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Open Laboratory as a Platform for Secondary STEM Education: A Case Study of a Science-Focused Secondary School in Sichuan Province

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Abstract: STEM education has emerged as a central global educational priority for cultivating the innovative talents required by twenty-first century knowledge economies, with hands-on practical inquiry widely recognized as its indispensable core pedagogical component. In China, successive national and provincial education policies over the past decade have increasingly emphasized the importance of opening school laboratories to expand practical learning opportunities and advance science and technology education for all students. Despite this strong policy impetus, most ordinary secondary schools in China still lack mature, sustainable, and genuinely inclusive STEM implementation models that can effectively operate within the constraints of local academic contexts and persistent high-stakes examination pressures. Existing STEM programs in Chinese secondary schools tend either to be elite competition-focused initiatives serving only a small minority of students, or superficial extracurricular activities with limited substantive educational impact. This study addresses this gap by adopting a single qualitative case study approach to systematically examine a well-established open laboratory system at a science-focused secondary school in Sichuan Province, China. Drawing on triangulated data sources including analysis of 27 official program documents, three full academic years of operational participation data, and structured observations of 8 laboratory sessions spanning all curriculum tiers, the study provides a comprehensive account of the model's structure, implementation, and effects. The findings reveal that the school has constructed a coherent four-tier progressive experimental curriculum system, supported by a refined scheduled appointment management mechanism and multi-faceted supporting systems including preparatory courses and multi-dimensional evaluation, together forming a genuinely inclusive STEM education platform accessible to students across all grade levels and ability levels. This model has demonstrated measurable educational effects, with participation growing from approximately 800 to over 1,500 student participations per semester over three years, and documented improvements in students' experimental skills, scientific inquiry abilities, and interest in STEM subjects. A key localized innovation is the model's deliberate integration of academic examination training with competency development, which enhances institutional sustainability by aligning STEM practice with core academic priorities rather than positioning the two as competing objectives. The study provides a valuable, replicable localized practice reference for promoting regularized, school-based STEM education in Chinese secondary schools, and enriches international scholarly understanding of how STEM education can be productively integrated within East Asian examination-oriented educational contexts.

Keywords: open laboratory; secondary STEM education; inquiry-based learning; inclusive education

1. Introduction

Global education reform has increasingly prioritized Science, Technology, Engineering, and Mathematics (STEM) education as a core national strategy for preparing students to navigate future technological and societal challenges (National Research Council, 2012). Unlike traditional subject-based instruction that delivers discrete disciplinary knowledge through didactic teaching, high-quality STEM education emphasizes authentic problem-solving, cross-disciplinary integration, and hands-on practical inquiry—learning outcomes that cannot be fully realized through classroom lectures alone(Ortiz-Revilla et al., 2023). A 2019 national vision report on STEM education from the US National Academies further emphasized that practice-based STEM learning in the K-12 years is the foundation for building a future innovative workforce, and that the accessibility and openness of laboratory spaces directly determine the quality of STEM implementation at the school level (National Academies of Sciences, Engineering, and Medicine, 2019).

In China, national and provincial education policies have repeatedly underscored the importance of opening school laboratories to expand practical learning opportunities for students. The 2019 Opinions on Strengthening and Improving Experimental Teaching in Primary and Secondary Schools issued by the Ministry of Education explicitly encouraged schools to open laboratories to students during after-school hours to support independent and collaborative inquiry (Ministry of Education of China, 2019). The 2025 Guidelines for Science Education in Primary and Secondary Schools elevated science and technology education to a strategic level of moral education and talent cultivation, further calling for increasing the proportion of open, inquiry-based experiments and developing diversified laboratory spaces to support hands-on learning(Ministry of Education of China, 2025). At the provincial level, Sichuan Province has incorporated laboratory opening into school evaluation systems, setting a clear requirement that laboratories should be open no less than 80% of after-school and holiday hours, pushing top-level policy design to translate into concrete school-based practice (Sichuan Provincial Department of Education, 2023).

However, secondary schools across China face persistent structural barriers to implementing STEM education through laboratory practices. Traditional school laboratories are restricted to fixed class hours and follow rigid "cookbook-style" confirmatory experiments that leave no room for student-led inquiry or creative exploration (Talafian et al., 2024). Additionally, the majority of existing STEM programs in Chinese secondary schools target elite students selected for competition teams, concentrating resources on a small minority and failing to provide inclusive STEM learning opportunities for the broader student body, resulting in a pronounced Matthew effect in resource distribution(Zhang & Wang, 2022). The inherent tension between examination-oriented academic pressure and competency-based STEM education further constrains large-scale implementation, as many schools perceive STEM as an extracurricular activity that takes time away from academic preparation, making it difficult to integrate into regular education systems (Zheng, 2026). How to leverage existing laboratory resources within current educational frameworks to build a sustainable, inclusive STEM practice model has become a core challenge for science and technology education development in Chinese secondary schools.

1.1 Research Questions

This study addresses three interrelated core research questions:

- **1.1.1** How can a secondary school build a systematic STEM education practice system using an open laborat ory platform? What are the defining characteristics of its operational mechanism, curriculum structure, and supporting systems?
- **1.1.2** What are the practical educational effects of this open laboratory STEM model? What localized charact eristics distinguish it from Western STEM models and domestic elite competition-focused STEM progr ams?
- **1.1.3** What theoretical value and practical implications does this model offer for localized STEM implementa tion in Chinese secondary schools? What are the boundary conditions for its transferability to other sch ool contexts?

1.2 Research Significance

1.2.1 Theoretical Significance

First, this study provides detailed empirical evidence from a Chinese secondary school case study, substantially enriching the growing literature on K-12 open laboratory education. It addresses a notable prevailing research gap where the majority of existing open laboratory studies focus on higher education contexts, with far less attention devoted to comprehensive multi-tiered open laboratory systems in basic education settings. By documenting a fully operational four-tier curriculum structure within a secondary school open laboratory, the study expands the scope of what is known about how open laboratories can be organized to serve diverse learning objectives across grade levels.

Second, this study directly responds to the active research agenda of STEM education localization in East Asian examination-oriented education systems. It proposes and empirically documents an integrated model that deliberately balances examination preparation and competency development within a single institutional framework, adding a valuable Chinese empirical perspective to the broader theoretical discourse on STEM integration in East Asian contexts. This contributes to the growing body of international research exploring how Western-originated STEM education concepts can be productively adapted to different cultural and institutional environments (Yata et al., 2022; Kim & Lee, 2021).

Third, this study integrates four complementary learning theories—inquiry-based learning, learning by doing, social constructivism, and situated learning—to develop a comprehensive analytical framework for understanding open laboratory STEM education. By applying all four theoretical lenses to the same case and demonstrating how each illuminates different dimensions of the model's operation and effects, the study expands the explanatory power of these established learning theories in basic education practice settings and illustrates the value of multi-theoretical approaches to analyzing complex educational interventions.

1.2.2 Practical Significance

First, this study presents a concrete, inclusive STEM implementation framework that deliberately balances academic examination needs and competency development goals, providing an actionable reference scheme for urban secondary schools with similar resource conditions. By documenting a model that operates within existing institutional structures rather than requiring wholesale curricular reform, the study substantially lowers the perceived threshold for STEM education implementation for schools considering similar initiatives.

Second, the specific operational mechanisms documented and analyzed in the study—including the refined appointment-based management system, the four-tier progressive curriculum structure, and the multi-dimensional evaluation support system—offer direct, transferable guidance for schools seeking to optimize their existing laboratory opening practices or develop new open laboratory programs. The detailed description of implementation details provides practical insights that cannot be derived from conceptual discussions alone.

Third, the analysis of localized practical characteristics can provide useful empirical evidence for local education administrative departments when formulating science and technology education policies. By identifying which features of the model contribute to its sustainability and broad appeal within the Chinese secondary education context, the study can help policymakers design support policies and evaluation frameworks that are more responsive to the actual realities and constraints of secondary schools.

2. Literature Review and Theoretical Foundation

2.1 Core Concept Definitions

2.1.1 Secondary STEM Education

For this study, secondary STEM education is defined as an integrated educational approach combining scientific inquiry, technological application, engineering design, and mathematical analysis, corresponding to the connotation of "science and technology education" in the Chinese basic education context. Its core goal is to cultivate students' scientific literacy, practical ability, and innovative consciousness through hands-on, problem-driven learning, rather than simply delivering separate subject knowledge (Li, Zhang, & Liu, 2023). Unlike Western STEM education models that prioritize engineering-led integration, STEM education in Chinese secondary schools must align with curriculum standards and academic assessment requirements, exhibiting stronger localized adaptation characteristics (Zhang & Wang, 2022).

2.1.2 Secondary School Open Laboratory

A secondary school open laboratory refers to a campus practical space accessible to students during after-school hours, weekends, and holidays through an independent appointment system. Different from closed experimental classes with unified schedules and content, open laboratories support multi-level experimental activities ranging from basic confirmatory experiments to independent innovative projects, enabling student-centered inquiry learning. Its core features include temporal flexibility, content selectivity, and learning autonomy, which distinguish it from conventional experimental classes with uniform pacing and standardized content (Talafian et al., 2024).

2.2 Current Research Progress

2.2.1 Implementation of STEM Education in Secondary Schools

International research over the past two decades has identified and validated multiple STEM curriculum implementation models, including project-based learning (PBL), problem-based learning, challenge-based learning, and engineering design process (EDP)-oriented approaches. Meta-analyses consistently show that EDP-anchored integrated models produce the strongest learning outcomes in secondary school contexts, significantly improving students' problem-solving abilities, systems thinking, and cross-disciplinary knowledge integration skills compared to siloed subject instruction (Fan, 2023). Research also documents a range of non-academic benefits, including increased student motivation, improved collaborative skills, and more positive attitudes toward STEM careers. However, successful implementation is highly context-dependent, and models developed in Western educational settings do not always transfer effectively to other cultural and institutional contexts.

In East Asian educational systems specifically, researchers have documented unique structural tensions between traditional subject-based instruction and integrated STEM approaches. The dominant examination-oriented accountability culture means that curricular content not directly assessed on high-stakes exams is often deprioritized, compressing the time and resources available for cross-disciplinary practical activities. STEM programs are frequently marginalized as optional extra curriculars rather than core components of the curriculum, limiting their reach and sustainability (Yata et al., 2022; Zheng, 2026). Comparative studies of STEM reform across South Korea, Japan, Singapore, and China reveal a shared core challenge: how to align integrated STEM learning with national curriculum standards and high-stakes assessment systems without diluting either academic rigor or the integrative essence of STEM education (Kim & Lee, 2021; Saito, 2020). South Korea's approach has focused on embedding STEM outcomes into university comprehensive evaluation systems to incentivize school participation, while Japan has pursued a more incremental strategy of aligning

STEM activities with existing subject principles rather than introducing fully separate interdisciplinary programs. Both approaches offer partial solutions, but neither has fully resolved the fundamental tension between integration and accountability.

Most existing Chinese STEM studies focus on curriculum design for specific grade levels or evaluation of elite competition programs, with limited empirical research on inclusive, school-wide STEM implementation models that serve all students (Li & Wang, 2023). Recent systematic reviews of Chinese STEM education literature highlight a pronounced structural imbalance: approximately 70% of published studies focus on top-notch innovative talent cultivation and competition-oriented programs, while fewer than 15% examine universal access or inclusive STEM models for the general student population (Zhang & Wang, 2022). This research priority mirrors the practical distribution of resources in Chinese schools, where STEM funding and teacher time are overwhelmingly directed toward select student teams preparing for national and international competitions. The vast majority of students who do not participate in competition teams receive little to no structured STEM learning beyond standard science and math classes. Furthermore, existing discussions of how STEM education can integrate into existing teaching systems and balance examination requirements with literacy development remain largely at the conceptual and policy advocacy level, with very few in-depth case studies of mature, sustainable school-based practice models that have successfully navigated these tensions (Wang & Li, 2024). This gap in empirical evidence makes it difficult for school leaders and policymakers to draw on proven models when designing local STEM implementation strategies.

2.2.2 Open Laboratories in K-12 Education

The educational value of laboratories in science education has been established through decades of international research, with scholars consistently emphasizing that hands-on laboratory experiences are irreplaceable for developing deep scientific understanding. In their landmark 2004 review, Hofstein and Lunetta synthesized forty years of research on laboratory learning, concluding that well-designed laboratory experiences are essential for helping students construct conceptual scientific understanding, develop scientific process skills, and cultivate positive attitudes toward science as a discipline (Hofstein & Lunetta, 2004). Subsequent research has further refined this understanding, distinguishing between different types of laboratory instruction and their respective learning outcomes. Confirmatory "cookbook" labs, where students follow prescribed steps to arrive at a known outcome, have been found to develop basic operational skills but do little to foster inquiry skills or scientific reasoning. In contrast, open-ended and inquiry-based laboratories, where students have greater autonomy over questions, methods, and analysis, produce significantly stronger gains in critical thinking, experimental design ability, and scientific argumentation skills.

Research specifically focused on open-access laboratory models—where laboratories are available to students outside formal class time—has grown alongside the broader shift toward student-centered learning. Studies across primary, secondary, and tertiary settings consistently confirm that open laboratory models support deeper inquiry-based learning, improve students' scientific process skills, and foster more positive attitudes toward science and STEM careers (Talafian et al., 2024; Buggé, 2023). A 2007 study by Clark and Ernst examining open-ended science labs in middle schools found that open laboratory environments significantly enhanced students' sense of ownership over their learning and their interest in science, with particularly pronounced benefits for average-achieving students who often struggle in traditional lecture-based science classes (Clark & Ernst, 2007). Other research has documented additional benefits including improved time management skills, increased collaborative learning among peers, and greater student confidence in asking scientific questions.

Despite these documented benefits, researchers have also identified significant barriers to implementing open laboratory programs in secondary schools. The most frequently cited challenges include limited available time within packed school schedules, substantially increased workload for laboratory teachers and technicians, complex safety management requirements, and fundamental misalignment between open inquiry learning and formal assessment systems that prioritize factual recall (Cheung, 2007; Ramnarain, 2016). Research by Blanchard et al. (2010) further demonstrated that in high-accountability educational environments where standardized test scores dominate school priorities, open inquiry experiments are systematically deprioritized in favor of examination-oriented confirmatory experiments that more directly prepare students for test questions—a tension that researchers have noted is especially pronounced in East Asian educational contexts with exceptionally high-stakes examination systems (Blanchard et al., 2010).

The majority of existing open laboratory research focuses on higher education settings or single-discipline contexts such as high school physics. There remains a notable scarcity of research examining comprehensive, multi-tiered open laboratory systems that cover all secondary school grades and integrate multiple STEM disciplines. This gap is particularly acute in the Chinese context, where national policy has increasingly emphasized laboratory opening, but there is still limited systematic empirical research on how such programs are designed, implemented, and sustained in actual secondary schools (Jiang, 2023). Most existing Chinese studies on laboratory opening are descriptive policy advocacy pieces rather than rigorous empirical case studies, leaving many practical questions about implementation design and effectiveness unanswered.

2.2.3 STEM Education Localization in East Asian Contexts

As STEM education has expanded across East Asia, a growing body of research has examined localizatio n and adaptation issues. Japan's STEM reform emphasizes alignment with the disciplinary principles of the natio nal curriculum standard, avoiding wholesale adoption of Western interdisciplinary models (Yata et al., 2022). In South Korea, STEM education policy has focused on connecting STEM outcomes to university comprehensive evaluation systems to increase recognition among schools and parents (Kim & Lee, 2021). Related research in C hina also points out that localized STEM education must respond to examination demands, and STEM programs completely disconnected from academic assessment struggle to sustain operation in secondary schools (Zheng, 2026; Li, Zhang, & Liu, 2023).

However, existing research on this topic consists primarily of policy analysis and theoretical discussion, with a dearth of in-depth empirical studies of school-based localized STEM models. In particular, there is limite d practical evidence on how laboratory opening—an incremental reform pathway—can advance STEM educatio n without disrupting existing teaching systems.

2.3 Research Gap

Existing literature confirms the educational value of open laboratories and STEM education, but three ke y gaps remain:

2.3.1 Systemic gap:

Most K-12 open laboratory studies focus on single-subject or single-level experiments, lacking research on multi-tiered systems that integrate foundational consolidation, examination improvement, interest expansion, and literacy integration. There is insufficient discussion of how open laboratories can carry comprehensive STE M education objectives.

2.3.2 Equity gap:

Existing secondary STEM research largely focuses on elite competition programs. There is insufficient re search on how to achieve inclusive STEM education for all students in ordinary Chinese secondary schools whe re examination pressure remains a core constraint, and limited attention to participation differences among stude nts at varying academic levels.

2.3.3 Local empirical gap:

There is limited empirical case evidence of sustainable, school-based open laboratory STEM models adapt ed to the Chinese basic education context. In particular, mature practical cases that address the core contradictio n of balancing examination preparation and literacy development remain scarce.

2.4 Theoretical Foundations

This study builds on four complementary learning theories to construct a comprehensive analytical frame work for understanding open laboratory STEM education. Each theory illuminates a different dimension of the l earning process, and together they provide a robust theoretical lens for examining how the four-tier open laborat ory model supports student learning.

2.4.1 Inquiry-Based Learning Theory

Inquiry-based learning theory, formalized by the US National Research Council, posits that students cons truct deep scientific knowledge by engaging in processes analogous to authentic scientific research: asking scien tifically oriented questions, designing and conducting investigations, analyzing and interpreting data, constructin g evidence-based explanations, and communicating findings (National Research Council, 2000). Unlike traditio nal didactic instruction where knowledge is transmitted from teacher to student, inquiry-based learning positions students as active knowledge builders who develop conceptual understanding alongside scientific reasoning skil ls. The theory distinguishes between different levels of inquiry ranging from highly structured confirmatory inqu iry to fully open student-directed inquiry, with research showing that gradual progression across these levels pro duces the strongest learning outcomes.

Open laboratories provide the temporal flexibility and spatial autonomy necessary for students to lead the ir own inquiry processes, moving beyond the rigid step-by-step format of traditional experimental classes to mor e authentic scientific practice. The four-tier curriculum design of the case school directly reflects this progressio n: the basic consolidation tier corresponds to structured confirmatory inquiry where students follow established procedures to verify known principles, while the literacy integration tier corresponds to open inquiry where students independently define problems and design investigations. This gradient design allows students to build foundational skills before advancing to more autonomous inquiry, aligning with established best practices in inquiry-based learning pedagogy.

2.4.2 Learning by Doing Theory

Rooted in John Dewey's pragmatic educational philosophy, learning by doing theory emphasizes that concrete, hands-on practical experience is the foundation of deep learning and durable skill development. Dewey argued that education is not simply a process of transmitting static knowledge to passive recipients, but an active, experiential process where learners construct understanding through engagement with real-world problems and materials. This perspective is particularly relevant for STEM education, where technical skills, engineering intuition, and scientific reasoning cannot be developed through passive reading or listening alone—they require repeated, iterative hands-on practice.

STEM literacy, by definition, encompasses not just conceptual knowledge but also procedural skills, design capabilities, and practical problem-solving abilities, none of which can be fully developed through passive knowledge reception. Open laboratory practices provide sustained opportunities for students to build technological and engineering competencies through tangible, iterative hands-on work. The interest expansion and literacy integration tiers of the curriculum are explicitly designed around this principle, centering project-based activities where students learn by designing, building, testing, and revising physical artifacts and solutions rather than simply studying theoretical concepts.

2.4.3 Social Constructivist Theory

Lev Vygotsky's social constructivist theory emphasizes that all learning is fundamentally a social process, with cognitive development occurring through interaction with more knowledgeable others—including teachers, peers, and cultural tools (Vygotsky, 1978). A core concept in the theory is the zone of proximal development (ZPD), which refers to the gap between what a learner can accomplish independently and what they can accomplish with guidance. Effective pedagogy works within this zone, providing scaffolding that supports learners as they stretch beyond their current independent capabilities. Peer learning is also central to the theory, as collaboration with more capable peers can provide developmentally appropriate scaffolding that adult teachers sometimes cannot.

Multiple features of the open laboratory model embody social constructivist principles. The student-led "Q&A board" mutual assistance mechanism creates structured opportunities for peer teaching and learning, where more experienced senior students provide scaffolding to younger or less experienced peers. The group-based PBL projects in the literacy integration tier are designed around collaborative knowledge construction, with students working in teams to solve problems that no single student could tackle alone. Even the multi-subject evaluation system reflects social constructivist assumptions about learning, incorporating self-assessment and peer assessment alongside teacher evaluation to capture the social dimensions of learning progress.

2.4.4 Situated Learning Theory

Proposed by Lave and Wenger, situated learning theory argues that learning is not an abstract, decontextualized process that occurs only inside individual minds, but rather a situated process that happens through legitimate peripheral participation in authentic communities of practice (Lave & Wenger, 1991). The theory holds that knowledge is inherently embedded in specific contexts and situations, and that learning is most powerful when it occurs in authentic settings that mirror real-world practice. As learners move from peripheral participation to more central roles in a community, they develop both practical skills and identity as members of that community.

The open laboratory model incorporates several key features aligned with situated learning principles. The real problem-oriented PBL projects—with themes grounded in actual campus life issues such as air quality monitoring and classroom lighting improvement—provide authentic, meaningful learning contexts rather than artificial textbook problems. Students are not just solving hypothetical exercises; they are investigating real issues that affect their daily school environment, which increases motivation and supports transfer of learning. The public showcase events at the end of each project cycle also create a community of practice where students present their work to peers, teachers, and parents, participating in the kinds of knowledge sharing practices that characterize real scientific and engineering communities.

These four theories complement one another and collectively provide a multi-faceted analytical framework for the open laboratory STEM model: inquiry-based learning provides a cognitive process perspective on how students build scientific understanding, learning by doing emphasizes the central role of practical operation in developing STEM competencies, social constructivism focuses on the social interaction and scaffolding mecha nisms that support learning, and situated learning highlights the importance of authentic contexts and communit y participation for meaningful learning.

3. Research Methodology

3.1 Research Design

This study employs a single qualitative case study approach, which is appropriate for exploring complex, context-dependent educational practices in their real-world settings. A case study design allows for holistic exa mination of the complete open laboratory STEM system, including its structure, implementation processes, and contextual adaptations, making it well-suited to answer "how" and "why" research questions aligned with this st udy's goal of exploring school-based practice models. A single-case design was selected because this case repres ents a critical, information-rich example of mature open laboratory STEM education at a science-focused second ary school, capable of providing rich insights and in-depth understanding.

3.2 Case Selection

The case selected for this study is a science-focused secondary school in Sichuan Province, China. The sc hool was selected for two key reasons:

3.2.1 Typicality:

It is a public complete secondary school serving both junior and senior high students, with a student popu lation size and enrollment structure representative of ordinary urban secondary schools in provincial capital citie s across China. It does not possess exceptional or rare resources, lending a degree of generalizability to the study 's findings.

3.2.2 Representativeness:

Its open laboratory system has been operating stably for over three years, with a complete curriculum sys tem, mature management mechanisms, and provincially recognized educational outcomes. It is a representative example of school-based STEM implementation in Sichuan Province, offering information richness and practica l maturity that make it suitable for in-depth case study.

3.3 Data Sources

To ensure triangulation and improve research validity, this study draws on three complementary sources of data, cross-validating findings across multiple dimensions:

3.3.1 Document materials:

Including the school's open laboratory curriculum plan, management regulations, policy documents, activ ity records, student achievement reports, and official achievement announcements, totaling 27 documents. Docu mentary materials provide the overall design framework and official records of the program, serving as the foun dational data for mapping the practice system.

3.3.2 Operational data:

Aggregated statistical data on student participation, experimental project reservations, activity frequency, a nd evaluation results from the 2023–2024, 2024–2025, and 2025–2026 academic years. Operational data provid e quantitative participation metrics and trends, used to analyze program coverage and developmental trajectories.

3.3.3 Classroom observations:

On-site observation of 8 open laboratory sessions spanning all four experimental tiers: two sessions at the basic tier, two at the competency improvement tier, two at the interest expansion tier, and two at the literacy inte gration tier. Each observation lasted 60–90 minutes, focusing on student engagement patterns, teacher guidance strategies, experimental completion rates, and peer interaction dynamics. Semi-structured field notes were recor ded in real time and cross-checked with activity logs after each session. Classroom observations provide first-ha nd qualitative data on implementation processes, complementing the process-level information that documents a nd aggregate statistics cannot capture.

These three data sources complement and cross-validate one another, ensuring the credibility and compre hensiveness of the research findings.

3.4 Data Analysis

Thematic coding was used to analyze qualitative data from observations and documents, following the pr ocedural grounded theory approach outlined by Strauss and Corbin and organized into three phases:

3.4.1 Open coding:

All documents and observation notes were read line-by-line to mark initial concepts related to operational mechanisms, curriculum content, supporting systems, and educational effects, generating 42 initial concepts in total.

3.4.2 Axial coding:

Initial concepts were categorized and linked to extract five core categories—operational mechanism, curriculum system, supporting systems, educational effects, and localized characteristics—along with 16 corresponding subcategories, forming the analytical framework presented in the findings section.

3.4.3 Selective coding:

Logical chains were constructed around core categories to build a complete narrative from practice system to effect characteristics, forming the final research conclusions.

Quantitative operational data were analyzed using descriptive statistics, calculating indicators such as participation volume, growth rates, and coverage proportions to supplement qualitative findings and achieve mixed-methods analysis of quantitative and qualitative data.

To enhance coding reliability, the coding process was completed independently by two researchers, with an inter-coder agreement of 87%. Discrepancies were resolved through discussion to minimize subjective bias from any single researcher.

3.5 Validity and Reliability Strategies

Qualitative case study research requires deliberate strategies to ensure the trustworthiness of findings, addressing concerns about credibility, transferability, dependability, and confirmability. This study employed four key strategies to enhance the validity and reliability of the research:

First, **data triangulation** was achieved by drawing on three complementary data sources—document materials, operational statistics, and classroom observations—that captured the open laboratory system from different perspectives. Document materials provided official accounts of program design and formal policies, operational data offered quantitative evidence of participation patterns and trends, and classroom observations provided first-hand insights into actual implementation processes and student experiences. Cross-verifying findings across these three independent sources reduced the risk of bias from any single data source and strengthened the credibility of the conclusions.

Second, **inter-coder reliability** was established through dual independent coding of all qualitative data. Two researchers separately conducted open coding and axial coding of the document and observation data, achieving an inter-coder agreement rate of 87%. All coding discrepancies were resolved through structured discussion until consensus was reached. This process minimized the influence of any single researcher's subjective interpretations and enhanced the dependability of the analytical findings.

Third, **thick description** was employed throughout the findings section, providing detailed contextual information about the school setting, the program's operational mechanisms, and the specific content of each curriculum tier. Extensive descriptive detail allows readers to assess the transferability of findings to their own contexts, determining the extent to which the model might be applicable to other school settings with similar characteristics.

Fourth, **member checking** was conducted at the document verification stage, where preliminary findings about program structure and operational processes were cross-referenced against official school documents to ensure factual accuracy. While formal member checking with all stakeholders was not feasible due to research access constraints, systematic cross-referencing with multiple official documents served as an alternative validity check to confirm that the study's descriptions aligned with the school's actual practices.

4. Implementation of the Open Laboratory STEM Model

4.1 Scheduled Open Operation Mechanism

The core of the school's open laboratory system is its student-centered scheduled management model, designed to break the time constraints of traditional experimental classes and form a complete closed-loop operational workflow: appointment → review → preparation → implementation → feedback.

4.1.1 Full-Period Coverage Schedule

Laboratories are open during after-school service hours on school days (16:30–18:00 daily), weekend mornings (9:00–11:30), and half-days on holidays, totaling over 15 hours of opening time per week. This flexible schedule allows students to choose time slots aligned with their own academic arrangements, avoiding conflicts b etween unified scheduling and academic tutoring—a key factor underlying the program's consistently high participation rates.

4.1.2 Refined Appointment Management Process

Students can independently or in small groups reserve experimental projects through an online appointment system 1–3 days in advance. The online platform allows students to browse a catalog of experimental projects categorized by difficulty level, view available slots for each time period, and register individually or in groups of 2–4 people. The full-time coordinator reviews all applications one day in advance, coordinates arrangements based on experimental difficulty and equipment availability, prepares corresponding instruments and reagents, and sends confirmation notifications to participants containing experimental guidelines and preparation instructions.

The school implements a three-tier "1+4+N" management structure:

(a) 1 full-time laboratory coordinator responsible for overall operational scheduling, appointment review, and safety management;
(b) 4 subject-specific experimental teachers (physics, chemistry, biology, technology) responsible for experimental guidance and curriculum design in their respective disciplines;
(c) Rotating student assistants selected from senior students with extensive laboratory experience to support daily operations.

This structure ensures coverage of professional guidance while reducing teacher workload through student assistants, supporting the sustainability of extended opening hours.

4.1.3 Multi-Level Safety and Mutual Support System

Safety is the bottom line for open laboratory operation, and the school has constructed a four-tier safety protection system spanning access, pre-session, in-process, and emergency response:

(a) Access tier: First-time participants must pass a pre-access safety quiz covering laboratory rules, hazard identification, and emergency procedures, earning a perfect score before gaining reservation eligibility.
(b) Pre-session tier: Before each session, the on-duty teacher delivers a 5-minute safety briefing tailored to the specific experiment, clarifying risk points and precautions.
(c) In-process tier: Teachers and student assistants conduct ongoing patrols during experiments to promptly correct non-standard operations.
(d) Emergency tier: Laboratories are fully equipped with first-aid kits, eyewash stations, and fire safety equipment, with clear evacuation routes posted and comprehensive emergency response plans in place.

A student-led "Q&A board" mutual assistance mechanism is also in place, where senior students with rich laboratory experience serve as student assistants responsible for equipment maintenance, order management, and answering basic operational questions. This mechanism not only reduces teachers' guidance pressure but also provides leadership development opportunities for senior students. Junior students are often more willing to ask questions of peer mentors, fostering a strong collaborative learning culture.

4.2 Four-Tier Progressive STEM Experimental Curriculum

The school has developed a four-tier progressive experimental content system covering all secondary school grades, corresponding to different dimensions of STEM literacy from foundational to advanced levels, forming a complete progression pathway: "consolidate foundations → align with examinations → stimulate interest → integrate literacies."

Tier 1: Basic Consolidation Experiments

This tier covers all 36 required curriculum-standard confirmatory experiments across physics, chemistry, and biology, including classic activities such as Ohm's law verification, acid-base titration, and microscopic cell observation. Its core positioning is to complement classroom instruction, providing repeat practice opportunities for students who struggle with in-class experimental content, with subject teachers offering step-by-step guidance tailored to students' weak points.

This tier corresponds to the Science (S) and Mathematics (M) dimensions of STEM education, serving as the foundation for all higher-level inquiry. Unlike classroom experiments, students can independently select weak items for repeated practice, controlling their own pace entirely and avoiding the common classroom problem where "strong students are under-challenged while weak students fall behind." Operational data show that the basic tier has the most stable reservation volume across all tiers, accounting for approximately 35% of total reserva tions, and serves as the core carrier of the open laboratory's inclusive mission.

Tier 2: Competency Improvement Experiments

Targeted at the latest middle and high school entrance examination syllabi, this tier focuses on 18 high-frequency experimental test points, including mechanical efficiency measurement, gas preparation and collection, and biological experiment design. Training content emphasizes standardized operation procedures and error analysis, complemented by test point explanations and real exam practice, to standardize students' operational skills and reinforce core experimental knowledge, directly aligning with academic assessment needs.

This tier is the core of the model's localized adaptation design, responding to the practical realities of Chinese secondary education and ensuring the open laboratory program aligns rather than conflicts with core academic goals. Integrating examination training into the open laboratory system both addresses students' practical academic needs and increases the program's appeal to schools, parents, and students—making it a critical pillar of the program's sustainable operation. This tier accounts for approximately 30% of total reservations, with reservation volumes rising significantly during mid-term and final exam seasons.

Tier 3: Interest Expansion Experiments

This tier focuses on technological and engineering experience, featuring over 25 low-threshold, engaging projects: fun science experiments, 3D printing of campus architectural models, basic drone flight and aerial mapping, simple circuit design, and robotic arm assembly. Most projects require only 1–2 sessions to complete, making them accessible for students with no prior STEM experience. The tier is designed to stimulate students' interest in science and technology, providing initial exposure to Technology (T) and Engineering (E) dimensions of STEM.

These low-barrier, highly engaging projects are particularly popular among junior high students, with over 70% of seventh and eighth graders participating at least once per semester, serving as a critical entry point for STEM interest development. Many students first build confidence in science through interest-tier projects and then progress to higher-level tiers, forming a developmental pathway from initial interest to deep learning. This tier accounts for approximately 20% of total reservations and draws the youngest participant profile of all four tiers.

Tier 4: Literacy Integration Projects

The highest tier consists of cross-disciplinary project-based learning (PBL) projects centered on real-world problems, typically running for 8–12 weeks. Students work in self-selected teams of 3–5 and are guided by multi-subject teacher groups. Representative projects include:

Campus air quality monitoring: Combining environmental science, data analysis, and engineering design, students independently design monitoring plans, collect data from different areas of the campus, analyze pollution sources, and propose improvement recommendations.

Intelligent classroom lighting system design: Integrating physics circuits, programming control, and ergonomics, students design intelligent adjustment solutions to address classroom lighting issues.

Crystal cultivation research: Involving chemistry crystallization principles, mathematical modeling, and scientific presentation, students explore the effects of different conditions on crystal growth and complete formal research reports.

Students complete the full cycle of scientific inquiry throughout each project: problem identification, scheme design, hands-on implementation, data analysis, and result presentation, integrating knowledge and skills across all four STEM disciplines. These projects cultivate comprehensive STEM literacy including critical thinking, collaborative problem-solving, and engineering design capabilities. Each project concludes with a public showcase where teams present their findings and receive feedback from teachers, peers, and parents. Outstanding projects are recommended for participation in science and technology innovation competitions at various levels. This tier accounts for approximately 15% of total reservations but delivers the deepest student engagement and learning gains, serving as the core output carrier of the school's STEM education outcomes.

4.3 Supporting Systems

4.3.1 Preparatory Science Introductory Courses

For seventh and eighth grade students who have not yet received formal physics and chemistry instruction, the school offers 8-week preparatory science courses before they formally participate in open laboratory activities. Each 45-minute weekly session focuses on everyday science phenomena and hands-on mini-experiments, s uch as building simple batteries, observing plant growth, and constructing simple structures.

These courses reduce the learning threshold for younger students, eliminate anxiety about science experiments, and require no prior knowledge, laying a foundation for subsequent deep participation. Courses are open to all interested students on a voluntary basis, and enrollment consistently exceeds planned capacity, reflecting young students' strong interest in hands-on science. The preparatory introductory courses connect seamlessly with the interest expansion tier, forming a complete STEM interest cultivation chain for the junior high school years.

4.3.2 Multi-Dimensional Evaluation System

The school adopts a "three-dimension, four-element" evaluation system using a weighted scoring model to comprehensively assess students' laboratory learning:

(a) Three evaluation dimensions:

Knowledge mastery (30%): Assessed via experimental quizzes and operation checks, measuring students' grasp of basic experimental knowledge and skills.

Inquiry process performance (40%): Evaluated on participation, problem-solving ability, collaborative performance, and creative thinking.

Comprehensive literacy development (30%): Assessed based on final project outcomes and presentation performance.

(b) Four evaluation subjects:

Teacher evaluation, student self-assessment, peer assessment, and project outcome evaluation.

Evaluation results are included in students' comprehensive quality assessment files, providing a complete record of students' STEM development trajectories. This multi-faceted evaluation approach moves beyond single-score assessment, aligning with the developmental goals of STEM education, more comprehensively reflecting students' practical abilities and literacy growth, and providing students with multi-dimensional feedback on their progress.

(c) Collaborative Teacher Support

A multi-disciplinary teaching team consisting of full-time laboratory teachers and subject teachers from physics, chemistry, biology, and information technology provides tiered guidance. Subject teachers focus on knowledge and skill guidance for basic and exam-oriented tiers, while specialized technology instructors support innovative project tiers.

Two supporting mechanisms are in place to ensure the quality of teacher guidance:

Monthly joint teaching research mechanism: The team holds monthly joint planning meetings to co-design integrated experimental projects, align tiered content with curriculum progress, and address operational challenges, breaking down disciplinary silos and improving the quality of cross-disciplinary project design.

Regular professional development: Teachers participate in ongoing professional training on topics including inquiry-based teaching, STEM integration strategies, and laboratory safety management, continuously updating their educational philosophies and guidance capabilities. Each relevant teacher completes no fewer than 20 hours of professional development training annually.

The cross-disciplinary teaching team and accompanying professional growth mechanisms are the core human resource guarantee for the high-quality implementation of the four-tier curriculum system.

5. Effects and Localized Characteristics of the Model

5.1 Practical Educational Effects

5.1.1 Broad Participation and Inclusive Coverage

Operational data shows a steady increase in open laboratory participation over three academic years, growing from approximately 800 participations per semester in the first year to over 1,500 per semester in the third year, with over 60% of students participating at least once per semester. Notably, participation is evenly distributed across different academic performance levels, with no significant gap between high-achieving and average-performing students. Even lower-achieving students participate at proportionally higher rates in the interest expansion tier.

Unlike elite STEM competition programs that only serve a small number of top students, this open laboratory system covers students across all grade levels and academic performance levels, with no selection threshold required for participation in basic-tier projects, achieving school-wide inclusive STEM education. This characteristic distinguishes the model from the approach adopted by most Chinese secondary schools, which concentrate STEM resources on building competition teams, and truly embodies the educational philosophy of science and t echnology for all students.

5.1.2 Improved STEM Literacy and Enhanced Learning Interest

Observation and document data indicate that long-term participation in open laboratory activities has improved students' experimental operation skills, scientific inquiry ability, and interest in STEM disciplines. Internal school assessment data shows that students who regularly participate in open laboratory activities perform better in science practical skill tests, with significantly stronger abilities in experimental design and error analysis compared to non-participating peers.

Junior high students who participated in preparatory courses showed significantly less anxiety about physics and chemistry learning, and the proportion of students choosing science-track electives has increased by approximately 15% since the program launched, reflecting growing interest in STEM subjects. For senior high students, open inquiry projects deepened their understanding of scientific research processes and enhanced their problem-solving and teamwork abilities. Many students who participated in PBL projects reported developing clearer interest in pursuing STEM majors at university.

5.1.3 Recognized Educational Outcomes

The school's open laboratory STEM practice has received official recognition at the provincial level, and has been named a Sichuan Provincial Demonstration Project for Experimental Teaching in Primary and Secondary Schools. Student projects developed in the open laboratory have won multiple awards in provincial youth science and technology competitions, with cumulative totals of over 10 provincial-level awards and over 30 municipal-level awards. The model has also been cited as a representative case of school-based science education in Sichuan Province, shared at regional teaching research events and exerting a degree of radiation and demonstration effect.

5.2 Localized Practical Characteristics

5.2.1 Inclusivity for All Students

Unlike many Chinese secondary schools that concentrate STEM resources on elite competition teams, this model adopts a tiered design that meets the needs of students with different foundations and interests. Basic tiers serve all students, while advanced tiers provide growth paths for students with strong interest in science and technology. No selection threshold is required for participation in basic-tier projects, ensuring STEM education benefits the entire student body rather than a small minority.

This inclusive characteristic aligns with the educational goal of universal access in Chinese basic education, and also conforms to the "universal participation and inclusive sharing" orientation of national science and technology education policy. Unlike the socioeconomic stratification often observed in Western STEM education, this model lowers the barriers to STEM participation through low-threshold basic and interest tiers, providing equal practical opportunities for students from different family backgrounds and academic levels, embodying the value orientation of educational equity.

5.2.2 Adaptation to Local Academic Contexts

A core feature of this model is its balance of academic examination needs and competency cultivation. By including exam-oriented experimental training as a core tier, the open laboratory program aligns with the core academic priorities of Chinese secondary schools, solving the common problem that STEM education is seen as "extracurricular" and disconnected from academic goals (Zheng, 2026). This design makes the program more sustainable and easier to promote in similar school contexts.

STEM education across East Asian countries generally faces constraints from examination pressure, and practices in both Japan and South Korea have explored pathways for aligning STEM with academic evaluation system (Yata et al., 2022; Kim & Lee, 2021). This model offers an incremental solution: rather than altering the main structure of existing teaching systems, it integrates examination training and literacy cultivation within the same space through after-school opening. This approach both meets academic needs and expands literacy development space, representing a highly context-appropriate localized innovation for Chinese secondary schools.

6. Discussion

6.1 Alignment with Existing Research

The findings of this study confirm and extend previous international research on the educational value of open-ended laboratories in K-12 settings. Consistent with prior studies, the case demonstrates that well-structured open laboratory environments can effectively support inquiry-based STEM learning, improve student engagement, and develop practical scientific abilities (Talafian et al., 2024; Buggé, 2023). However, this study goes be yond simply confirming established findings by presenting a comprehensive four-tier curricular system that integrates basic consolidation, exam preparation, interest expansion, and literacy integration within a single open laboratory program. This multi-layered design addresses a notable gap in existing research, where most documented open laboratory programs focus on a single type or level of experimental activity, and enriches the literature on curriculum models for K-12 open laboratories. The study's finding of broad participation across all academic ability levels also echoes Clark and Ernst's (2007) earlier finding that open laboratory environments produce particularly pronounced benefits for average-achieving middle school students [27], further supporting the argument that tiered, accessible open laboratory designs can reach a broader and more diverse student population than traditional selective science programs.

Furthermore, this study makes a meaningful contribution to the growing body of research on STEM education localization in East Asian contexts, a theme that has gained increasing scholarly attention in recent years (Yata et al., 2022; Li, Zhang, & Liu, 2023). The case school's model—deliberately balancing examination-oriented experimental training with open-ended competency development—provides concrete empirical evidence for how STEM education can take root and thrive in examination-oriented education systems without requiring complete subversion of existing teaching structures. This finding complements existing research on STEM localization from South Korea and Japan (Kim & Lee, 2021; Saito, 2024), where scholars have similarly explored strategies for aligning STEM education with national curricula and assessment systems. Taken together, these studies suggest that "aligning with academic assessment systems and advancing through incremental reform" may be a broadly viable pathway for STEM education implementation across East Asian contexts, rather than the wholesale adoption of Western interdisciplinary models that often struggle to gain traction in high-stakes examination environments. This study thus expands the theoretical perspective on localized STEM education by adding detailed empirical evidence from the Chinese context.

Meanwhile, the study's findings on broad, inclusive participation also contribute to ongoing scholarly discussions about equity in Chinese STEM education (Jiang, 2023; Zhang & Wang, 2022). Previous research has consistently documented a strong elite-oriented tendency in Chinese STEM education, with the majority of resources and attention directed toward select competition teams and high-achieving students. This case study demonstrates that, through deliberate tiered curriculum design and low-threshold open access mechanisms, secondary schools can fully achieve inclusive STEM education that serves all students rather than only a privileged minority. The model documented here thus provides a practical counterexample and potential solution to addressing the well-documented Matthew effect in Chinese STEM education resource distribution.

6.2 Theoretical Implications

This study also carries several important theoretical implications for understanding how open laboratories support STEM learning. First, the four-tier curriculum structure empirically validates the developmental progression from structured confirmatory inquiry to open student-directed inquiry that is central to inquiry-based learning theory (National Research Council, 2000). The case demonstrates that this gradual progression is not just a theoretical ideal but a practically implementable design in real secondary school settings, and that building from foundational skills to open inquiry supports broader student participation than starting with fully open inquiry. This finding has implications for how inquiry-based learning pedagogy should be sequenced in resource-constrained educational contexts.

Second, the model's success provides empirical support for the argument that STEM education does not need to be positioned as an alternative to or replacement for existing academic instruction. Instead, it can be productively integrated as a complementary extension that serves multiple purposes simultaneously. This challenges the common binary framing of "examination versus competency" that dominates much discussion of Chinese education reform, suggesting instead that well-designed programs can serve both goals within a single institutional structure. This perspective aligns with broader theoretical discussions of curriculum adaptation in high-accountability educational systems.

Third, the student assistant mutual assistance mechanism documented in this case illustrates how peer learning structures can effectively extend the capacity of laboratory programs without requiring proportional increases in teacher staffing. This finding connects social constructivist theories of peer scaffolding (Vygotsky, 1978) to practical institutional design, showing how structured peer leadership roles can both support younger learners and provide valuable developmental opportunities for the older students serving as mentors.

6.3 Practical Implications for Secondary STEM Education

The findings of this study yield four concrete practical implications for schools and education policymakers seeking to advance STEM education in Chinese secondary schools:

First, open laboratories represent a particularly low-threshold pathway for secondary schools to advance STEM education. Rather than undertaking the difficult work of building entirely new STEM curricula that confl ict with existing subject-based teaching systems, schools can leverage their existing laboratory infrastructure and simply extend opening hours to implement incremental STEM education reform. This model requires no large-scale teacher restructuring or comprehensive curriculum redesign, imposes minimal disruption to existing teaching systems, and is therefore much more easily implemented and scaled in ordinary secondary schools. For schools with limited initial resources, a phased implementation strategy starting with just the basic consolidation and interest expansion tiers, with gradual addition of higher tiers as capacity develops, can substantially reduce the difficulty and risk of reform.

Second, tiered curriculum design is the key mechanism for achieving genuinely inclusive STEM education. Differentiated content at multiple difficulty levels can meet the diverse needs of students at different learning levels and with different interest orientations, ensuring that STEM education is accessible and meaningful for all students rather than being limited to elite groups who can already engage with advanced material. The specific gradient design observed in this case—where the basic tier aligns with academic needs, the interest tier sparks initial motivation for younger or less confident students, and advanced tiers support deep development for highly interested students—both guarantees broad population coverage and accommodates talent cultivation for advanced learners, achieving a productive balance between universal popularization and excellence development.

Third, deliberate alignment with existing academic assessment systems is critical for the long-term sustainability of STEM programs in Chinese secondary schools. Incorporating grade-relevant academic skill training into STEM practice can substantially reduce resistance from school administrators, teachers, and parents, creating a much more supportive institutional environment for implementation. In educational contexts where examination pressure remains a core structural constraint, STEM programs that are completely disconnected from academic priorities often struggle to secure sufficient resource support and struggle to attract sustained student participation. Framing academic skill development as an integral component of the STEM system, rather than treating it as an opposing force, is a key design insight for building sustainable localized STEM models.

Fourth, robust safety management systems and structured student mutual assistance mechanisms are important practical guarantees for extended laboratory opening. Safety concerns and risk management have long been major factors constraining schools from opening laboratories more broadly (Cheung, 2007). The four-tier safety system and student assistant model documented in this case provide a replicable institutional solution to this practical challenge, simultaneously safeguarding the non-negotiable safety bottom line and improving overall operational efficiency through distributed responsibility.

7. Conclusion and Future Research

7.1 Main Conclusions

This study systematically examines the structure, implementation, and effects of an open laboratory STEM education model at a science-focused secondary school in Sichuan Province, China, drawing on three years of operational data, documentary evidence, and classroom observations. The analysis leads to three core conclusions that contribute to both theoretical understanding and practical guidance for secondary STEM education in Chinese contexts.

First, a well-designed scheduled open laboratory represents an effective and sustainable platform for delivering regularized, school-based STEM education in secondary school settings. By implementing a structured appointment management system, a comprehensive four-level safety protocol, and a student-led mutual assistance mechanism, the model successfully breaks through the temporal and pedagogical limitations of traditional fixed-schedule experimental classes. Crucially, this approach enables STEM education to operate as a regular, integrated component of school life without requiring disruptive changes to existing teaching systems or curricular structures. The after-school delivery model means that STEM practice complements rather than competes with core academic instruction, addressing one of the most persistent barriers to STEM implementation in examination-oriented educational systems.

Second, the four-tier progressive curriculum structure, when paired with preparatory foundational courses and a multi-dimensional evaluation support system, achieves two important goals simultaneously: broad inclusive coverage across the entire student population and thoughtful localized adaptation to China's specific academic context. The tiered design ensures that STEM education is genuinely accessible to all students, regardless of their prior academic achievement or science background, while the deliberate integration of examination-aligned training content enhances the model's institutional sustainability and stakeholder buy-in. This combination of universal access and contextual adaptation makes the model a particularly well-suited localized STEM practice solution for Chinese secondary schools operating within high-accountability educational environments. Unlike elite competition-focused STEM programs that serve only a small minority, this model delivers meaningful STEM learning experiences to the majority of students while still providing advanced pathways for highly interested and capable learners.

Third, this incremental, balanced approach to STEM implementation provides a valuable and replicable reference framework for other Chinese secondary schools seeking to advance STEM education within their existing institutional frameworks. A key conceptual contribution of the study is its demonstration that inclusive STEM education and academic examination requirements are not inherently contradictory or mutually exclusive. Through careful system design that positions academic skill development as an integrated component rather than an external constraint, schools can achieve coordinated development of both competency-based STEM literacy and examination performance. This finding challenges the common zero-sum framing of STEM versus academics in Chinese education discourse and offers a pragmatic middle path that can be adapted to a wide range of school contexts with varying resource levels.

7.2 Future Research Directions

Building on the findings of this case study, future research on open laboratory STEM education in China can productively expand in four promising directions:

First, researchers should conduct multi-case comparative studies across different types of schools to examine how the model translates across varied contexts. Systematic comparisons between urban and county schools, between resource-rich and resource-constrained schools, and between science-focused and general comprehensive schools would help verify the generalizability of the findings and identify context-specific adaptation strategies. Such research would also contribute to building a richer typology of localized STEM implementation models in China, moving beyond single-case descriptions toward more generalizable theory about what works, for whom, and under what conditions.

Second, the development and validation of standardized secondary school STEM literacy assessment tools would enable more rigorous evaluation of program effects. Longitudinal quantitative tracking using validated instruments, combined with quasi-experimental study designs including matched comparison groups, would allow researchers to more confidently estimate the causal impact of open laboratory participation on students' STEM literacy development, academic achievement trajectories, and long-term interest in STEM fields. More robust evidence on effectiveness would strengthen the case for broader policy support and school adoption of these models.

Third, exploring digital and smart technology upgrades for open laboratories represents an important direction for both research and practice. The integration of virtual simulation experiments to expand the range of feasible projects, digital appointment management systems to improve operational efficiency, and AI-assisted guidance tools to extend teacher capacity could all significantly enhance the quality and reach of open laboratory STEM programs. Research on how best to design and implement these technological enhancements, and what effects they have on student learning outcomes, would help guide future program development.

Fourth, research adopting a home-school collaboration perspective would deepen understanding of the broader ecosystem factors shaping student participation. Investigating how parental perceptions of STEM education, family educational capital, and home support for science learning influence students' likelihood of participating in and benefiting from open laboratory programs would provide important insights for improving program access and effectiveness. Building evidence-based home-school collaborative STEM education strategies could further expand participation rates and enhance the educational impact of these programs, particularly for students from families with less exposure to STEM learning opportunities.

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