them to explore, tinker, and create (Godwin et al., 2016; Wang et al., 2013).

The main objective is to promote students' interest and creativity already in the elementary school and to link theoretical knowledge with the practice. The ATLs also provides more than tangible STEM knowledge by giving the students critical thinking skills for their potential careers and for the progress of the Indian economy and its population's general competency in technology (Kanjilal et al., 2021b; Manikutty et al., 2024; Ulfah, 2023b). These labs play a crucial role in cultivating future innovators and problem solvers for India's innovation growth path.

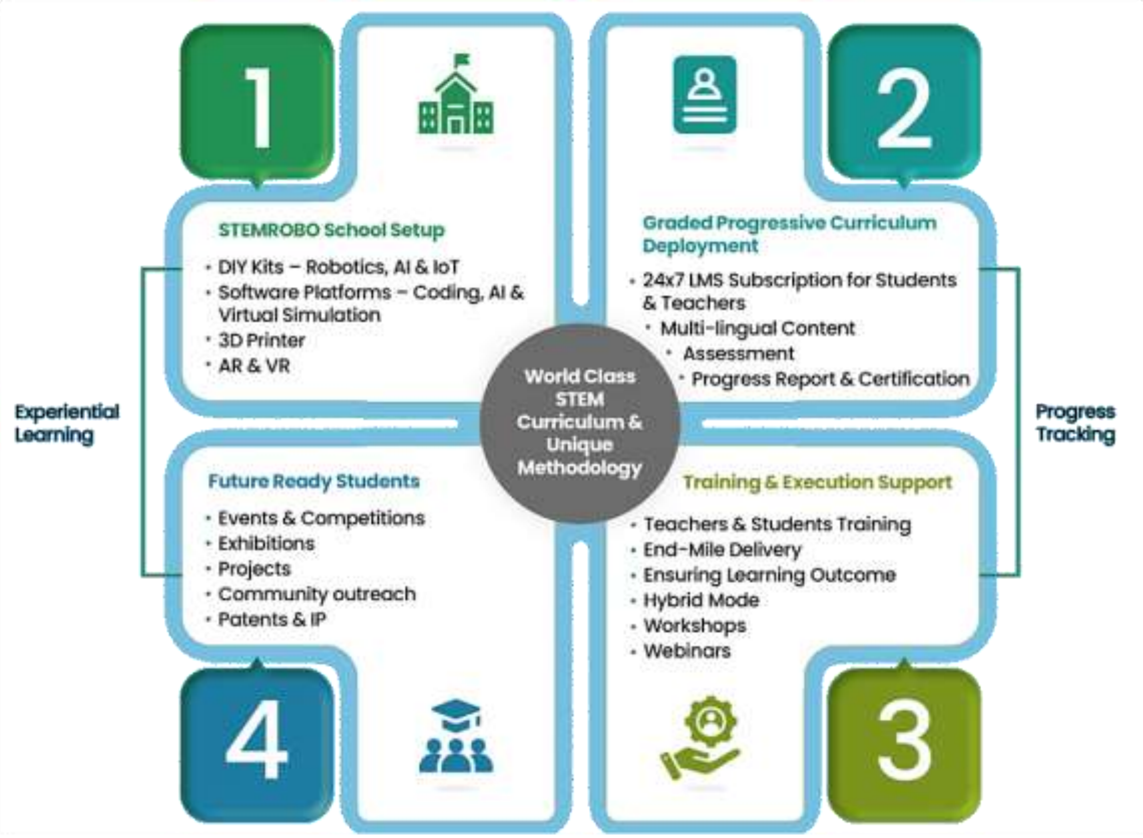

Fig. 4 Atal Tinkering Lab methodology for END-TO-END school solution

The findings from the previous study (Mishra & Gupta, 2023a) obtained in view of the three analytical dimensions, namely, Clarity of the Concept, Self-Efficacy, and Subject Knowledge, offer insights. The majority of teachers (559) responded that they perceived STEM concepts with fair clarity whereas only 447 responded that this clarity was strong suggesting there is potential for teachers to develop a richer understanding of STEM. Self-efficacy stood out as the most robust dimension with 496 teachers strongly agreeing with their ability to deal with and teach STEM content. Subject knowledge was endorsed most, 629 respondents were very strong with it, highlighting strong anchoring knowledge in this regard. Figure 5 illustrates these results and indicates that although perceived self-efficacy and instructional self-efficacy were high most of the teachers, clarity of concepts was slightly less. The data also reveal very low levels of perceived disagreement and/or uncertainty further indicating a positive baseline perception of STEM. Nonetheless, the lack of equivalence in conceptual clarity indicates that there is a dire need to have specific capacity-building programs to enhance the SCs understanding on awareness and practical impendment of STEM educational practices in effective and efficient Schools.

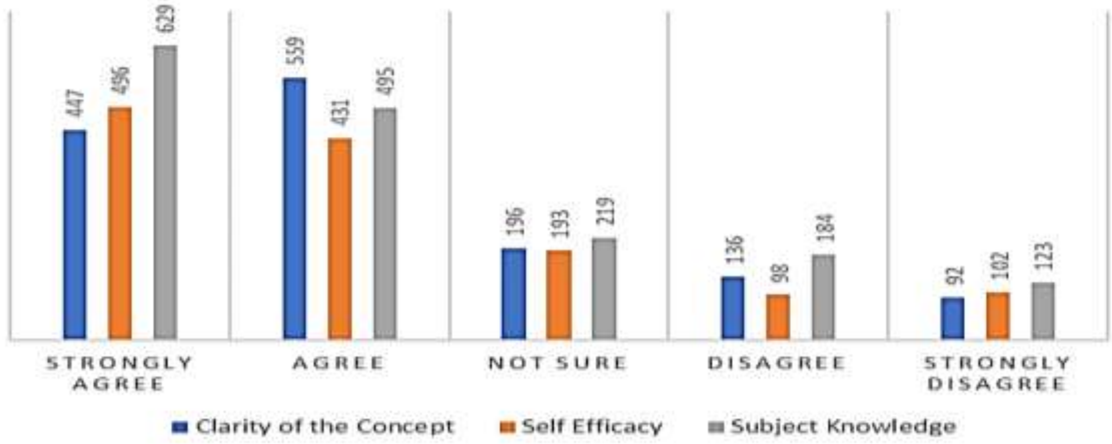

Fig. 5 The responses collected on the items related to the dimensions of STEM education (Mishra & Gupta, 2023a)

Challenges in Rural Implementation

Infrastructure and Resource Constraints: The rural schools often face the inadequate physical infrastructure, unreliable electricity and internet connectivity. These limitations sometimes hinder the effective functioning of ATLs, which depend on a stable power supply and access to digital resources (Agrawal, 2015; Kankana, 2017; Manikutty et al., 2024).

Teacher Training and Capacity Building: A critical bottleneck in implementing ATLs is the lack of adequately trained teachers, who can teach and guide the students in using the advanced tools and technologies (Akshay et al., 2018). There is an one week program for teacher training but that is sometimes not very effective to understand lots of knowledge related to some high-end equipments. The absence of professional development programs further exacerbates this issue (Aashish & Rohit, 2024).

Cultural and Socioeconomic Barriers: Many rural communities face challenges such as resistance to change, limited understanding of STEM education, and socio-economic hardships, which can make it difficult for them to fully embrace the ATL initiative. Parents and educators may prioritize traditional curricula over innovative, hands-on learning models(Aashish & Rohit, 2024; Akshay et al., 2018; Dey et al., 2019).

Sustainability Concerns: Ensuring the long-term sustainability of ATLs poses another significant challenge. Maintenance of equipment, regular updates of software and tools, and continued teacher engagement require consistent funding and management, which is often lacking in rural setups(Khalid et al., 2019; Roy, 2012).

Cultural and linguistic barriers that hinder the adoption of new pedagogical tools Opportunities in Rural Schools (Anowar & Khatun, 2024; For & Maguire, 2001; Zahra Khalid & Bilal Shayiq, 2019):

1. **Hub-and-Spoke Models**: States like Andhra Pradesh have piloted hub-and-spoke models where model schools act as resource hubs for neighbouring schools. This decentralized approach enables resource-sharing and capacity-building, particularly in rural regions.

2. **Public-Private Partnerships**: Collaborations with private industry and non-profits can provide the financial and technical support required to maintain ATLs. Corporate Social Responsibility (CSR) initiatives have proven effective in bridging funding gaps and introducing cutting-edge technology to rural schools.

3. **Capacity Building through Training Programs**: initiatives such as Karnataka's SRISHTI initiative and Andhra Pradesh's state-level training centers highlight the critical importance of teacher training in the success of ATLs. These programs help to provide educators with the skills they need to be able to successfully lead and

inspire students. Teacher professional development is important as it not only increases the knowledge and skills of teachers but also promotes more student take-up and involvement in STEM by way of regular workshops, hands-on sessions, and online training opportunities.

4. **Student Empowerment through Innovation Challenges**: The concentration on innovation challenges, and students' project activities has been considered to be a positive change that ATL brings to learners. These challenges help young people try to solve real life problems in the best manner possible provoking inventiveness. For example, smart irrigation systems and solar-powered streetlights are examples of how the students are design practical solutions for local problems. These experiences enable students to design for themselves as innovators in a position to change their society.

Despite these hurdles, rural schools also bring forth unique opportunities:

Local problem-solving: Students can leverage ATL tools to address local challenges such as water scarcity or agricultural inefficiencies (Abdul Nasir Kiazai et al., 2020).

Community engagement: ATL Labs can serve as hubs for innovation, fostering collaboration among students, teachers, and local communities (Baker et al., 2015).

Impact and Way Forward

ATL has already shown us its transformative potential for the educational landscape of India by nurturing a new generation of innovators and entrepreneurs. Still, the initiative needs to tackle its implementation hurdles to realize its full potential. Infrastructure improvements, partnerships, and teacher training are important components to ensure all students have fair access to innovation. Genuine challenges abound in rural schools, alongside a wealth of untapped talent, and rural schools are an ocean of opportunity for ATL; an opportunity to contribute to India's hinterland-based innovation ecosystem.

This study is to prove that though challenges of implementing ATLs in rural schools are big the opportunities that they offer in terms of revamping education and stimulating innovation requires them to be an inseparable part of India's education agenda. As these labs continue to evolve, they hold the promise of bridging the urban-rural divide and empowering every child to dream, innovate, and achieve.

Challenges in Implementing ATL in Rural Schools

ATL initiative is a transformative initiative that fosters innovation and creativity in the minds of the young. However, owing to socioeconomic, infrastructural, and cultural limitations, there are a unique set of challenges to successful implementation in rural schools. As such, this section analyzes the key barriers that have affected ATL in rural regions with the help of academic literature and policy documents.

Infrastructure Deficiency

Whenever one is seeking to provide education, infrastructure will always be an imperative factor that has to be provided. However, even if they exist, rural schools can be seriously lacking the basics needed to institute and maintain the ATLs. The following key aspects highlight these deficiencies:

Electricity and Internet Access: Of electricity supply, previous literature (Chaudhari & Nagwanshee, 2019) established that 54% of the rural schools in India use unreliable electrical supplies, and of internet connection, about 70% of the schools lacked broadband connections. These are important barriers since ATL operations depend on the supply of power at all times for 3D printers, computers and other technologically sensitive equipment. Any schools that do not have internet connection makes students denied that opportunity to practice on line learning as well as learning from virtual workshops that are a key input to ATL programs.

Space Constraints: Limited Space: In many rural schools, there are few classrooms and little space. Since it is very difficult to find rooms exclusively for ATL Lab, ATL lab are required to make some arrangement in other essential functions. According to a NITI Aayog survey undertaken in 2021 ("Niti Aayog Annual Report," 2021), more than 40% of Hindi median schools in rural areas had to combine classrooms and use staff rooms to accommodate ATL Labs, affecting overall functionality

Maintenance of Tools and Equipment: 3D printers, robotics kits, and similar high-end equipment need regular maintenance to avoid breakage, which is difficult to get in rural areas due to lack of trained technicians (Abdul Nasir Kiazai et al., 2020).

Lack of Teacher Training

Effective utilization of ATL resources depends on the skills and confidence of educators. However, rural schools face severe shortages of trained teachers capable of integrating ATL activities into the curriculum.

Limited Technical Proficiency: Teachers in rural areas often have minimal exposure to advanced technologies like Arduino programming, robotics, and IoT(Anowar & Khatun, 2024). They feel overwhelmed by the technical demands of ATL tools, which impacts the quality of instruction provided to students.

Irregular Training Programs: Although training programs for ATL facilitators are conducted by NITI Aayog and its partners, their reach in rural regions remains inadequate. A study by (Agrawal, 2015) revealed that only 18% of teachers from rural ATL schools received hands-on training, leaving the majority to rely on theoretical knowledge or self-learning.

High Turnover of Teachers: Rural schools often face high teacher turnover due to challenging living conditions and limited career growth opportunities. This disrupts continuity in ATL operations and necessitates frequent retraining, which strains financial and administrative resources(Chaudhari & Nagwanshee, 2019).

Socio-Economic Barriers

Socioeconomic challenges in rural communities significantly influence the adoption and success of ATL initiatives. These barriers include:

Parental Perceptions: Parents in rural areas often prioritize conventional subjects like mathematics and sciences over innovative learning methods, fearing that non-traditional programs may not translate into stable career paths. (Aashish & Rohit, 2024) observed that nearly 65% of parents in rural schools were skeptical about the utility of ATL Labs.

Economic Constraints: Many families in rural areas cannot afford to buy supplementary materials, such as additional robotics components or electronics kits, required for ATL projects. Even though ATLs are funded for basic infrastructure, limited personal resources restrict students from fully participating in advanced projects (Agrawal, 2015).

Student Attendance: Socioeconomic pressures force many students in rural areas to prioritize household chores or agricultural work over school activities. This inconsistent attendance hampers engagement with ATL programs, which often require sustained involvement for skill development (Easwaran, 2022).

Policy and Administrative Challenges

The implementation of ATL Labs in rural schools involves navigating bureaucratic and administrative hurdles. These challenges often result in delayed or ineffective outcomes.

Delayed Fund Disbursements: Although NITI Aayog allocates funds for ATL Labs, delays in disbursement create gaps in the establishment and functioning of labs. A 2021 policy analysis by NITI Aayog revealed that over 30% of rural ATLs experienced delays exceeding six months, impacting their readiness (“Niti Aayog Annual Report,” 2021).

Lack of Monitoring and Accountability: Rural ATLs often lack proper oversight mechanisms to ensure their effective utilization. Instances of underutilized labs, misplaced funds, or incomplete setups are more prevalent in rural regions due to limited monitoring (Mishra & Gupta, 2023b).

Rigid Implementation Frameworks: Policies surrounding ATLs are often designed with a one-size-fits-all approach, failing to address the unique needs of rural schools. For instance, many schools struggle with the procurement of equipment due to a lack of localized suppliers, as identified by a study from the (Renn, 2015).

Gender Disparity

Gender inequity is a significant barrier to the success of ATL programs in rural schools, as it limits the participation of girls in STEM-related activities. "*Current employment opportunities come with greater demands for competencies in STEM. Girls particularly miss out on opportunities to learn and practice STEM. Thus, UNICEF is proud to support building a strong foundation for critical thinking in the early years of learning. The BMW-UNICEF partnership makes this possible by investing in making education more accessible and inclusive, especially for girls. The result is greater economic and social self-reliance leading to more opportunities*", said Cynthia McCaffrey, UNICEF India Representative (Megha Chaturvedi, 2024). As per the leading newspaper, education specialist at Unicef, Parul Sharma, said, "*The goal of providing these girls with quality STEM education is to bridge gender gaps in education and open up new opportunities for economic and social empowerment. Low-cost maker spaces will be established within schools, allowing adolescent girls to explore creative STEM subjects such as design thinking, computational analysis, and physical computing*" (Kritika Tiwary, 2024). BMW Group and UNICEF have partnered to revolutionize the educational landscape for 100,000 children in rural India, focusing on providing quality STEM (Science, Technology, Engineering, and Mathematics) education. Focusing on adolescent girls from Kasturba Gandhi Balika Vidyalayas and Tribal Ashramshalas**,** the program aims to reach the most marginalized groups in rural areas. The initiative will provide tailored teacher training in STEM instruction, addressing gender stereotypes, and empowering girls through leadership programs.

Societal Restrictions: In rural areas, cultural norms and biases often discourage girls from pursuing technical or scientific education. (Amirtham S & Kumar, 2021) found that in over 60% of rural Indian schools, parents viewed STEM activities as less suitable for girls, citing societal expectations and safety concerns.

Early Dropout Rates: Many girls leave school prematurely due to financial constraints, household responsibilities, or early marriages. As a result, they miss opportunities to engage with ATL Labs. The ASER Report (2023) (ASER, 2023) highlighted that rural dropout rates for girls in secondary education exceeded 40%, severely limiting their exposure to STEM.

Lack of Female Role Models: The absence of women mentors in STEM fields further exacerbates the gender gap. Recent studies have showed that girls who attend the rural schools are less interested in STEM activities especially if they do not have any relatable gender models (González-Pérez et al., 2020; Tal et al., 2024).

Addressing the Challenges

While these challenges are significant, targeted interventions can help mitigate their impact:

Infrastructure Investments: Allocating additional funds for rural school infrastructure, such as solar panels for power and low-cost internet solutions, can improve access(Agrawal, 2015).

Comprehensive Teacher Training: Regular and context-specific training programs, supplemented with remote mentoring, can empower teachers to effectively use ATL tools(Aslam et al., 2023; Mishra & Gupta, 2023a).

Community Engagement: Raising awareness among parents and local leaders about the benefits of STEM education can improve participation rates(Khalid et al., 2019).

Gender-Sensitive Policies: Implementing scholarships and safety measures specifically for girls can promote equitable participation in ATL activities (Tal et al., 2024).

By addressing these multifaceted challenges, ATL Labs can realize their full potential in rural areas, empowering students to become creators and innovators. The successful integration of these initiatives will require sustained efforts from policymakers, educators, and communities.

Table 2. Comparative analysis of ATLs in rural and urban schools

Parameters	Rural Schools ATLs	Urban Schools ATLs
Access to Resources	Limited availability of tools, equipment, and raw materials.	Better access to advanced tools, equipment, and resources.
Technical Support	Lack of trained mentors and teachers; often rely on local staff with limited expertise.	Access to skilled mentors, industry experts, and trained teachers for guidance.
Infrastructure	Basic infrastructure with space constraints and power issues in some cases.	Well-equipped infrastructure with dedicated lab spaces and reliable facilities.
Student Engagement	Slower initial engagement due to limited exposure to technology and tinkering.	Higher enthusiasm and participation due to better awareness and prior exposure.
Learning Outcomes	Focus on practical, frugal innovations; emphasis on problem-solving for local needs.	Focus on advanced technology integration and innovative prototypes.
Project Quality	Simple, low-cost solutions to address local challenges like agriculture, energy, etc.	Complex, tech-driven projects that solve broader/global challenges.
Exposure to Competitions	Fewer opportunities to participate in national/international competitions.	Regular participation in national and international innovation competitions.

Community Impact	High local impact; solutions often directly benefit rural communities.	Broader urban reach; solutions often focus on societal and industrial applications.
Innovation Culture	Emerging innovation culture with a focus on jugaad (frugal innovation).	Stronger innovation culture due to exposure to STEM fields and maker culture.
Digital Connectivity	Limited internet access, leading to difficulty in accessing online resources.	Reliable internet access facilitates research, training, and virtual collaborations.
Government/NGO Support	More dependency on government initiatives for funding and training.	Additional support from NGOs, private organizations, and CSR initiatives.
Student Aspirations	Focus on solving immediate, practical problems within the community.	Aspirations include entrepreneurship and technological innovation at a larger scale.
Teacher Training	Limited teacher training programs due to geographical constraints.	Frequent workshops and access to online teacher training programs.
Parental Awareness	Limited awareness about the value of STEM education and tinkering activities.	Higher awareness among parents who encourage participation in ATL programs.
Collaboration Opportunities	Limited opportunities for collaborations with industries, experts, and peers.	Greater collaboration opportunities with industry leaders, tech experts, and peers.

Table 2 shows the growth and achievements made in rural and urban school ATLs. The results also show that compared with rural ATLs, urban ATLs have comparatively more well-equipped infrastructures, better resource accessibility and higher rates of employing innovative activities due to far better access to technology, funds and professional guidance. Some challenges that are magnified in rural schools include low internet connection, and mediocre teachers training; these affect students' engagement and innovation results. Nevertheless, the current study suggests that rural ATLs have potential to contribute considerably to the enhancement of STEM casualness and creativity of students, and show a consistent growth trend that could be further enhanced with proper support.

Conclusion

The extendibility of ATL in rural schools is a reform towards providing equal opportunity in STEM education and innovation in society's root of India. Yet the process of introducing ATL Labs to rural schools and specifically to the areas characterized by significant socioeconomic and infrastructural divide remains a challenging narrative. This paper has pursued the opportunities and challenges that existed when implementing ATL in the rural schools and the critical areas that should attract the concern of stakeholders.

Key Findings

Rural schools encounter significant challenges including inadequate infrastructure, absence of teacher training, socio-economic limitations, policy implementation, and gender biases. These problems make it difficult for ATL Labs to work as impactful frameworks for rural education. Not with standing these challenges, when implemented well, ATL Labs hold tremendous potential for bridging the urban-rural divide in STEM education.

Infrastructure Deficiency: This means that necessities like electricity supply, internet connection and availability of specific premises are requisites of functioning ATLs. Some of the learning needs are not met in rural schools as documented by (Chaudhari & Nagwanshee, 2019) and ("Niti Aayog Annual Report," (2021).

Teacher Training: The lack of trained facilitators is a significant bottleneck, with (Abdul Nasir Kiazai et al., 2020; Aslam et al., 2023) emphasizing the need for specialized and sustained teacher training programs.

Socio-Economic Barriers: (Easwaran, 2022) underlined how socio-economic challenges impact parental perceptions and student engagement, limiting ATL Labs' reach and effectiveness.

Policy and Administrative Challenges: Policy gaps, delayed funding, and inadequate monitoring further exacerbate the issues, reducing the efficiency and sustainability of ATL Labs in rural settings (“Niti Aayog Annual Report,” 2021).
Gender Disparity: (Amirtham S & Kumar, 2021; Tal et al., 2024) documented the cultural and systemic barriers that restrict girls' participation in STEM activities, calling for gender-sensitive interventions.

Opportunities for Improvement

The paper also highlights opportunities to address these challenges by leveraging community engagement, policy enhancements and innovative technological approaches. Some of these recommendations stand out:
Infrastructure Investments: The government as well as private stakeholders will have to invest in enhancing the physical and digital infrastructure of rural schools. Gaps can be filled with innovations like solar-powered labs and low-cost internet solutions.
Teacher Capacity Building: To enhance the use of ATL tools among educators, region-sensitive workshops for developing practical training models and ongoing supportive programs have to be provided.
Engaging Communities: Changing mindsets towards STEM education can stem from parental and local community awareness activities.
Gender-Inclusive Policies: More scholarships for girls, mentorship programs to support participation and assurance of a safe environment can all help to bridge the gender gap in the STEM Pipeline.

Long-Term Vision

In the broader context, ATL Labs symbolize a shift in India's educational philosophy, as envisioned by the National Education Policy (NEP) 2020(NEP, 2020). By cultivating a culture of innovation and entrepreneurship, these labs aim to prepare rural students for the challenges of the 21st century. However, their success hinges on sustained efforts from all stakeholders—government bodies, educators, communities, and students themselves.

Call to Action

The effective implementation of ATL Labs in rural schools requires coordinated action. Policymakers must design localized solutions, ensuring that the unique challenges of rural regions are addressed. Schools must adopt a holistic approach, integrating ATL activities into mainstream education while fostering an inclusive environment. Non-governmental organizations and the private sector can play an instrumental role in resource mobilization, training, and advocacy.

Future Research Directions

This study highlights the need for further empirical research to measure the long-term impact of ATL Labs in rural settings. Future studies could focus on:
The role of public-private partnerships in scaling ATL Labs.
Longitudinal studies to track student outcomes post-ATL exposure.
Evaluations of gender-focused interventions and their effectiveness in promoting STEM education.
Technological innovations tailored for low-resource settings to enhance the sustainability of ATL Labs.
The ATL initiative, with its vision to create a generation of thinkers and innovators, has the potential to transform rural education. While challenges are inevitable, they are not insurmountable. By addressing infrastructural gaps, empowering educators, engaging communities, and fostering inclusivity, ATL Labs can become beacons of change in rural India. As the nation marches toward a knowledge-based economy, ensuring equitable access to STEM education for rural students is not just an aspiration but a necessity.
Rural ATLs excel in frugal innovation and practical solutions for local challenges, often fostering grassroots-level creativity. Urban ATLs, however, focus on advanced, technology-driven prototypes and benefit from better infrastructure, mentorship, and exposure to competitions. Both have significant roles in fostering an innovation ecosystem, but bridging gaps in resources, infrastructure, and mentorship in rural areas can further enhance their efficiency and impact. By overcoming these barriers, India can harness the untapped potential of its rural youth, fostering an era of inclusive innovation that drives both individual and national progress.
Declarations

Availability of data and material

The data and materials utilized in the review paper, are derived from publicly available sources, published studies, and institutional records. The data used during the preparation of this manuscript, are available from the corresponding author, upon reasonable request.

Ethical approval

Not applicable. This study did not involve experiments with human tissue or participants requiring ethical approval from an institutional review board or equivalent ethics committee.

Competing interests

The authors declare that there is no conflict of interest.

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Authors' contributions

PR contributed to the conceptualization of the study, literature review, and writing of the manuscript. AC provided expertise in the educational framework, data analysis, and interpretation of findings. RKR designed the methodology, contributed to the technical analysis, and reviewed the manuscript for intellectual content. All authors collaborated in the drafting and final approval of the manuscript. All authors read and approved the final manuscript.

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