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ENHANCING PRESERVICE PHYSICS TEACHERS' SCIENTIFIC INQUIRY SKILLS THROUGH PHOTONICS EXPLORER KIT-SUPPORTED INQUIRY ACTIVITIES[i]

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Abstract:
Scientific inquiry skills are a central component of science teacher education, yet preservice teachers often have limited opportunities to engage in sustained, inquiry-oriented practical work, particularly in resource-constrained contexts. This study examined how a Photonics Explorer Kit-supported intervention influenced the development of preservice physics teachers' Scientific Inquiry skills, collaborative and critical thinking skills within a structured learning environment. Guided by a multidimensional conceptualisation of inquiry and an Educational Design Research approach, the study involved two iterative cohorts of Bachelor of Physics Education students who participated in a 10-lesson optics intervention organised using the 7E instructional model. Data were collected through a two-tier diagnostic test, lesson observations, questionnaires, reflective journals, and a researcher's logbook. Inferential analysis conducted for the first cohort revealed a statistically significant improvement in inquiry-related performance ($t(51) = 25.78$, $p < .001$), with a very large effect size ($d = 1.95$), indicating a substantial impact of the intervention. Descriptive comparisons across cohorts further showed consistent patterns of improvement, with the second cohort demonstrating slightly stronger outcomes following iterative refinement of the instructional design. Findings indicate that inquiry skill development was multidimensional and uneven. Observable and participatory practices showed stronger gains, while more complex practices, including experimental design and knowledge transfer, remained comparatively less developed. The study advances a multidimensional account of inquiry development by demonstrating how combined material and instructional scaffolds shape differential skill growth and highlights the role

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[i] AMÉLIORATION DES COMPÉTENCES D'INVESTIGATION SCIENTIFIQUE DES FUTURS ENSEIGNANTS DE PHYSIQUE GRÂCE À DES ACTIVITÉS REPOSANT SUR LE KIT PHOTONICS EXPLORER

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of iterative design in strengthening inquiry-based teacher education in resource-constrained teacher education.

Keywords: educational design research, inquiry-based learning, optics education, photonics explorer kit, scientific inquiry skills

Résumé :

Les compétences d'investigation scientifique constituent un élément central de la formation des enseignants de sciences. Pourtant, les futurs enseignants ont souvent des opportunités limitées de s'engager dans des travaux pratiques durables et axés sur l'investigation, en particulier dans des contextes de pénurie de ressources. Cette étude a examiné comment une intervention s'appuyant sur le kit *Photonics Explorer* a influencé le développement des compétences d'investigation scientifique, ainsi que des compétences de collaboration et d'esprit critique de futurs enseignants de physique au sein d'un environnement d'apprentissage structuré. Guidée par une conceptualisation multidimensionnelle de l'investigation et une approche de recherche en design pédagogique (*Educational Design Research*), l'étude a impliqué deux cohortes itératives d'étudiants en licence de l'enseignement de la physique (*Bachelor of Physics Education*) ayant participé à une intervention de 10 leçons d'optique organisée selon le modèle pédagogique des 7E. Les données ont été recueillies au moyen d'un test diagnostique à deux niveaux, d'observations de leçons, de questionnaires, de journaux de réflexion et d'un journal de bord du chercheur. L'analyse inférentielle menée pour la première cohorte a révélé une amélioration statistiquement significative des performances liées à l'investigation ($t(51) = 25,78$, $p < ,001$), avec une taille d'effet très importante ($d = 1,95$), indiquant un impact substantiel de l'intervention. Des comparaisons descriptives entre les cohortes ont également montré des schémas d'amélioration constants, la deuxième cohorte affichant des résultats légèrement supérieurs suite à l'affinement itératif de la conception pédagogique. Les résultats indiquent que le développement des compétences d'investigation est multidimensionnel et inégal. Les pratiques observables et participatives ont enregistré les gains les plus importants, tandis que les pratiques plus complexes, notamment la conception expérimentale et le transfert de connaissances, sont restées comparativement moins développées. L'étude propose un compte rendu multidimensionnel du développement de l'investigation en démontrant comment la combinaison d'échafaudages matériels et pédagogiques façonne la croissance différentielle des compétences, et met en évidence le rôle de la conception itérative dans le renforcement de la formation des enseignants basée sur l'investigation au sein d'institutions de formation d'enseignants aux ressources limitées.

Mots clés : recherche en design pédagogique, enseignement des sciences fondé sur l'investigation, enseignement de l'optique, kit photonics explorer, compétences d'investigation scientifique

1. Introduction

Scientific inquiry skills (SIS) are widely recognised as a central goal of science education because they enable learners to engage with the processes by which scientific knowledge is generated, evaluated, and applied. Beyond acquiring content knowledge, learners are expected to develop the capacity to ask questions, design and conduct investigations, interpret evidence, and construct explanations grounded in data (Chen & She, 2015; National Research Council, 2015). These processes involve critical thinking and collaborative skills because learners will often have to work in groups, reason from evidence, evaluate explanations, and justify their conclusions. In the context of teacher education, this expectation is particularly significant because preservice teachers must not only develop SIS but also develop the pedagogical competence to facilitate inquiry-oriented learning in their future classrooms (Abedi *et al.*, 2024; Bybee, 2006; Lederman *et al.*, 2013; National Council for Curriculum and Assessment [NaCCA], 2018, 2021). A research study by Delgado-Iglesias *et al.* (2024) found that while preservice teachers showed improvement in inquiry procedures after instruction, persistent gaps remained in their didactic content knowledge of inquiry, and many anticipated difficulties in applying inquiry approaches in their future classrooms. This points to the need for preservice teacher education to address not only the development of inquiry skills but also the pedagogical knowledge required to facilitate inquiry-based learning.

Despite its recognised importance, many preservice teachers still have limited opportunities to engage in sustained and meaningful inquiry-based practical work. In both well-resourced and resource-constrained educational systems, inquiry-based approaches are often unevenly implemented, with instruction frequently characterised by teacher-centred practices and an emphasis on procedural knowledge rather than epistemic engagement (Abrahams & Millar, 2008; Özer & Sarıbaş, 2023). As a result, many preservice teachers finish their training without grasping the concept of scientific inquiry. They often have only partial exposure to important skills such as forming hypotheses, designing experiments, interpreting data, and building scientific explanations (Irwanto, 2023; García-Carmona, 2019; Gizaw & Sota, 2023). In addition to being a minor weakness in their training, this issue also makes it difficult for teachers to conduct lessons that genuinely enable students to learn through investigation and discovery (García-Carmona, 2019).

These difficulties become more noticeable in physics, where many ideas are not directly visible and require learners to think deeply while also engaging with real-world evidence. Topics in optics, for instance, naturally lend themselves to activities like observing light behaviour, experimenting with lenses and mirrors, and taking measurements. However, many classrooms still primarily teach optics through explanations, diagrams, and memorisation with very few hands-on activities (Abrahams & Millar, 2008; Galili & Hazan, 2000). In such situations, students may be able to repeat definitions and state laws but often do not develop the skills needed to test ideas, make sense of results, or link what they learn to what they actually observe. For preservice physics teachers, this gap not only makes the understanding of these concepts difficult but also makes them unable to confidently design meaningful learning experiences for their future learners.

Because of these concerns, inquiry-based learning has gained strong support as an approach that can help students engage more deeply with science. However, its success depends heavily on having the right support systems in place, both in terms of teaching materials and instructional guidance. Teachers in many educational settings, particularly those with limited laboratory equipment, lack easy access to the necessary tools for sustained practical work. This has necessitated the growing interest in simple, portable, and well-structured teaching resources that can make hands-on science more realistic and manageable in different classrooms.

One example of such a resource is the Photonics Explorer Kit (PEK). The kit comprises optical components, guided activities, and teaching materials specifically designed to facilitate learners' exploration of concepts in optics and photonics through inquiry. Studies suggest that tools like the PEK can increase student engagement and make abstract scientific ideas easier to understand by allowing learners to experiment in a structured way (Prasad *et al.*, 2012). However, most of the existing research has focused on pre-tertiary students or general science concepts. Preservice teacher education has received significantly less attention, particularly in terms of how such tools aid future teachers in developing strong inquiry teaching skills. Furthermore, much of the literature has emphasised overall learning gains without examining how different dimensions of SIS develop through structured interventions with limited resources.

This gap points to two important limitations in the current literature. First, there is insufficient understanding of how inquiry-oriented instructional tools support the development of specific dimensions of SIS. Second, there is limited design-based evidence on how such tools can be effectively integrated and refined within authentic teacher education contexts, particularly in resource-constrained settings where instructional conditions and culture differ significantly from those in which many inquiry-based approaches are developed.

The present study addresses these gaps by examining the integration of the PEK within a structured inquiry-based optics intervention for preservice physics teachers in Ghana. Adopting an Educational Design Research (EDR) approach, the study investigates not only whether the intervention supports inquiry skill development but also how different dimensions of inquiry evolve across iterative implementation cycles and how refinements influence learning outcomes.

Specifically, the study is guided by a multidimensional conceptualisation of SIS that focuses on four key domains:

1) generating questions and hypotheses;
2) designing and conducting investigations;
3) analysing and interpreting data; and
4) communicating and applying scientific explanations.

By examining these dimensions across two cohorts, the study provides a more fine-grained account of inquiry development than is typically reported in the literature. This study views SIS as a set of related but distinct abilities. This approach acknowledges that students do not develop all aspects of inquiry at the same pace. Some skills may improve more quickly than others, depending on the type of instruction and learning environment. By breaking inquiry into these components, the study allows for a more detailed understanding of how each skill develops over time because modern perspectives describe inquiry as a complex and multidimensional practice.

This study makes three contributions to science education research. First, it advances a multidimensional perspective on SIS development by showing how different inquiry practices respond unevenly to structured instructional interventions. Second, this study adds to existing knowledge on scaffolding in inquiry-based learning by exploring how both physical learning resources like the PEK and structured teaching approaches (the 7Es instructional model) work together to support students' engagement in inquiry-based activities. Third, it makes a design-based contribution by showing how repeated cycles of planning, implementation, reflection, and refinement can gradually improve the effectiveness of inquiry-based teaching strategies in real preservice teacher education settings.

Overall, by focusing on a context where resources are limited, the study also sheds light on how inquiry-based learning can still be meaningfully implemented in environments where traditional laboratory equipment is not readily available and how alternative instructional designs can help bridge that gap. In doing so, it speaks to broader international concerns about equity, access, and the practical realisation of inquiry-oriented science education in order to achieve SDG 4.

The study is guided by the following research questions:

1) To what extent does participation in a PEK-supported inquiry-based optics intervention influence preservice physics teachers' scientific inquiry skills?
2) Which dimensions of scientific inquiry skills show the greatest and least development following the intervention?
3) How do preservice physics teachers describe the advantages and constraints of using the PEK to engage in inquiry-oriented optics learning?

2. Theoretical Framework

The study is grounded in a social constructivist view of learning, which emphasises that knowledge develops through participation, interaction, and collaboration. From this perspective, students build inquiry skills by engaging in structured activities, using tools, and sharing ideas with others. Learning does not happen in isolation; it is supported by both tangible resources and symbolic tools such as language, diagrams, and other forms of representation. In practical terms, this means students learn better when they have access to the right materials, opportunities to actively engage in hands-on work, and clear instructional guidance. When these supports are missing, inquiry can easily become too abstract, making it difficult for learners to fully understand or participate in the process. This study employed scientific inquiry skills as learning practices that encompass both critical thinking and collaboration. Inquiry-based learning needs learners to go beyond memorising scientific concepts to asking questions, developing investigation skills, observing scientific phenomena, explaining evidence and communicating explanations. These processes require critical thinking because learners must evaluate evidence, compare ideas, justify results, and reflect on the correctness of their explanations. Furthermore, inquiry activities usually take place through group work, where learners share duties and deliberate on observations, challenge others' views and come to a consensus (Gülen, 2019; Mugabekazi *et al.,* 2025). Hence, in this study, the PEK hands-on activities were considered a practical way that could aid preservice physics teachers to develop scientific inquiry skills through evidence-based learning, peer group interaction, and collaborative construction of scientific explanations in optics.

From this perspective, the PEK is not just a collection of teaching aids; rather, it functions as a scaffold for learning. It provides preservice physics teachers with physical components like lenses and mirrors, along with structured worksheets and guided activities that help shape their investigative process. These supports reduce the challenges of planning and conducting experiments, particularly for learners who are still building their confidence in practical inquiry. In this way, the PEK enables learners to connect abstract scientific ideas with tangible, hands-on experiences, helping to make concepts in optics more concrete and easier to understand. By working directly with materials, students are able to see how theoretical ideas play out in real situations, which supports a deeper understanding of the subject matter.

However, simply providing access to materials does not automatically result in meaningful inquiry learning. The effectiveness of such resources depends largely on how they are thoughtfully integrated into teaching. In this study, the 7E instructional model provides this structure by guiding learning through a sequence of phases, including eliciting prior knowledge, engaging learners, supporting exploration, facilitating explanation, encouraging elaboration, assessing understanding, and extending learning. This structured progression gradually supports students in transitioning from familiar ideas to more complex reasoning and deeper conceptual understanding.

When used together, the PEK and the 7E model function as a complementary support system. The PEK offers the physical means for experimentation, while the 7E framework shapes how learners interact with those materials in purposeful ways. This combination strengthens the development of inquiry skills, particularly those that involve active participation, such as observing, discussing, and conducting guided investigations.

This study is further informed by Educational Design Research (EDR), which views educational interventions not as fixed solutions but as evolving designs that are continuously refined through cycles of implementation and improvement. This includes designing, implementing, analysing, and refining teaching strategies in real classroom settings. EDR focuses not only on whether an approach is effective but also on how and why it works, for whom, and under what conditions. This makes it particularly suitable for examining how the PEK and 7E models support the development of inquiry skills over multiple cycles of implementation.

A key aim of EDR is to generate insights that improve both theory and practice. In this study, this involves examining how different inquiry skills respond to structured teaching and how changes in implementation affect learning outcomes. By comparing two groups of students, the study goes beyond measuring overall improvement. It also explores how variations in teaching influence the development of SIS.

Overall, this framework presents SIS development as a complex, scaffolded, and context-dependent process. It highlights the importance of both material tools and instructional strategies in supporting learning. At the same time, it acknowledges that different inquiry skills may develop unevenly. This perspective provides a useful framework for comprehending the aspects of inquiry that receive more support and those that necessitate further focus.

3. Methods

3.1 Research Design

The study employed Educational Design Research (EDR) to design, implement, examine, and refine a PEK-supported inquiry intervention in an authentic teacher education setting. EDR was appropriate because the purpose of the study was not simply to test a fixed treatment but to examine how an instructional design worked and how iterative refinement could strengthen implementation cycles in practice (McKenney & Reeves, 2013; Plomp, 2013). In line with this logic, the study was conducted with two successive cohorts of preservice teachers who experienced the same broad intervention structure, with refinements introduced in the second cycle on the basis of lessons learned from the first cohorts.

The study was carried out at the University of Education, Winneba, Ghana, in the context of optics instruction for preservice teachers enrolled in physics education programmes. Two intact classes were purposively selected because of institutional timetable and course structure constraints. This is consistent with the use of purposive sampling in educational research, where participants are selected because they fit the purposes and practical conditions of the study (Johnson & Christensen, 2024). The first cohort comprised 51 preservice teachers, and the second cohort comprised 48, giving a total of 99 participants. These participants were drawn from Bachelor of Education programmes in Physics and Chemistry, where optics formed part of their course experience. The use of intact cohorts reflected the practical realities of the setting and was consistent with the classroom-based nature of EDR, which aims to provide a more authentic learning experience that mirrors actual teaching environments.

Although the study involved two cohorts, they were not treated as strict experimental and control groups. Rather, they represented two implementation cycles within a design-based process. Both cohorts were taught by the same facilitator, covered the same optics content, and received the same overall instructional time. Each cohort completed pre-intervention and post-intervention assessments using the same general testing procedure. However, after reflection on the first implementation cycle, aspects of the second cycle were refined to improve clarity, alignment, and pedagogical support. In particular, the phrasing of selected assessment items and learning prompts was revised to improve clarity and strengthen their connection to instructional content and everyday experience.

3.2 Intervention Context and Instructional Design

The intervention focused on the university optics course outline and was implemented using the 7E instructional model: Elicit, Engage, Explore, Explain, Elaborate, Evaluate, and Expand. This model was adopted because it provides a clear structure for activating prior knowledge and further encouraging transfer of learning (Eisenkraft, 2003). Across the intervention, the preservice physics teachers worked in small groups of three or four and used the PEK to investigate optical concepts through observation and interpretation of data.

The PEK served as the principal pedagogical resource in this intervention. It includes optical hardware such as lenses and mirrors together with learner materials, a teacher's guide, and lesson resources that support hands-on inquiry. These resources facilitated the exploration of reflection, refraction and diffraction. The intervention did not treat the kit as equipment alone; instead, the PEK was embedded within a broader lesson structure.

The intervention lasted three months and involved ten optics lessons, amounting to 30 hours of structured engagement. The opening phase included orientation to the materials, classroom procedures, and safety expectations, as well as administration of the pre-intervention diagnostic test. The closing phase included the post-intervention test and administration of the questionnaire. During the lessons, participants engaged in guided inquiry tasks designed to support key dimensions of SIS development, such as making observations, formulating questions and applying scientific research results.

A preparatory phase preceded the intervention phase of the intervention. During this phase, the researcher, laboratory technician, and three teaching assistants were orientated on how to use the PEK materials and prepare inquiry-based lesson activities that aligned with the 7E model. The preservice teachers did not undergo separate, standalone training before the intervention. Instead, they were introduced to the use of the kit, task expectations, and safety procedures within the lesson process itself. In this way, the study examined SIS development as it emerged through sustained engagement with the intervention activities rather than through prior external training.

3.3 Data Sources and Instruments

Multiple sources of instruments, including a two-tier diagnostic test, an observation checklist, a questionnaire, reflective journals, and a researcher's logbook, helped to capture participants' inquiry skill development and their experiences during the intervention. The use of multiple instruments allowed for triangulation across quantitative and qualitative data sources. This approach is widely recommended in mixed methods and educational research because it supports a more comprehensive understanding of the concept under study (Creswell & Plano Clark, 2018; Dawadi *et al.*, 2021).

A 30-item two-tier diagnostic test was used as the main quantitative instrument to assess preservice physics teachers' SIS in optics before and after the intervention. Each item included a first tier in multiple-choice format and a second tier that required a brief explanation or justification for the selected response. This is also consistent with the idea of two-tier diagnostic instruments, which are designed to capture both answer choice and underlying reasoning (Fulmer *et al.*, 2015). The test was designed to assess inquiry-related engagement with optics content, including observation, reasoning, interpretation, and evidence-based explanation in relation to the topics covered during the intervention. Responses were scored using a four-level scheme. A response received 3 points when both the selected answer and the accompanying explanation were correct, 2 points when partial evidence of scientific inquiry understanding was demonstrated, 1 point when only the first-tier answer was correct, and 0 points when the response was incorrect or omitted. The test was reviewed by three experts in physics education for relevance, clarity, and alignment with the intended inquiry dimensions. It was also piloted in preservice teacher education with similar optics content before the main study to improve the wording, content and structure of the items.

An observation checklist was used to monitor the extent to which intended SIS were evident during the 10-week lesson implementation. The checklist comprised 30 items organised under four dimensions: (1) making observations, raising questions, and formulating hypotheses; (2) designing and conducting investigations; (3) analysing and interpreting results of scientific investigations; and (4) communicating and applying the results of scientific investigations. There were three levels of evidence for each item: very evident (3), evident (2), and not evident (1). The checklist was reviewed by three experts in physics and science education to ensure content relevance and clarity. During implementation, the checklist was independently completed by three observers across the optics lessons. Their ratings were averaged to generate composite lesson-level scores for the targeted inquiry dimensions. These average scores were then used to examine lesson-by-lesson patterns of inquiry development across the two cohorts.

A questionnaire was administered at the end of the intervention to capture participants' views on the PEK-supported inquiry learning experience. The instrument comprised three sections. Section A collected background information on participants. Section B contained four open-ended items through which participants described their experiences, perceived learning gains, and challenges encountered during the intervention. Section C consisted of seven Likert-type items rated on a five-point scale, which elicited more structured responses on participants' perceived development of inquiry-related skills during the optics lessons. The questionnaire, therefore, generated both quantitative and qualitative data. The structured items were used to examine participants' self-reported development in areas such as observation, experimental design, analysis, communication, critical thinking, creativity, and collaboration during the intervention. The open-ended responses were used to better understand the perceived affordances and constraints of learning optics with PEK. The questionnaire was piloted with Level 300 preservice teachers to improve usability and clarity.

Participants were also invited to record their experiences, reactions, perceived learning gains, and challenges in reflective journals during the intervention. These journal entries provided first-person accounts of how they engaged with optics concepts and inquiry tasks over time. In addition, the researcher maintained a logbook throughout the ten lessons to document classroom events, interactions, implementation issues, and observations not fully captured by the structured checklist. Both the journals and the logbook served as supplementary qualitative sources that supported the interpretation of the broader findings.

3.4 Validity, Reliability, and Implementation of Fidelity

Several steps were taken to strengthen the quality of the study. Content validity of the observation checklist and the two-tier diagnostic test was supported through expert review by specialists in physics and science education, who examined the instruments for clarity, relevance, and alignment with the intended inquiry dimensions. Pilot testing was also conducted to improve wording, usability, and internal consistency. The reliability of the Likert-type questionnaire scale was supported by Cronbach's alpha coefficient of 0.898, while the pilot correlation coefficient of 0.894 further indicated the instrument's acceptable stability. Implementation of fidelity was monitored throughout the intervention. The lesson observations by three independent observers provided evidence of the extent to which the intended inquiry dimensions were enacted during teaching and learning. In addition, the use of a common lesson structure, the same facilitator across both cohorts, and the same broad instructional content helped support consistent implementation. Participant feedback, observation records, and logbook entries were also reviewed during the reflective phase of the design process to identify aspects of the intervention that worked well and those requiring refinement for the second cohort.

3.5 Data Analysis

Quantitative and qualitative data were analysed in ways that were consistent with the mixed-source and design-based orientations of the study. The quantitative data from the questionnaire and diagnostic tests were analysed in R. Descriptive statistics (means, standard deviations, and percentages) were used to summarise the preservice teachers' performances and their perceived development of inquiry-related skills throughout the intervention. In addition, a paired-samples *t*-test was conducted for Cohort 1 to examine pre–post differences in inquiry-related performance based on the two-tier diagnostic test. This inferential analysis was included to determine whether the observed changes in performance were statistically significant. Cohort 2 was analysed descriptively in line with the iterative and design-based orientation of the study. Given the Educational Design Research orientation of the study, the quantitative analysis was used mainly to examine patterns of development within and across the two implementation cohorts rather than to make strong causal claims. For the reported areas of skill acquisition, participants were allowed to provide more than one response. The frequency of each reported skill area was counted for each cohort. Percentages were then calculated by dividing each frequency by the total number of participants in that cohort and multiplying by 100.

Qualitative data from open-ended questionnaires, reflective journals, observation records, and researcher logbooks were analysed thematically. The researcher first read the full dataset repeatedly to gain familiarity with participants' experiences and the lesson processes observed across the intervention. Initial codes were generated from segments of text relating to inquiry participation, perceived skill development, affordances of the PEK, and challenges encountered during the lessons. Related codes were then grouped into broader categories and refined into themes aligned with the targeted scientific inquiry dimensions and participants' reported learning experiences. To strengthen credibility, patterns identified in one qualitative source were compared with those from the other sources so that interpretations were based on converging evidence rather than isolated statements.

4. Results

4.1 Inferential Analysis of Pre–Post Inquiry Performance

Table 1: Analysis of Pre- and Post-Intervention Test Means for the First Cohort

Test	N	M	SD	d.f.	t	p	Cohen's D
Pre-test	51	7.75	1.65	50	25.78	0.001	1.95
Post-test	51	11.14	1.81				

Note: $p < 0.05$ is significant.

To examine whether participation in the PEK-supported inquiry intervention resulted in statistically significant improvement in preservice teachers' inquiry-related performance, a paired-samples *t*-test was conducted for Cohort 1, comparing pre-intervention and post-intervention diagnostic test scores.

The results indicated a statistically significant increase in scores following the intervention, $t(50) = 25.78$, $p < .001$. The mean score improved from 7.75 (SD = 1.65) at pre-test to 11.14 (SD = 1.81) at post-test, reflecting a substantial gain in participants' performance on inquiry-oriented optics tasks, as shown in Table 1. The effect size (Cohen's $d = 1.95$) (Table 1) indicates a very large effect, suggesting that the intervention had a strong impact on participants' inquiry-related performance. This statistically significant improvement provides a quantitative basis for interpreting the descriptive and qualitative findings that follow.

For Cohort 2, inferential statistical analysis was not conducted. Instead, comparison is based on descriptive trends and patterns observed across multiple data sources, including lesson observations, questionnaire responses, and reported skill acquisition. These data indicate a similar pattern of improvement, with Cohort 2 showing slightly stronger performance across several measures, particularly in later lessons and self-reported inquiry-related skills.

Although direct statistical comparison between the two cohorts is not possible, the consistent pattern of improvement observed across both groups suggests that the intervention was effective in supporting inquiry skill development. The relatively stronger outcomes observed in Cohort 2 further indicate that refinements introduced during the second implementation cycle may have enhanced the effectiveness of the instructional design. This pattern is consistent with the Educational Design Research approach underpinning the study, where iterative refinement is expected to improve instructional alignment and learning outcomes across successive cycles.

Taken together, these findings provide both statistical and descriptive evidence that the PEK-supported inquiry intervention contributed to improvements in preservice teachers' inquiry-related performance. At the same time, when considered alongside the dimension-specific findings, they reinforce the conclusion that inquiry skill development remained uneven, with more complex practices such as experimental design and knowledge transfer showing comparatively limited improvement.

4.2 Development of Observed SIS Across the Intervention

Figure 1: Trend in observed SIS development across the ten lessons in Cohorts 1 and 2

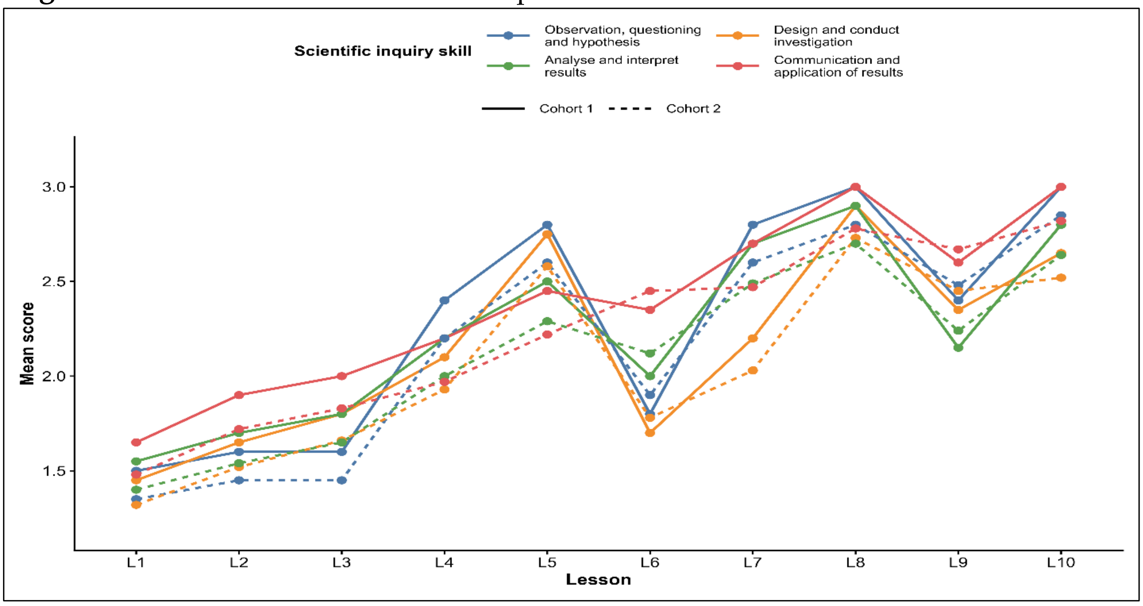

Figure 1 presents the average lesson-based ratings of the four SIS dimensions as observed across the ten optics lessons in the two implementation cohorts. In both cohorts, the results show an overall upward trend across the intervention period, indicating progressive development in participants' observed inquiry practices during the PEK-supported lessons.

In Cohort 1, the mean ratings across the four inquiry dimensions increased from about 1.4-1.7 in Lesson 1 to about 2.8-3.0 by Lessons 8-10. A similar pattern was observed in Cohort 2, although the second cohort generally showed slightly stronger ratings across the later lessons. In both cohorts, the trends were not perfectly linear. A noticeable decline appeared around Lesson 6 after earlier improvements, followed by renewed growth from Lesson 7 onwards. By the final lessons, the highest observed mean values were found particularly in the dimensions relating to analysing and interpreting results and communicating and applying results, both of which approached the upper end of the three-point observation scale.

Overall, the pattern shown in Figure 1 suggests that participants' inquiry engagement strengthened over time and that repeated exposure to the inquiry-oriented optics activities was associated with greater visibility of the targeted scientific inquiry practices across the lessons. This observed progression across lessons is consistent with the statistically significant improvement identified in the inferential analysis, suggesting that gains in inquiry-related performance were reflected in observable classroom practices.

4.3 Preservice Teachers' Perceived Development of Inquiry-Related Skills

Table 2 presents the mean ratings of preservice teachers' perceived development of inquiry-related skills across the cohorts following the intervention. The results show relatively high ratings across all seven items in both cohorts.

Table 2: Mean Scores of Preservice Teachers' Inquiry-Related Skills During PEK-Supported Optics Activities Across Two Cohorts

Item	Inquiry-related skill	Cohort 1	Cohort 2
SD1	Observation during optics activities	4.10	4.28
SD2	Experimental design in optics	3.42	3.61
SD3	Analysis of scientific investigations	3.86	4.05
SD4	Communication of results during optics activities	4.18	4.32
SD5	Critical thinking during optics activities	4.20	4.38
SD6	Creative thinking about optics-related tasks	4.08	4.22
SD7	Collaboration with peers during optics activities	4.12	4.27

Note: M = mean. SD1-SD7 represent questionnaire items on participants' perceived development of inquiry-related skills during the PEK-supported intervention.

In Cohort 1, the mean scores ranged from 3.42 to 4.20, while in Cohort 2 they ranged from 3.61 to 4.38. The highest-rated item in both cohorts was critical thinking during optics activities (Cohort 1: M = 4.20; Cohort 2: M = 4.38). Both groups also rated highly the communication of results, collaboration with peers, and observation during optics activities. By contrast, experimental design in optics received the lowest mean score in each cohort, although the rating improved slightly from Cohort 1 (M = 3.42) to Cohort 2 (M = 3.61).

Across all seven items, Cohort 2 recorded slightly higher mean ratings than Cohort 1, with differences ranging from 0.14 to 0.19 points. Although these differences were modest, the pattern was consistent across the set of measured skills. This suggests that participants in the second implementation cycle perceived a somewhat stronger development of inquiry-related learning behaviours during the intervention. These perceptions align with the inferential results, which indicate that the intervention supported meaningful improvement in inquiry-related performance.

4.4 Reported Areas of Skill Acquisition Across the Two Cohorts

Figure 2: Percentage distribution of reported areas of skill acquisition across Cohorts 1 and 2

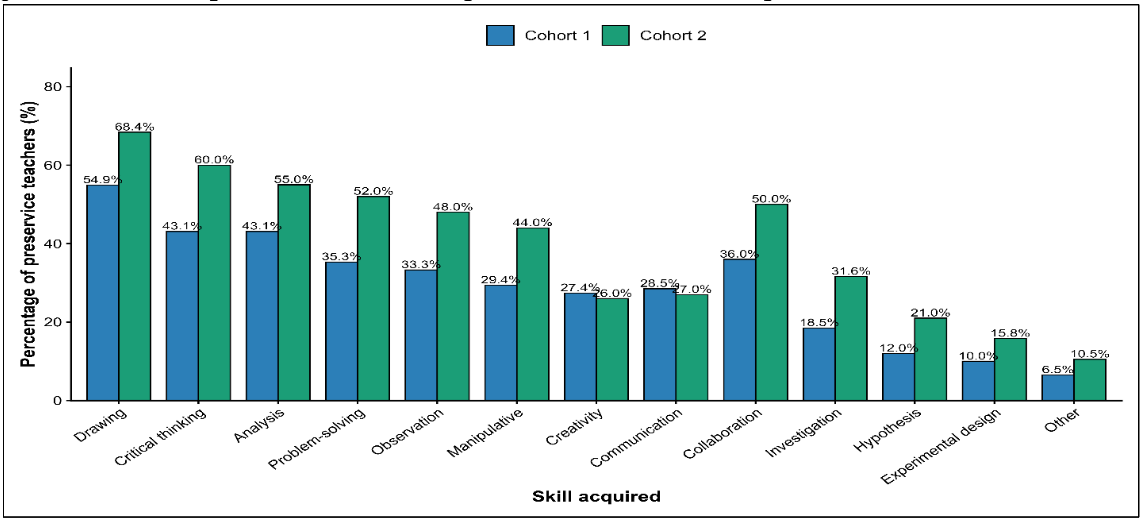

Figure 2 shows the percentage distribution of participants' reported areas of skill acquisition across the two cohorts. Overall, Cohort 2 reported higher percentages than Cohort 1 in most categories. The largest values in both cohorts were recorded for drawing, critical thinking, and analysis of scientific results. Drawing increased from 54.9% in Cohort 1 to 68.4% in Cohort 2, while critical thinking increased from 43.1% to 60.0% and analysis of scientific results from 43.1% to 55.0%.

Other skill areas also showed increases between the two cohorts, including problem-solving, observation, and collaboration. Problem-solving rose from 35.3% in Cohort 1 to 52.0% in Cohort 2, observation (33.3% to 48.0%), and collaboration (36.0% to 50.0%). These inquiry skills reflected deep critical reasoning and collaborative learning of the preservice physics teachers. By contrast, creativity and communication showed little improvement across cohorts, with creativity declining slightly from 27.4% to 26.0% and communication from 28.5% to 27.0%.

Together, these results suggest that the second implementation cycle was associated with broader reported skill acquisition in most areas, although the pattern was not equally strong across all categories. This pattern of reported skill acquisition aligns with the inferential results, reinforcing the conclusion that the intervention produced meaningful improvements, although these gains were not uniformly distributed across all inquiry dimensions.

4.5 Qualitative Evidence of Inquiry Skill Development

Table 3 presents sample qualitative responses from preservice physics teachers across the two cohorts. The responses illustrate participants' experiences in relation to four main dimensions of scientific inquiry: hypothesis formulation, designing and conducting experiments, data analysis and interpretation, and communication and application of results.

Table 3: SIS Dimensions and Illustrative Participant Statements

Scientific inquiry dimension	**Sample participant statements**
Hypothesis formulation	*"The PEK hands-on activities helped me formulate a hypothesis that different object distances will produce different images in spherical mirrors."* *"I was able to predict that total internal reflection will occur when the critical angle is exceeded based on what I was taught at the SHS."*
Designing and conducting experiments	*"I can now select the PEK materials I need for my experiment, which I couldn't do at the semester's start."* *"With the help of the optics manual, I was able to perform the experiments more easily than doing them myself."*
Data analysis and interpretation	*"I could draw experimental tables for the values of different angles of incidence and reflection and see that both are equal."* *"I was able to use a formula to form it, but I couldn't interpret it using scientific terms."*
Communication and application of results	*"I was able to use the ray diagrams in plane mirrors in explaining image characteristics formed by plane mirrors, including lateral inversion."* *"I found it difficult to relate the principle of image formation in cameras to the formation of images in the human eye."*

The responses suggest that participants were able to describe concrete gains in several areas. Some indicated that the hands-on activities helped them make predictions about image formation and total internal reflection. Others reported increased confidence in selecting relevant PEK materials and carrying out optics experiments with the support of the kit manual. Participants also described using tables and formula-based reasoning to organise and interpret experimental results, and some reported improved ability to explain image characteristics in spherical mirrors and lenses using ray diagrams.

At the same time, the responses also reveal continuing difficulty in some aspects of inquiry. For example, some participants noted that although they could calculate or tabulate results, they still found it difficult to interpret them using appropriate scientific language. Others reported difficulty in transferring optical ideas from one context to another, such as relating image formation in cameras to the human eye. These findings further support the conclusion drawn from both the descriptive and inferential analyses that, while the intervention produced significant overall gains, the development of higher-order inquiry practices remained more limited and uneven. The self-reported perceptions further validate the inferential findings, suggesting that the statistically significant improvement in test performance coincided with a perceived growth in inquiry-related competencies.

5. Discussion

This study examined how the integration of the PEK within a structured 7E-based inquiry approach supported the development of preservice physics teachers' SIS across two cohorts. The findings show that inquiry skill development was multidimensional, scaffolded, and uneven. Different aspects of inquiry responded differently to the combined material and instructional supports used in the intervention (DeStefano & Widenhorn, 2024; Furtak *et al.*, 2012; Lederman *et al.*, 2013). These findings are supported by both inferential and descriptive evidence and indicate that participation in the PEK-supported inquiry intervention resulted in a statistically significant improvement in preservice teachers' inquiry-related performance.

A key finding is that inquiry skills did not develop uniformly across all dimensions. Observable and participatory skills, such as observation, communication, collaboration, and aspects of data analysis, showed stronger and more consistent improvement. In contrast, more complex practices, including experimental design, higher-level interpretation, and knowledge transfer, were less developed. This pattern supports the view that inquiry competence is not a single skill but a set of different abilities that grow at different rates (Lederman *et al.*, 2013; Özer & Sarıbaş, 2023). Structured inquiry environments appear to support procedural and participatory practices more easily, especially those involving visible activities like observing, discussing, and carrying out guided experiments (Babalola *et al.*, 2020). The hands-on features of the PEK and the structured stages of the 7E model directly support these practices.

However, more advanced inquiry practices require deeper thinking and greater independence. Skills such as designing investigations, interpreting results using scientific language, and applying knowledge across contexts demand higher levels of reasoning (Osborne, 2014). They involve making decisions, justifying ideas, and transferring understanding. The weaker development observed in these areas suggests that such skills are less responsive to short-term interventions. They likely require more time, explicit instruction, and opportunities for independent inquiry. This highlights that engaging in inquiry activities alone does not automatically lead to full scientific understanding. Different dimensions of inquiry require different types and levels of support (Lederman *et al.*, 2013).

The study also highlights the role of the PEK and the 7E model as a dual-layered scaffolding system. The PEK helped make abstract optical concepts more concrete through hands-on activities. At the same time, the 7E model provided a structured learning pathway that guided students through different stages of inquiry (Eisenkraft, 2003). Together, they supported gradual participation in inquiry practices, especially for learners with limited prior experience. The steady improvement across lessons suggests that repeated exposure allowed participants to become more familiar with inquiry processes. Despite this progress, the scaffolding was not equally effective across all inquiry dimensions. It worked well for guided experimentation and collaboration but was less effective in promoting independent thinking and deeper interpretation. This suggests that while scaffolding supports participation, it may also limit autonomy if it is not gradually reduced or adapted (Hmelo-Silver *et al.*, 2007). These findings extend existing views about scaffolding by showing that support structures can favour some inquiry skills over others. They also point to the need for flexible scaffolding that evolves to encourage independence. The very large effect size observed suggests that structured inquiry environments supported by both material and pedagogical scaffolds can produce substantial gains in observable inquiry practices within relatively short instructional periods.

The lesson-by-lesson trends further show that inquiry development is gradual and not always linear. The temporary decline observed midway through the intervention suggests that performance may drop as tasks become more demanding. Rather than indicating failure, such a dip can reflect productive struggle, which is normal when learning complex skills. The improvement in later lessons highlights the importance of sustained engagement and continued support. This aligns with the Educational Design Research perspective, which views learning as an ongoing process shaped by interaction between instructional design and learner experience (McKenney & Reeves, 2013).

The comparison between the two cohorts further reveals the role of iterative design. Although both groups improved, the second cohort showed more consistent and slightly stronger results. This suggests that adjustments made after the first implementation, such as clearer instructions and better alignment between tasks and assessments, improved the effectiveness of the intervention. It shows that instructional tools are not fixed solutions but become more effective when refined over time to suit learners and context.

These findings have important implications for preservice physics teacher education, especially in resource-limited settings. First, tools like the PEK can support active learning by making abstract concepts more tangible and enabling hands-on experimentation. This facilitates the connection between theoretical knowledge and practical application. Second, the study indicates that higher-order inquiry skills require more than structured activities. Skills such as experimental design and knowledge transfer need explicit teaching, opportunities for independent work, and reflection on reasoning. Third, inquiry-based teacher education should be considered a gradual process. The early stages should focus on participation and engagement, while the later stages should emphasise independence, deeper reasoning, and applications across contexts.

Overall, this study contributes to science education research in several ways. It provides evidence that inquiry is multidimensional and develops unevenly. It shows how material and instructional scaffolds interact to support different inquiry skills, such as critical thinking skills and collaborative learning. It also highlights the importance of iterative design in improving teaching effectiveness. By focusing on a resource-constrained context, the study adds to broader discussions on inquiry-based learning. It demonstrates how structured and portable tools can support meaningful engagement while also revealing their limits in developing more advanced inquiry competencies. The PEK hands-on activities not only explain optics concepts to learners but also create a learning environment where learners develop 21st Century skills such as critical thinking, collaboration, creativity and communication skills, which are lifelong learning skills.

6. Limitations

This study should be interpreted with consideration of several limitations. First, the intervention was conducted with two intact cohorts in a single teacher education institution, and participants were not randomly assigned. The findings should therefore be understood as context-bound rather than as evidence of a strong causal effect. Second, because the intervention combined several features, including the PEK, the 7E inquiry structure, facilitator guidance, collaborative group work, and repeated practice, it is not possible to isolate the effect of the PEK alone. Third, although multiple data sources were used, some of the findings relied on participants' self-reports and perceived learning gains, which may not fully correspond to demonstrated competence. Fourth, the intervention covered a limited period and focused on optics within one programme context, which may restrict the transferability of the findings to other science topics or teacher education settings. Despite these limitations, the study provides useful design-based insight into how a portable optics kit can be integrated into inquiry-oriented preservice teacher education in a resource-constrained context.

7. Conclusion

This study examined how the integration of the PEK within a structured, inquiry-based optics intervention supported the development of preservice physics teachers' scientific inquiry skills across two iterative implementation cohorts in Ghana. The findings suggest that the intervention created meaningful opportunities for participants to engage in inquiry-oriented practices through hands-on experimentation, observation, discussion, interpretation, and the application of optical concepts. Across the two cohorts, both the observed lesson trends and participants' self-reports pointed to improvement in several inquiry-related areas, particularly observation, collaboration, critical thinking, analysis of results, and communication during optics activities.

At the same time, the findings also show that inquiry skill development was not uniform across all dimensions. Experimental design, advanced scientific interpretation, and the transference of concepts across contexts are still relatively underdeveloped, indicating that these facets of inquiry necessitate more explicit scaffolding and extended durations of guided practice. The stronger pattern observed in the second cohort further indicates that iterative refinement of the intervention improved its pedagogical fit and strengthened participants' inquiry engagement. This is important because it indicates that the value of the intervention did not lie in the PEK alone but in the way the kit was embedded within a carefully structured, inquiry-based learning design, which included specific teaching strategies and assessment methods that enhanced student engagement and learning outcomes.

All in all, the study contributes context-specific evidence from Ghanaian preservice physics teacher education and shows how a portable optics kit can function as a pedagogical scaffold for inquiry in a resource-constrained setting. The findings suggest that such a tool may be especially useful for supporting active participation and practical engagement in teacher preparation, but more complex inquiry practices need sustained support if they are to develop more fully. Future research should therefore examine the use of similar interventions across longer timeframes, additional science topics, and multiple institutional contexts to better understand their wider applicability and longer-term value in science teacher education.

Conflict of Interest Statement

The author declares no conflicts of interest.

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