A Practice-Oriented Study on Innovative Design of Biology Experiments for Teacher Education Programs

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Abstract: Biology experiments play a central role in teacher education programs by supporting the integration of scientific knowledge and instructional practice. However, experimental activities in many pre-service teacher programs remain largely procedure-driven, with limited attention to instructional design and classroom implementation. This study adopts a practice-oriented perspective to examine how innovative design of biology experiments can better support the professional development of future biology teachers. Focusing on experimental activities embedded in teacher education courses, the study analyzes the alignment between experimental design, teaching objectives, and reflective practice. Drawing on classroom observations, experimental design tasks, and reflective records, the study identifies key limitations in conventional experiment-based training, including insufficient emphasis on pedagogical intent and limited opportunities for reflective engagement. In response, a set of practice-oriented strategies is proposed, emphasizing instructional relevance, contextualized implementation, and structured reflection. The findings suggest that innovative experiment design, when framed as a pedagogical practice rather than a purely technical activity, can effectively enhance pre-service teachers' capacity to plan, conduct, and evaluate experimental teaching. The study contributes to ongoing discussions on biology teacher education by highlighting the role of experimental design as a bridge between disciplinary learning and instructional competence.

Keywords: Biology experiment design; Teacher education; Practice-oriented learning; Experimental teaching competence; Reflective practice

DOI: 10.62639/ssperi01.20260201

1. Introduction

Experimental activities have long been regarded as a foundational component of biology education. Within teacher education programs, experiments are commonly expected to serve a dual function: supporting disciplinary understanding and preparing future teachers for classroom instruction. In practice, however, these two functions are not always equally addressed. Experimental training for pre-service biology teachers often prioritizes technical accuracy and procedural completion, while the instructional implications of experimental activities receive comparatively limited attention.

As a result, many pre-service teachers demonstrate adequate experimental operation skills but encounter difficulties when required to adapt experiments for classroom teaching. Challenges such as clarifying instructional objectives, anticipating student responses, and managing experimental processes in real teaching contexts are frequently observed. This gap suggests that conventional approaches to biology experiments in teacher education may not fully support the transition from learner to teacher.

Against this background, there is a growing need to reconsider how biology experiments are designed and

(Manuscript NO.: ERI-26-1-68001)

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implemented within teacher education programs. Rather than treating experiments solely as tools for content learning, a practice-oriented perspective emphasizes their role in fostering instructional competence through design, enactment, and reflection. This study explores how innovative design of biology experiments, grounded in teaching practice, can contribute to the professional development of pre-service biology teachers. By examining experimental activities within teacher education contexts, the study aims to clarify key challenges and propose strategies that better align experimental training with future teaching demands.

2. Overview of Innovative Biology Experiment Design in Teacher Education

Innovative biology experiment design in teacher education reflects a fundamental reorientation of how experimental activities are positioned within teacher preparation. Rather than being defined by sophisticated instruments or technically complex procedures, innovation in this context emphasizes a pedagogical shift in which experiments function as flexible instructional resources. Under this orientation, experimental design is embedded within teaching practice and treated as an integral component of instructional decision-making, rather than as a subsidiary technical exercise. This reconceptualization challenges the conventional separation between experimental activity and instructional planning by positioning experiments at the center of learning design.

(1) Repositioning experiments as instructional resources

At the core of innovative biology experiment design is the repositioning of experiments from fixed demonstrations to adaptable instructional tools. In traditional laboratory-based instruction, experiments are often organized as standardized procedures aimed at confirming established biological principles. While such approaches support disciplinary understanding, they tend to isolate experimental activity from broader teaching considerations.

In contrast, innovative experiment design situates experiments within instructional frameworks. Experimental activities are conceived as resources that can be adjusted, reorganized, or simplified to support different learning objectives. This shift foregrounds the instructional value of experiments and emphasizes their role in shaping learning experiences. As a result, experimental design becomes a component of teaching practice rather than a purely technical task, encouraging pre-service teachers to consider how experiments structure explanation, inquiry, and interaction in the classroom.

(2) Emphasizing instructional intent in experimental design

From a practice-oriented perspective, innovative experiment design emphasizes the functional relationship between experimental activity and instructional intent. Experimental tasks are no longer planned solely to verify biological knowledge, but to support specific teaching purposes, such as conceptual clarification, inquiry development, or classroom dialogue. This requires pre-service teachers to approach experiments as pedagogical constructs rather than procedural routines.

Within this framework, pre-service teachers are expected to engage in instructional reasoning during experimental planning. Decisions regarding materials, procedures, and sequencing are guided by anticipated learning processes rather than by fixed laboratory protocols. Such engagement shifts attention from experimental completion toward purposeful teaching design. Over time, pre-service teachers learn to evaluate experimental effectiveness in relation to instructional outcomes, strengthening their capacity to design experiments that align with teaching goals.

(3) Integrating reflection as a continuous design process

A further defining characteristic of innovative biology experiment design lies in the systematic integration of reflection across the experimental process. Reflection functions as a mediating mechanism that connects experimental experience with professional learning. Rather than being confined to retrospective summaries of results, reflective activity is distributed across planning, enactment, and review.

During the planning stage, reflection supports the examination of instructional intent and design rationale, encouraging pre-service teachers to anticipate learning difficulties and instructional constraints. During implementation, reflective awareness enables responsive adjustment to emerging classroom dynamics, such as student misunderstanding or procedural challenges. Following experimentation, reflection facilitates analysis of instructional effectiveness, focusing on how experimental design influenced student engagement and conceptual development. This continuous reflective structure contributes to the development of pedagogical judgment and reinforces professional awareness.

Importantly, reflective engagement is not limited to individual introspection. Structured prompts, guided discussion, and peer interaction often support reflection, helping pre-service teachers articulate and refine their instructional thinking. Through repeated cycles of design, implementation, and reflection, experimental activities become iterative learning experiences that foster sustained professional growth rather than isolated training tasks.

(4) Enhancing authenticity through teaching-oriented contexts

Innovative experiment design also emphasizes authenticity within teacher education programs by situating experimental activities in teaching-oriented contexts. These contexts may include micro-teaching sessions, simulated classroom environments, or peer-instruction scenarios in which experiments are implemented as part of a teaching sequence. Such arrangements require pre-service teachers to consider instructional constraints that are often absent from traditional laboratory settings, including time allocation, clarity of explanation, and student participation.

Authentic contexts support the integration of experimental design with broader instructional responsibilities. Pre-service teachers must coordinate experimental activities with lesson objectives, classroom interaction, and assessment considerations. This coordination highlights the complexity of experimental teaching and underscores the need for flexible design strategies. By engaging with experiments in realistic instructional situations, pre-service teachers develop a more nuanced understanding of how experimental activities function within classroom practice.

Approaching experiments from the perspective of future teachers rather than learners alone enables clearer connections between disciplinary knowledge and instructional practice. Experiments are experienced not merely as learning activities, but as teaching tools that require adaptation to diverse classroom conditions. This perspective enhances the relevance of experimental learning to prospective teaching roles and supports the integration of biological knowledge with pedagogical competence.

3. Problems in Current Biology Experiment Design for Teacher Education

Despite the widely acknowledged importance of experimental activities in biology teacher education, a range of structural and pedagogical limitations continues to constrain their effectiveness. These problems do not arise from a lack of experimental provision, but from the ways in which experimental activities are conceptualized, organized, and interpreted within teacher preparation programs. As a result, experimental practice does not consistently support the development of instructional competence among pre-service biology teachers.

(1) Misalignment between experimental objectives and instructional goals

A central limitation in current biology experiment design lies in the weak alignment between experimental objectives and instructional goals. In many teacher education programs, experiments are primarily designed to verify established biological principles, with learning outcomes assessed through procedural accuracy and the correctness of results. While such objectives contribute to disciplinary understanding, they often marginalize the instructional functions that experiments are expected to serve in classroom teaching.

Under these conditions, pre-service teachers tend to approach experiments as self-contained tasks rather than as instructional tools. Experimental success is frequently equated with correct execution, while limited attention is paid to

how experimental activities might support explanation, questioning, or student inquiry. As a consequence, pre-service teachers may acquire technical proficiency without developing strategies for organizing experimental learning or guiding students through complex learning processes.

This misalignment has important implications for teaching practice. When experimental activities are disconnected from instructional intent, pre-service teachers may struggle to translate laboratory experience into classroom teaching. They may lack confidence in adapting experiments to different learner needs or in using experimental outcomes to support conceptual understanding. The separation between experimental completion and pedagogical purpose thus constrains the transfer of experimental experience to authentic teaching contexts.

(2) Limited participation in experimental design and decision-making

Another persistent problem concerns the limited involvement of pre-service teachers in experimental design and decision-making processes. In many teacher education settings, experimental activities are delivered through standardized protocols that prescribe materials, procedures, and expected outcomes in detail. Although such standardization promotes efficiency and consistency, it significantly reduces opportunities for pre-service teachers to engage in instructional planning and adaptation.

When experimental design choices are predetermined, pre-service teachers primarily assume the role of executors rather than designers. This restricts their engagement with key teaching-related decisions, such as selecting appropriate experimental conditions, anticipating potential difficulties, or modifying procedures in response to learner diversity. As a result, experimental practice provides limited preparation for the dynamic and context-sensitive nature of classroom teaching.

The absence of design responsibility also affects professional confidence. Without sustained experience in making instructional decisions during experimental activities, pre-service teachers may perceive experimental teaching as rigid and difficult to adapt. This perception can discourage experimentation and innovation in future classroom practice. Consequently, experimental training remains detached from the realities of instructional planning, where flexibility and judgment are essential.

(3) Superficial integration of reflective practice

A further challenge lies in the superficial integration of reflection within experimental training. Although reflective activities are sometimes included, they often focus narrowly on procedural accuracy or discrepancies in experimental results. Such reflections typically emphasize technical correction rather than pedagogical analysis, limiting their contribution to professional learning.

When reflection is confined to evaluating operational performance, pre-service teachers may identify errors without examining the instructional assumptions underlying experimental design. Questions related to student engagement, instructional clarity, or classroom interaction are frequently overlooked. Moreover, reflection is often positioned as a post-experiment requirement, detached from planning and implementation processes.

This fragmented approach reduces the potential of experimental practice as a site for reflective teaching development. Without continuous reflection across planning, enactment, and evaluation, pre-service teachers have limited opportunities to develop pedagogical judgment or to refine instructional strategies. As a result, the formative value of experiments for teacher professional growth remains underdeveloped, reinforcing the gap between experimental experience and teaching competence.

4. Practice-Oriented Strategies for Innovative Biology Experiment Design

In response to the challenges identified in current biology experiment design for teacher education, this study

proposes a set of practice-oriented strategies aimed at strengthening the instructional function of experimental activities. Rather than expanding experimental content or increasing technical complexity, these strategies focus on restructuring the design and implementation processes of experiments so that they contribute more directly to the development of teaching competence. Central to this approach are four interconnected dimensions: alignment with instructional intent, contextualization within teaching practice, systematic reflection, and collaborative design. Together, these dimensions form a coherent framework that repositions experimental activities as pedagogical practices rather than auxiliary technical exercises.

(1) Aligning experimental design with instructional intent

Aligning experimental design with instructional intent constitutes a foundational strategy for enhancing the pedagogical value of biology experiments in teacher education. In many conventional settings, experiments are planned primarily around disciplinary content, with limited articulation of how experimental activities support specific learning objectives. As a result, experimental success is often judged by procedural accuracy rather than instructional effectiveness. A practice-oriented approach requires pre-service teachers to begin experimental planning by explicitly clarifying instructional aims, including targeted biological concepts, inquiry skills, and anticipated forms of student engagement.

This alignment process shifts experimental design from procedural execution to pedagogical reasoning. Pre-service teachers are encouraged to examine how each experimental step contributes to explanation, questioning, or conceptual development, and to consider whether experimental procedures are appropriate for intended learners. Through this process, experimental activities are reframed as structured learning experiences that guide student understanding, rather than isolated technical tasks to be completed.

Aligning design with instructional intent also supports coherence within lessons. When experiments are planned with clear teaching purposes, they can be more effectively integrated with explanations, discussion, and follow-up activities. Pre-service teachers learn to view experiments as components of broader instructional sequences rather than stand-alone events. This perspective strengthens their capacity to design lessons in which experimental activity meaningfully supports learning objectives.

Moreover, alignment with instructional intent fosters flexibility in experimental design. When experiments are understood as means to achieve pedagogical goals, procedures can be adjusted in response to classroom conditions without undermining educational value. This capacity for adaptation is essential for future teaching practice, where time constraints, learner diversity, and resource availability often require modification of experimental activities. Through repeated engagement in intent-driven design, pre-service teachers gradually develop the ability to design experiments that are both scientifically sound and instructionally effective.

(2) Embedding experimental activities in authentic teaching contexts

A second strategy emphasizes embedding experimental activities within authentic teaching contexts. Experimental learning in teacher education is most effective when pre-service teachers engage with experiments from the perspective of future instructors rather than solely as learners. Authentic contexts may include micro-teaching sessions, simulated classroom environments, or peer-based instructional activities in which experiments are implemented as part of a teaching sequence.

Situating experiments in teaching-oriented contexts introduces practical considerations that are often absent in conventional laboratory settings. Pre-service teachers must address issues such as instructional clarity, time management, classroom organization, and student participation. These factors significantly influence the effectiveness of experimental teaching but are rarely encountered when experiments are conducted as isolated laboratory exercises. By engaging with such constraints, pre-service teachers gain insight into the complexities of experimental instruction.

Embedding experimental activities in authentic contexts also supports the integration of disciplinary knowledge

with pedagogical decision-making. Pre-service teachers are required to translate biological content into teachable forms, anticipate student responses, and adjust instructional strategies accordingly. This process highlights the interpretive nature of teaching, in which content knowledge must be continuously adapted to instructional situations.

In addition, authentic contexts provide opportunities for pre-service teachers to experience the interactional dimensions of experimental teaching. Managing questions, responding to unexpected outcomes, and facilitating discussion around experimental results become integral parts of the learning process. These experiences strengthen the connection between experimental practice and classroom teaching, facilitating the transfer of experimental experience to future professional contexts. As a result, experiments function as opportunities for developing instructional competence rather than remaining confined to technical training.

(3) Integrating structured reflection across experimental processes

The systematic integration of reflection is essential for transforming experimental activities into sustained professional learning. Reflection enables pre-service teachers to critically examine their design decisions, implementation strategies, and instructional outcomes. In a practice-oriented framework, reflection is distributed across the experimental process, beginning with planning, continuing through implementation, and extending into post-activity evaluation.

During the planning stage, reflective consideration encourages pre-service teachers to examine the rationale underlying experimental design choices and to anticipate potential instructional challenges. This form of anticipatory reflection supports more deliberate planning and helps align experimental activities with instructional objectives. By articulating design intentions in advance, pre-service teachers become more aware of the assumptions guiding their instructional decisions.

During implementation, reflection functions as a responsive process that supports real-time adjustment. Pre-service teachers are encouraged to monitor student understanding, engagement, and procedural difficulties as experimental activities unfold. Reflective awareness enables them to modify explanations, pacing, or experimental arrangements in response to emerging classroom dynamics. This responsiveness is a critical component of effective teaching and is difficult to develop through post-hoc evaluation alone.

Post-experiment reflection moves beyond evaluation of technical accuracy to focus on instructional effectiveness. Pre-service teachers are encouraged to analyze how experimental design influenced student engagement, conceptual understanding, and classroom interaction. Structured reflective prompts and guided discussion can support deeper analysis by directing attention to pedagogical considerations rather than procedural outcomes alone. Through repeated reflective engagement, pre-service teachers develop habits of inquiry that contribute to long-term professional growth and instructional adaptability.

(4) Promoting collaborative experimental design and peer feedback

Collaborative design and peer feedback constitute a further strategy for enhancing experimental practice in teacher education. Experimental design is inherently interpretive and benefits from multiple perspectives. Group-based planning activities allow pre-service teachers to share instructional ideas, compare alternative design approaches, and negotiate pedagogical decisions in a supportive environment.

Through collaborative engagement, experimental design becomes a collective professional activity rather than an individual technical task. Peer discussion exposes pre-service teachers to diverse ways of structuring experimental learning and encourages critical examination of instructional assumptions. By articulating and defending design choices, pre-service teachers refine their instructional reasoning and develop greater awareness of alternative pedagogical possibilities.

Peer feedback further supports reflective revision by prompting comparison between intended and perceived

instructional effects. Feedback from peers helps pre-service teachers identify strengths and limitations in experimental design that may not be apparent from an individual perspective. This process encourages iterative refinement and reinforces the view of experimental design as an evolving practice rather than a fixed product.

Such collaborative practices mirror the professional communities in which teachers operate and contribute to the development of communication skills and shared pedagogical understanding. By participating in collaborative design processes, pre-service teachers learn to articulate instructional reasoning, respond constructively to critique, and refine experimental designs through dialogue. These experiences strengthen both individual competence and collective professional awareness, reinforcing the role of experimental design as a socially situated teaching practice.

5. Development Trends in Biology Experiment Design for Teacher Education

The development of biology experiment design in teacher education is increasingly characterized by a shift toward deeper integration with teaching practice. Rather than functioning as supplementary technical activities, experiments are gradually being repositioned as central components of instructional preparation. This transformation reflects changes in how experimental learning is understood within teacher education and points toward several interconnected development trends.

(1) A shift toward process-oriented experimental learning

One significant development trend is the growing emphasis on process-oriented experimental learning. Traditional experimental design in teacher education has often focused on achieving correct results through standardized procedures. While such an approach supports disciplinary accuracy, it provides limited insight into how learning unfolds during experimental activities.

In contrast, emerging designs prioritize inquiry processes, instructional decision-making, and reasoning strategies. Experimental activities increasingly emphasize how questions are generated, how evidence is interpreted, and how instructional guidance shapes student understanding. This shift encourages pre-service teachers to attend to learning processes rather than outcomes alone. As a result, experiments become opportunities for examining how instructional choices influence conceptual development, supporting the cultivation of pedagogical sensitivity and instructional awareness.

From a teacher preparation perspective, process-oriented experimentation aligns more closely with classroom realities, where learning outcomes are shaped by interaction, explanation, and adaptation. By engaging with experiments as evolving instructional processes, pre-service teachers are better prepared to manage the dynamic nature of experimental teaching.

(2) The increasing use of iterative experimental design sequences

A second important trend involves the growing adoption of iterative experimental design sequences. Instead of treating experiments as isolated tasks completed within a single session, teacher education programs are increasingly organizing experimental activities into connected sequences. These sequences allow pre-service teachers to revisit experimental designs, reflect on instructional effectiveness, and make informed revisions over time.

Iterative design supports sustained engagement with pedagogical challenges. Through repeated cycles of planning, implementation, and revision, pre-service teachers develop a deeper understanding of how experimental structure influences teaching and learning. This approach also encourages responsiveness to feedback, as design decisions are continuously refined rather than finalized prematurely.

The use of iterative experimental sequences mirrors authentic teaching practice, where instructional strategies are adjusted based on experience and reflection. By engaging in iterative design, pre-service teachers cultivate habits of continuous improvement and develop greater confidence in adapting experiments to diverse instructional contexts.

(3) Expanding the role of reflective documentation in experimental training

Another notable trend is the expanding role of reflective documentation in experimental training. Written reflections, instructional notes, and experimental design rationales are increasingly integrated into teacher education programs as tools for professional learning. These forms of documentation extend reflection beyond immediate activity and encourage systematic examination of instructional thinking.

Reflective documentation supports the articulation of pedagogical reasoning by prompting pre-service teachers to make their design intentions and instructional decisions explicit. By documenting how experimental activities are planned, implemented, and evaluated, pre-service teachers gain insight into the relationship between instructional design and learning outcomes. Such records also facilitate dialogue with peers and instructors, creating opportunities for feedback and collaborative reflection.

Over time, reflective documentation contributes to the development of professional identity. As pre-service teachers accumulate records of experimental practice, they build a personal repertoire of instructional experiences that inform future teaching decisions. This trend highlights the growing recognition of reflection as an ongoing professional practice rather than a discrete evaluative task.

(4) Repositioning experimental design as a core component of teacher preparation

Taken together, these trends indicate a broader repositioning of experimental design within teacher education. Experiments are increasingly viewed not as supplementary activities that accompany theoretical instruction, but as central pedagogical practices through which teaching competence is developed. This repositioning reflects an understanding that experimental design integrates disciplinary knowledge, instructional reasoning, and reflective practice in ways that are essential for effective teaching.

As biology experiment design becomes more closely aligned with teaching practice, its role in teacher preparation is likely to expand further. Experimental activities are expected to function as structured environments for developing instructional judgment, adaptability, and professional awareness. This shift underscores the importance of designing experimental experiences that support long-term professional growth rather than short-term task completion.

6. Conclusion

This study adopts a practice-oriented perspective to examine innovative design of biology experiments within teacher education programs. By analyzing existing challenges and proposing targeted strategies, the study highlights the importance of aligning experimental activities with instructional goals and reflective practice. The findings suggest that when experiments are designed as pedagogical practices, they can effectively support the development of teaching competence among pre-service biology teachers. While the study focuses on biology education, its insights may also inform experimental training in other science disciplines. Future research may further explore how sustained experimental design practice contributes to long-term professional growth.

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