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Analyzing Pre-Service Physics Teachers' 4C Skills Through Laboratory Reports to Guide the Enhancement of Physics Laboratory Practices

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ABSTRACT
Developing pre-service physics teachers' critical thinking, creativity, collaboration, and communication (4C) skills is an important goal of science education. This study analyzed these skills through laboratory report assessment and identified instructional priorities for Basic Physics Laboratory learning. A descriptive evaluative design involved 54 pre-service physics teachers at Universitas Islam Negeri Walisongo Semarang. Individual reports from eight practicum modules were assessed using a previously validated 4C-oriented analytic rubric. The results were analyzed descriptively at the dimension and indicator levels. Critical thinking showed the highest achievement (77.7%), followed by collaboration (69.4%) and communication (61.8%); creativity showed the lowest achievement (38.4%). Originality of ideas, scientific discussion, coherence among report sections, and innovative data presentation were identified as priorities for improvement. An assessment-informed framework was proposed to connect these findings with instructional strategies. The framework has not yet been implemented or empirically evaluated. The findings suggest that laboratory report assessment can inform instructional planning by identifying strengths and areas for improvement across the assessed 4C dimensions.

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INTRODUCTION

Preparing pre-service physics teachers for the demands of 21st-century education requires more than developing conceptual knowledge in physics. Future teachers are expected to demonstrate higher-order competencies that enable them to analyze problems critically, generate creative solutions, collaborate effectively, and communicate scientific ideas clearly. These competencies, commonly known as the 4C skills, have become fundamental learning outcomes in science education because they support scientific inquiry, problem solving, and lifelong learning (Piirto, 2021). Among these competencies, critical thinking has received particular attention because it is closely associated with scientific reasoning and evidence-based decision making (Derman & Bezen, 2026; Ma et al., 2023). Creativity is equally important in physics education as it enables learners to construct original explanations and innovative solutions for scientific problems (Ellianawati et al., 2025; Filipe et al., 2024). Meanwhile, collaboration and communication are increasingly recognized as indispensable competencies for conducting scientific investigations and participating in collaborative knowledge construction (Allen et al., 2024; Bressler et al., 2022). Consequently, developing balanced 4C skills has become a major objective of physics teacher education programs, and several recent studies have highlighted the importance of assessing these competencies among prospective physics teachers (Bhakti et al., 2025; Nurhayati et al., 2025).

Physics laboratory courses provide an authentic learning environment in which students actively construct scientific knowledge through experimentation, discussion, and reflection. Unlike lecture-based instruction, laboratory activities require students to formulate hypotheses, solve experimental problems, interpret evidence, justify conclusions, and communicate scientific findings, thereby integrating cognitive, social, and communication processes within a single learning experience (Agustina et al., 2022; Misbah et al.,

2024). Such characteristics make laboratory learning particularly suitable for fostering the 4C skills expected of future physics teachers.

Previous studies have demonstrated that laboratory-based learning can effectively strengthen multiple dimensions of the 4C skills when practical activities are designed around inquiry, collaboration, and authentic problem solving. For example, project-based laboratory learning has been shown to promote critical thinking, creativity, collaboration, and communication simultaneously in physics practicum settings (Firmansyah et al., 2022). Similarly, collaborative computational laboratory activities encourage students to negotiate ideas and solve interdisciplinary scientific problems collectively (Allen et al., 2024), while inquiry-oriented virtual laboratories support scientific communication and collaborative investigation (Fatmaryanti et al., 2022). Other studies also indicate that collaboration during physics practical work contributes positively to conceptual understanding, problem solving, and learning engagement (Bressler et al., 2022; Danzglock et al., 2026; Kosmača & Siiman, 2023). Collectively, these findings suggest that physics laboratory learning provides rich opportunities for simultaneously developing students' critical thinking, creativity, collaboration, and communication skills.

Despite the considerable potential of laboratory learning for developing higher-order competencies, assessment practices in physics laboratories continue to focus primarily on measuring conceptual understanding, procedural accuracy, science process skills, and experimental outcomes (Adlim et al., 2018; Artun et al., 2020). Such assessments are essential for evaluating students' mastery of scientific concepts; however, they provide only limited information about the extent to which students demonstrate the broader competencies required for 21st-century learning (Arslan et al., 2023; Ekici & Erdem, 2020).

Consequently, many studies in physics education have concentrated on developing instructional approaches that enhance specific 4C skills. Problem-based learning has consistently been reported to improve students' critical thinking in physics (Gunawan et al., 2026; Suhirman & Prayogi, 2023; Wahyudi et al., 2023), whereas STEAM- and STEM-based learning environments have shown positive effects on creativity and scientific innovation (Çoban & Erol, 2025; Ellianawati et al., 2025; Khoiri et al., 2023). Likewise, digital learning technologies, augmented reality, and virtual simulations have been widely implemented to strengthen students' higher-order thinking and creative performance (Faridi et al., 2021; Rahmayani et al., 2024; Rizki et al., 2025). Although these instructional interventions have demonstrated encouraging results, considerably less attention has been devoted to how routine laboratory assessment can be utilized to evaluate students' 4C skills comprehensively. Consequently, laboratory assessment often functions primarily as a grading mechanism rather than as a source of evidence for improving laboratory teaching.

Among the various products generated during laboratory learning, laboratory reports represent one of the richest sources of authentic assessment evidence. A laboratory report documents not only the experimental procedures but also students' interpretation of evidence, logical reasoning, justification of conclusions, organization of scientific ideas, and communication of experimental findings. In addition, reports produced through collaborative laboratory activities may also reflect how students negotiate ideas and integrate contributions from different group members (Baloyi et al., 2015; Grooms, 2020; Walker & Sampson, 2013).

The growing emphasis on authentic assessment has encouraged educators to utilize learning artifacts as evidence of complex competencies rather than relying solely on conventional achievement tests. Studies on scientific writing assessment and authentic performance assessment have demonstrated that written products provide valuable evidence of higher-order thinking and scientific reasoning (Sartono et al., 2025; Zakharov et al., 2021). Recent assessment research has also highlighted the importance of developing valid and reliable instruments capable of capturing complex competencies within authentic learning contexts (Bhakti et al., 2025; Hardianto et al., 2025; Kassiavera et al., 2024). Nevertheless, in physics laboratory courses, reports are still predominantly evaluated to determine students' academic achievement. Their potential to reveal strengths and weaknesses across different dimensions of the 4C skills has received relatively limited attention. More importantly, assessment evidence extracted from

laboratory reports has rarely been translated into pedagogically meaningful information that can guide improvements in laboratory instruction.

The limited use of authentic laboratory assessment highlights an important gap between assessment and instructional improvement. In many laboratory courses, assessment concludes once students receive scores or grades, while the information embedded within assessment results remains largely unused for supporting subsequent instructional decisions. Such a practice overlooks the diagnostic value of assessment, particularly for identifying competency areas requiring pedagogical intervention.

Although previous studies have successfully developed assessment instruments for measuring critical thinking and other higher-order competencies in physics education (Bhakti et al., 2025; Nurhayati et al., 2025; Sartono et al., 2025), relatively few have investigated how assessment evidence can be transformed into instructional knowledge for improving laboratory practices. Likewise, studies examining students' critical thinking or creativity generally report competency levels or the effectiveness of instructional interventions (Marisda et al., 2024; Muslim et al., 2025; Nehru et al., 2024), but seldom use authentic assessment results to establish instructional priorities across multiple dimensions of the 4C skills. This study addresses this gap by extending the function of laboratory assessment beyond performance measurement toward instructional diagnosis. Rather than treating laboratory reports solely as summative assessment products, the present study utilizes assessment evidence to identify strengths and weaknesses in pre-service physics teachers' 4C skills and to establish priorities for enhancing physics laboratory practices.

Accordingly, this study analyzes the 4C skills of pre-service physics teachers using evidence obtained from laboratory reports assessed with a previously validated assessment instrument. Specifically, the study aims to identify the strengths and weaknesses of each dimension of the 4C skills, determine instructional priority areas that require further improvement, and propose evidence-based recommendations for enhancing physics laboratory practices. By repositioning authentic laboratory assessment as a source of instructional evidence rather than merely a tool for grading student performance, this study contributes to a more meaningful use of assessment in supporting continuous improvement of laboratory learning and the development of future physics teachers' 4C skills.

METHODS

The methodological procedures employed to analyze pre-service physics teachers' 4C skills and establish instructional priorities for enhancing Basic Physics Laboratory learning are described in the following sections.

Research Design

This study employed a descriptive evaluative design to analyze the 4C skills demonstrated by pre-service physics teachers through laboratory reports. The study utilized a previously validated laboratory report assessment rubric to generate diagnostic information on students' critical thinking, creativity, collaboration, and communication skills. The analysis was intended to identify competency strengths and weaknesses and to establish instructional priorities for enhancing physics laboratory practices.

Participants

The participants were 54 pre-service physics teachers enrolled in the Basic Physics Laboratory course at Universitas Islam Negeri Walisongo Semarang during the 2025/2026 academic year. Purposive sampling was employed because the participants had completed all laboratory activities included in the course and submitted laboratory reports that met the assessment requirements. The laboratory curriculum covered basic measurement, mechanics, oscillations, fluid mechanics, thermodynamics, and collision phenomena, represented through eight practicum modules involving measurement, mathematical pendulum, spring oscillation, Atwood machine, viscosity, calorimetry, collisions, and projectile motion. Each participant's laboratory reports were assessed individually across the completed practicum modules rather than using a single representative report, and the resulting scores were used to describe the participant's 4C skill achievement at both the dimension and indicator levels.

Instrument and Data Collection

Data were collected using students' laboratory reports, which were assessed with a validated 4C laboratory report assessment rubric developed in a previous study (Fariyani et al., 2024). The rubric comprised four dimensions (critical thinking, creativity, collaboration, and communication) represented by eight assessment indicators. Each indicator was operationalized through observable assessment criteria reflecting the manifestation of the corresponding 4C skill in laboratory reports.

Critical thinking was assessed through three indicators: completeness of report components, accuracy of data analysis, and depth of scientific discussion. Creativity comprised two indicators: originality of ideas and innovative presentation of data and analysis. Collaboration was assessed through one indicator concerning coordination and integration among group members as reflected in the laboratory report. Communication comprised two indicators: systematic scientific writing and coherence among report sections.

The rubric employed criterion-referenced analytic scoring, with scoring ranges varying across indicators. The completeness of report components was scored on a 1–10 scale based on the number of required report components fulfilled. Accuracy of data analysis, depth of scientific discussion, innovative presentation of data and analysis, and systematic scientific writing were scored on a 1–4 scale according to the specified criteria, whereas collaboration and coherence among report sections were scored on a 1–3 scale. Originality of ideas was assessed using four criteria, each scored 0 (not met) or 1 (met), giving a total score of 0–4. The percentage was calculated as the mean total score divided by the maximum score of 4, multiplied by 100% (0.870 ÷ 4 × 100% = 21.75%). For each indicator, higher scores represented a greater degree of fulfillment of the specified assessment criteria.

Laboratory data collection was conducted collaboratively in small groups, but each student prepared and submitted a laboratory report individually. Students within the same group therefore worked with the same experimental data, while their reports could receive different scores according to their individual analysis, interpretation, presentation, and writing. At the completion of each laboratory activity, the individual reports were collected and evaluated using the rubric. All reports were assessed by a single instructor using the same validated rubric. Because the assessment involved a single rater, inter-rater reliability was not applicable. The assessment covered eight practicum modules addressing basic measurement, mechanics, oscillations, fluid mechanics, thermodynamics, and collision phenomena.

Data Analysis

The assessment results were analyzed descriptively for diagnostic purposes. First, the scores obtained by each student across the completed practicum modules were converted into percentage achievement scores relative to the maximum possible score for each 4C dimension. This procedure accounted for the different scoring ranges of the indicators within the rubric. Second, the percentage achievement of each student was calculated for the four 4C dimensions (critical thinking, creativity, collaboration, and communication) and the mean percentage across the 54 participants was used to describe overall achievement for each dimension. Standard deviations and score ranges were also calculated to describe variation in student achievement.

At the indicator level, mean percentage achievement was examined to identify specific strengths and areas requiring instructional improvement. Indicators with relatively lower achievement were identified as instructional priority areas, whereas indicators with relatively higher achievement were interpreted as existing strengths to be maintained and reinforced. The dimension- and indicator-level findings were then used to formulate assessment-informed priorities for improving Basic Physics Laboratory instruction.

RESULTS AND DISCUSSION

The findings of the laboratory report assessment are presented and discussed in three stages: overall analysis of students' 4C skills, indicator-level analysis, and translating assessment evidence into instructional priorities for enhancing Basic Physics Laboratory learning.

Overall Analysis of Pre-Service Physics Teachers' 4C Skills

The overall achievement of pre-service physics

teachers' 4C skills is presented in Figure 1. The figure shows the mean percentage achievement across the 54 participants for each 4C dimension, calculated from the students' individual assessment results across the completed Basic Physics Laboratory activities. The results provide an overall profile of students' demonstrated critical thinking, creativity, collaboration, and communication skills based on their individual laboratory reports.

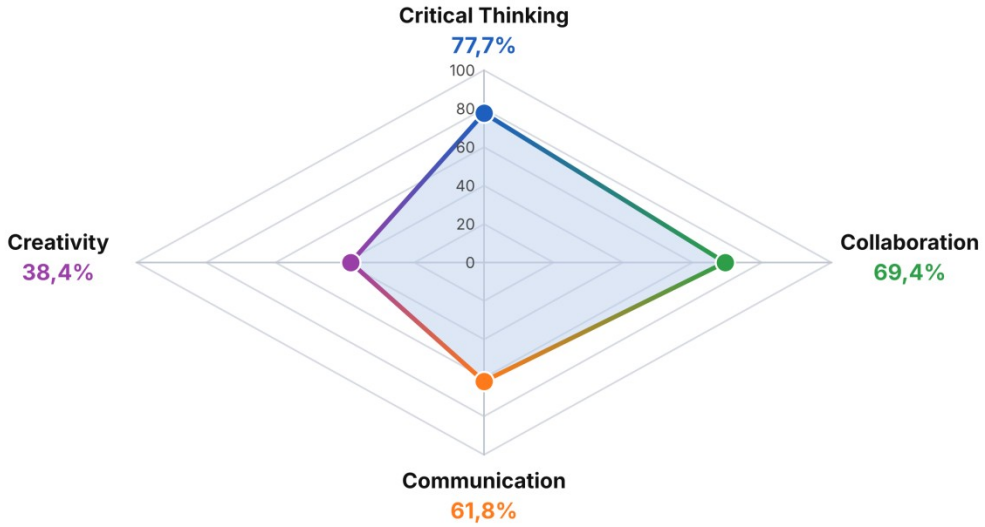

Figure 1. Mean percentage achievement of pre-service physics teachers' 4C skills

As shown in Figure 1, pre-service physics teachers demonstrated different levels of achievement across the four dimensions of the 4C skills. The radar profile illustrates an uneven distribution of competencies, showing higher assessed achievement in some dimensions of the 4C skills than in others. Critical thinking emerged as the strongest competency, with an achievement of 77.7%, followed by collaboration (69.4%) and communication (61.8%). In contrast, creativity recorded the lowest achievement, reaching only 38.4%. These findings indicate relatively strong analytical performance in the assessed reports and identify creativity and scientific communication as potential priorities for instructional improvement.

The relatively high achievement in critical thinking reflects students' ability to analyze experimental data, interpret observations, and formulate conclusions based on empirical evidence. Such findings are consistent with the fundamental characteristics of physics laboratory learning, where students continuously engage in observation, measurement, evidence interpretation, and scientific reasoning. Laboratory environments naturally encourage students to evaluate data rather than merely memorize concepts, making critical thinking one of the competencies most frequently developed during practical work. Previous studies similarly reported that inquiry-oriented physics instruction and laboratory-based learning significantly improve students' critical thinking because students are required to justify conclusions using experimental evidence instead of relying solely on theoretical knowledge (Sermeus et al., 2021; Ubaidillah et al., 2023). Likewise, Bhakti et al. (2025) demonstrated that contextual physics assessment effectively captures students' critical thinking performance by emphasizing scientific reasoning rather than factual recall, while Gunawan et al. (2026) showed that project-based learning integrated with digital learning resources further strengthens analytical thinking among pre-service physics teachers.

Although critical thinking achieved the highest score, the findings should not be interpreted as indicating that this competency has been fully developed. Rather, the result indicates higher assessed achievement in analytical reasoning than in other components of the 4C skills. As argued by Heim et al. (2025), critical thinking in physics extends beyond analyzing experimental data to include interdisciplinary reasoning, evaluating alternative explanations, and making evidence-informed decisions. Therefore, maintaining

students' relatively strong critical thinking should remain an important objective while simultaneously expanding opportunities for higher levels of scientific reasoning.

In contrast, creativity was identified as the weakest dimension of students' 4C skills. The considerably lower achievement suggests that students demonstrated limited originality in proposing ideas, developing alternative interpretations, or presenting experimental findings in innovative ways. Instead, most laboratory reports closely followed the prescribed procedures and reporting structures provided in the laboratory manual. Such findings indicate that the current laboratory implementation remains predominantly verification-oriented, where students reproduce existing experimental procedures rather than explore multiple scientific possibilities. Similar observations have been reported by Piirto (2021), who argued that creativity requires learning environments that encourage originality, flexibility, and divergent thinking rather than procedural conformity. Likewise, Filipe et al. (2024) found that integrated STEAM learning enhances students' creativity by providing authentic opportunities for designing and evaluating alternative solutions. Ellianawati et al. (2025) further demonstrated that collaborative STEAM-based learning improves creativity when students are encouraged to solve real-world scientific problems through multiple approaches instead of completing predetermined experimental procedures.

The moderate achievement in collaboration (69.4%) indicates that students generally participated effectively in group laboratory activities. Nevertheless, the assessment results also suggest that collaboration was primarily reflected through task completion rather than through deeper collaborative knowledge construction. Effective collaboration in scientific inquiry requires students to exchange ideas, negotiate interpretations, critique evidence, and construct shared understanding collectively. Allen et al. (2024) emphasized that collaborative laboratory activities are most effective when students jointly solve authentic scientific problems instead of simply distributing tasks among group members. Similarly, Danzglock et al. (2026) demonstrated that collaborative interaction contributes substantially to conceptual learning only when group members actively discuss and evaluate alternative reasoning. Therefore, the present findings imply that future laboratory activities should place greater emphasis on collaborative scientific discourse rather than procedural cooperation alone.

Communication demonstrated a moderate level of achievement (61.8%), indicating that students were generally capable of preparing structured laboratory reports but experienced greater difficulty in constructing coherent scientific explanations. Scientific communication within laboratory learning extends beyond writing reports according to prescribed formats; it also involves presenting logical arguments, linking evidence with theoretical concepts, and communicating conclusions in a scientifically convincing manner. Fatmaryanti et al. (2022) highlighted that inquiry-based laboratory learning supports scientific communication when students are explicitly guided to justify interpretations and discuss experimental findings critically. Likewise, Muslim et al. (2025) reported that integrating scientific writing heuristics into physics learning significantly improves students' ability to communicate scientific reasoning. The present findings therefore suggest that communication skills should be strengthened by increasing opportunities for argumentative writing, peer review, and reflective discussion during laboratory activities.

Overall, the competency profile presented in Figure 1 demonstrates that students demonstrated relatively strong analytical performance in the assessed reports, alongside an uneven profile across the four dimensions of the 4C skills. The substantial gap between critical thinking and creativity indicates that students are more accustomed to analyzing existing evidence than generating original scientific ideas. Likewise, the moderate performance in collaboration and communication suggests that laboratory activities still emphasize procedural completion over collaborative knowledge construction and scientific argumentation. These findings support the growing view that laboratory learning should evolve from a verification-oriented model toward a more authentic inquiry environment that intentionally integrates opportunities for creativity, collaboration, and scientific communication alongside critical thinking (Allen et al., 2024; Fatmaryanti et al., 2022; Firmansyah et al., 2022). Consequently,

assessment should not merely document students' achievement but also serve as diagnostic evidence for identifying competency areas that require pedagogical improvement. The indicator-level analysis presented in the following section provides a more detailed understanding of the specific strengths and weaknesses underlying the overall 4C competency profile.

Indicator-Level Analysis of Each 4C Skill

Figure 2 illustrates the mean percentage achievement of the eight assessment indicators representing the four dimensions of 4C skills across the 54 participants. The indicator-level analysis provides a more detailed profile of students' 4C skills than the dimension-level results presented in Figure 1, allowing differences in achievement among indicators within the same dimension to be identified. By revealing relative strengths and lower-achievement areas at the indicator level, the analysis provides diagnostic evidence for determining instructional priorities and informing the enhancement of Basic Physics Laboratory learning.

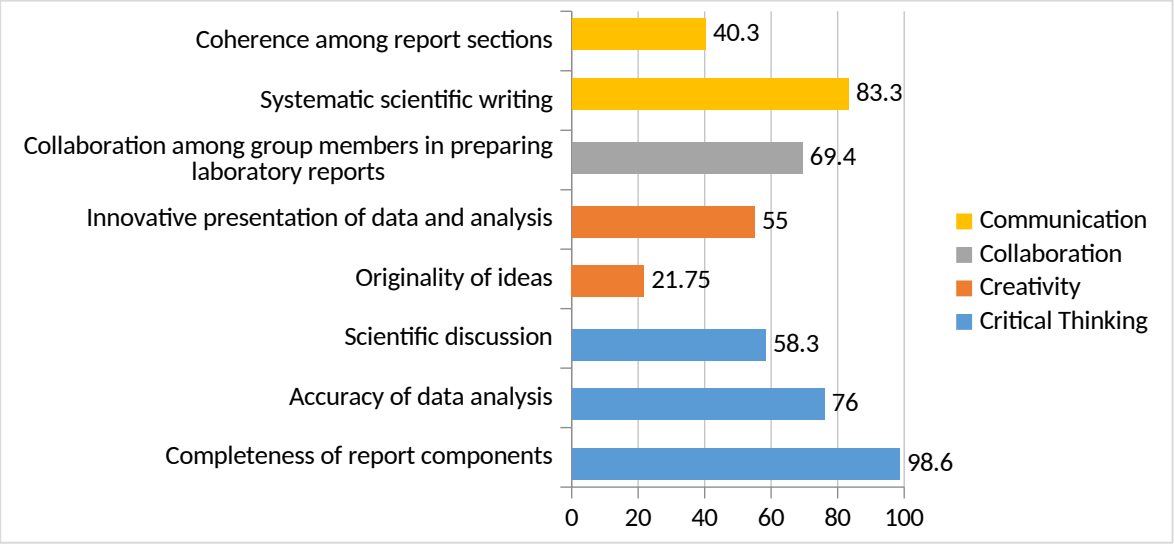

Figure 2. Mean percentage achievement of the eight indicators of pre-service physics teachers' 4C skills

As illustrated in Figure 2, the indicator-level analysis provides a more detailed understanding of students' demonstrated competencies than the overall 4C profile alone. Although the overall analysis identified critical thinking as the strongest dimension, the indicator analysis reveals considerable variation among the individual competencies that constitute each dimension. This finding highlights the importance of examining assessment results beyond aggregated scores, as overall achievement may conceal specific strengths and weaknesses that are pedagogically meaningful.

The highest achievement was observed for the completeness of laboratory report components (98.6%). Nearly all students successfully included the required sections of a scientific report, indicating familiarity with the expected report structure and laboratory documentation procedures. This result suggests that students were well accustomed to the formal requirements of laboratory reporting, possibly because report organization followed a standardized format throughout the laboratory course. In the rubric used in this study, completeness of report components was classified under critical thinking because a complete report provides the structural context in which students document their observations, analyzes, interpretations, and conclusions. However, this indicator does not by itself constitute direct evidence of higher-order critical thinking, as the presence of required report sections primarily reflects compliance with reporting conventions rather than the quality of reasoning expressed within those sections.

This distinction is important when interpreting the overall critical thinking score of 77.7%, because the 98.6% completeness score contributes substantially to the dimension-level result.

Therefore, the critical thinking result should be interpreted as reflecting a combination of report completeness and the quality of students' data analysis and scientific discussion, rather than as a direct measure of sophisticated critical reasoning alone. The relatively high completeness score thus indicates strength in laboratory reporting procedures, whereas evidence of critical thinking is more directly reflected in indicators concerning the accuracy and depth of data analysis and scientific discussion. This finding is consistent with the distinction made in authentic assessment research between adherence to reporting conventions and the demonstration of scientific reasoning (Hardianto et al., 2025; Zakharov et al., 2021).

A different pattern emerged for the remaining critical thinking indicators. While students demonstrated relatively good performance in the accuracy of data analysis (76.0%), achievement declined noticeably for the scientific discussion indicator (58.3%). This discrepancy indicates that students were generally capable of processing experimental data and performing calculations but experienced greater difficulty when interpreting the meaning of those findings within relevant scientific concepts. Such a pattern has frequently been reported in physics education, where students are often proficient in executing experimental procedures yet struggle to construct evidence-based explanations and evaluate experimental results critically (Ma et al., 2023; Sermeus et al., 2021). Developing scientific discussion therefore requires instructional activities that explicitly support argumentation, justification, and reflective interpretation rather than focusing solely on procedural accuracy (Muslim et al., 2025; Siswanto et al., 2025).

The most prominent weakness identified in this study was the originality of ideas, which achieved only 21.75%, the lowest score among all indicators. This finding suggests that laboratory reports rarely contained original interpretations, alternative explanations, or independently developed ideas beyond those provided in the laboratory manual. Instead, students tended to reproduce established procedures and conventional explanations. Such results imply that the current laboratory activities remain predominantly verification-oriented, leaving limited opportunities for divergent thinking and creative inquiry. Previous studies consistently argue that creativity cannot develop optimally within highly structured laboratory environments but requires open-ended investigations, authentic design challenges, and opportunities to generate multiple solutions (Filipe et al., 2024; Piirto, 2021). Similar findings have also been reported in physics education, where creativity improves significantly when students engage in project-based or STEAM-oriented laboratory activities that encourage innovation and independent exploration (Çoban & Erol, 2025; Ellianawati et al., 2025).

The second creativity indicator, innovative presentation of data and analysis (55.0%), also demonstrated relatively low achievement. Although students generally presented experimental data correctly, they rarely employed alternative visualizations, comparative representations, or innovative approaches to communicating scientific evidence. Most reports relied on conventional tables and standard calculations without extending the presentation through graphical comparisons or interpretative visual representations. This finding supports previous research showing that creativity in science education encompasses not only idea generation but also the ability to communicate scientific information in meaningful and original ways (Hai et al., 2023; Rizki et al., 2025).

Communication indicators revealed another noteworthy contrast. Students achieved a relatively high score for systematic scientific writing (83.3%), indicating that they generally followed the prescribed structure of laboratory reports. However, the achievement decreased substantially for coherence among report sections (40.3%), suggesting that many reports lacked logical connections between objectives, methods, results, discussions, and conclusions. In other words, students understood how to organize report sections but encountered difficulties in constructing an integrated scientific narrative. This finding reinforces the view that scientific communication extends beyond adherence to writing conventions and requires coherent reasoning supported by empirical evidence (Fatmaryanti et al., 2022). Similar observations were reported by Muslim et al. (2025), who found that students' scientific writing improved when instructional activities explicitly emphasized evidence-based argumentation and reflective explanation. To address this gap, laboratory instruction could incorporate structured

scaffolding that explicitly connects evidence across report sections. For example, claim–evidence–reasoning (CER) guiding questions could help students formulate claims from their experimental findings, identify the evidence supporting those claims, and explain the underlying physical principles. Section-linking prompts or guided writing checklists could require students to connect the stated objectives with the methods used, relate results to the objectives in the discussion, and derive conclusions directly from the evidence presented. Annotated model reports and brief peer-review activities could further help students identify and revise breaks in logical coherence before submitting their final reports.

The collaboration indicator showed moderate achievement (69.4%), indicating that students generally worked together in completing laboratory reports. Nevertheless, the assessment evidence primarily reflected collaborative task completion rather than collaborative knowledge construction. Effective collaboration requires students to negotiate interpretations, exchange arguments, evaluate evidence collectively, and develop shared understanding throughout the inquiry process (Allen et al., 2024). Research has shown that collaborative learning produces greater educational benefits when interaction is characterized by active discussion and joint reasoning instead of simple division of labor (Bressler et al., 2022; Danzglock et al., 2026). To strengthen collaborative knowledge construction during laboratory inquiry, instruction could assign structured and rotating roles, such as data analyst, evidence evaluator, discussion facilitator, and scientific critic, with each member responsible for a distinct contribution to interpreting and evaluating the experimental evidence. Role-specific guiding questions could require students to explain their reasoning to peers, question alternative interpretations, and reach a shared conclusion based on the available evidence. Requiring brief group discussion records or jointly developed evidence-based conclusions could further make the collaborative reasoning process more explicit rather than focusing only on the completion of assigned tasks.

Taken together, the indicator-level analysis demonstrates that the principal challenges in developing students' 4C skills do not lie in mastering procedural aspects of laboratory work but in cultivating higher-order scientific practices. Students performed well in organizing reports and conducting data analysis, yet showed considerably lower achievement in generating original ideas, constructing coherent scientific arguments, and developing in-depth scientific discussions. These findings suggest that future improvements in Basic Physics Laboratory learning should focus less on reinforcing procedural laboratory skills and more on creating learning environments that promote creativity, scientific argumentation, collaborative knowledge construction, and reflective communication. Consequently, the assessment results provide not only evidence of students' current competencies but also a diagnostic basis for determining instructional priorities, which are discussed in the following section.

Translating Assessment Evidence into Instructional Priorities for Physics Laboratory Learning

The indicator-level analysis demonstrates that laboratory reports provide more than evidence of students' academic performance. When interpreted diagnostically, the assessment results reveal specific competency areas that require pedagogical attention and therefore offer a valuable basis for improving laboratory instruction. Rather than treating assessment as the final stage of learning, the present findings support a formative perspective in which assessment evidence informs instructional decision-making and guides the continuous enhancement of laboratory learning.

The results indicate that students exhibited relatively strong performance in procedural aspects of laboratory work, including the completeness of report components and systematic scientific writing. However, considerably lower achievement was observed in originality of ideas, coherence among report sections, scientific discussion, and innovative presentation of data. These findings suggest that students demonstrated procedural competence in their reports, while authentic scientific inquiry, creative problem solving, and reflective scientific communication remain potential areas for instructional development. Similar concerns have been raised in contemporary physics education research, which argues that laboratory instruction should move beyond verification experiments toward inquiry-oriented environments that

encourage students to construct knowledge, evaluate evidence, and communicate scientific arguments (Allen et al., 2024; Fatmaryanti et al., 2022; Firmansyah et al., 2022).

Accordingly, the assessment findings were synthesized into a set of instructional priorities, as presented in Table 1. Each priority was derived from indicators with relatively low mean achievement and was linked to instructional strategies intended to address the specific weakness identified in the assessment. The suggested strategies were informed by evidence-based approaches reported in previous studies.

Table 1. Instructional priorities derived from indicator-level assessment findings

Assessment finding	Interpretation	Instructional priority	Suggested laboratory strategy
Originality of ideas (21.75%)	Students relied heavily on laboratory manuals and reproduced existing procedures.	Foster creative scientific inquiry.	Introduce open-ended investigations that allow multiple possible solutions, require students to formulate their own hypotheses, and encourage them to propose alternative experimental designs (Filipe et al., 2024; Piirto, 2021).
Coherence among report sections (40.3%)	Students experienced difficulty connecting objectives, methods, results, discussion, and conclusions into a coherent scientific narrative.	Strengthen scientific argumentation and writing.	Provide structured scientific-writing guidance that requires students to explicitly link the research objective to the method, connect results to the discussion, and derive conclusions from the reported evidence. Guided questions, annotated model reports, and peer review can be incorporated throughout the reporting process (Fatmaryanti et al., 2022; Muslim et al., 2025).
Innovative presentation of data (55.0%)	Data presentation remained conventional and descriptive.	Promote multiple scientific representations.	Require students to represent experimental findings using more than one appropriate form, such as graphs, tables, concept maps, comparative visualizations, or digital representations, and to justify why each representation is appropriate for the data (Hai et al., 2023; Rizki et al., 2025).
Scientific discussion (58.3%)	Students interpreted data descriptively but provided limited scientific justification.	Improve evidence-based reasoning.	Integrate argument-driven inquiry, guided scientific questions, and evidence-based discussion activities that require students to interpret experimental results, relate them to relevant physics concepts, justify claims with evidence, and discuss possible sources of discrepancy (Sermeus et al., 2021; Siswanto et al., 2025).
Collaboration (69.4%)	Collaboration focused primarily on task completion.	Develop collaborative knowledge construction.	Design laboratory investigations with structured and rotating collaborative roles, such as data analyst, evidence evaluator, discussion facilitator, and scientific critic, requiring students to compare interpretations, critique peers' reasoning, and reach shared evidence-based conclusions rather than simply divide tasks (Allen et al., 2024; Danzglock et al., 2026).

Table 1 demonstrates that each instructional priority is explicitly linked to assessment evidence rather than derived from general pedagogical assumptions. This evidence-based approach enables laboratory instructors to identify which aspects of students' competencies require the greatest instructional attention and to align learning activities with the specific competencies that need further development. Such use of assessment extends its traditional summative function by

supporting data-informed instructional planning.

Building upon these priorities, a conceptual framework is proposed to illustrate how assessment evidence can be systematically translated into improvements in laboratory learning (Figure 3).

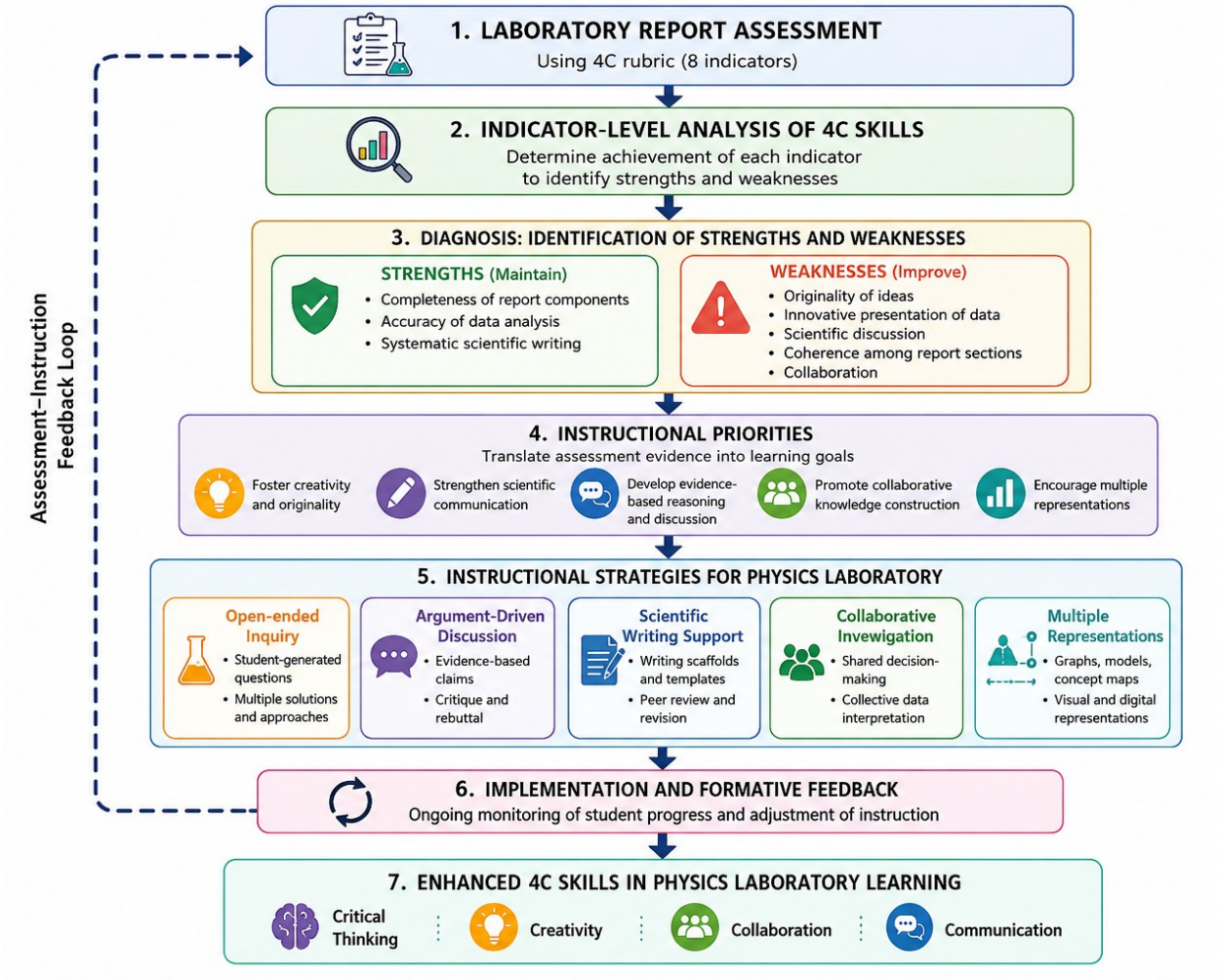

Figure 3. Assessment-informed framework for enhancing 4C skills in physics laboratory learning

The proposed framework positions assessment as an integral component of instructional improvement rather than merely an instrument for measuring student achievement. Instead of ending the assessment process with numerical scores, laboratory report evaluation becomes the starting point for identifying competency gaps and determining subsequent instructional actions. This perspective is consistent with the growing emphasis on assessment for learning, which views assessment as a continuous source of evidence for improving teaching and learning processes rather than solely for certifying learning outcomes (Zakharov et al., 2021).

The framework also reflects recent developments in physics laboratory education that advocate a shift from verification-oriented practical work toward authentic inquiry and collaborative knowledge construction. Previous studies have demonstrated that open-ended laboratory investigations provide greater opportunities for developing creativity and critical thinking because students are encouraged to formulate hypotheses, evaluate alternative explanations, and design their own investigative approaches (Çoban & Erol, 2025; Ellianawati et al., 2025). Similarly, collaborative inquiry and argument-driven laboratory instruction have been shown to strengthen scientific communication and collaborative reasoning by engaging students in negotiating evidence and constructing shared explanations (Allen et al., 2024; Bressler et al., 2022; Danzglock et al., 2026).

An important implication of this study is that authentic assessment can serve not only as a means of evaluating learning outcomes but also as a mechanism for guiding curriculum refinement and instructional redesign. Through systematic analysis of laboratory reports, instructors can identify specific competency gaps and subsequently select learning strategies that directly target those weaknesses. This approach enables continuous improvement of laboratory learning based on empirical evidence generated during routine instructional practice, thereby strengthening the alignment between assessment, instruction, and the intended development of 4C skills.

Finally, although the proposed framework has not yet been implemented or empirically evaluated, it offers a theoretically informed model grounded in authentic assessment evidence. Future studies should empirically evaluate the framework using indicators such as changes in students' mean 4C achievement percentages, effect sizes of pre–post changes, and improvements in the specific indicators identified as instructional priorities, particularly originality of ideas, coherence among report sections, innovative presentation of data, scientific discussion, and collaborative knowledge construction. Changes in the quality of laboratory reports and students' perceptions of the laboratory learning process may also be examined as complementary outcomes. Such studies could investigate the effectiveness of the framework across different laboratory contexts and science disciplines.

CONCLUSION

This study shows that laboratory report assessment provides valuable evidence for analyzing pre-service physics teachers' 4C skills beyond measuring academic achievement. The findings revealed an uneven competency profile, with critical thinking emerging as the strongest dimension, while creativity represented the greatest area for improvement. Indicator-level analysis further identified specific weaknesses in originality of ideas, scientific discussion, report coherence, and innovative data presentation, indicating that students require greater opportunities to engage in authentic inquiry, scientific argumentation, and creative problem solving. Based on these findings, an assessment-informed framework was proposed to translate diagnostic evidence into instructional priorities for improving physics laboratory learning. Although the proposed framework has not yet been empirically implemented, it offers a practical and evidence-based reference for physics teacher educators seeking to redesign laboratory instruction around students' diagnosed learning needs and to provide more structured opportunities for inquiry, scientific reasoning, creative thinking, and collaborative engagement. Future studies should examine how the framework can be implemented and evaluated within physics teacher education, particularly through laboratory learning designs that target the identified areas of weakness and support more balanced development of critical thinking, creativity, collaboration, and communication.

DECLARATIONS

Author Contributions: The authors' contributions were defined according to the Contributor Roles Taxonomy (CRediT). Qisthi Fariyani: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Project administration. Widyastuti: Investigation, Writing – review & editing. Anisya Nur Faizah: Resources. All authors have read and approved the final version of the manuscript.

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Declaration of Generative AI Use: During the preparation of this manuscript, Grammarly was used to improve language, grammar, and readability, while ChatGPT (OpenAI) was used solely to assist in creating the visual representation in Figure 3. No AI tools were used to generate research data, develop research ideas, conduct data analysis, interpret findings, or formulate conclusions. Following the use of these

applications, the authors carefully reviewed and edited the manuscript as necessary and take full responsibility for the content, accuracy, and integrity of the publication.

Ethics Statement: Ethical principles were observed throughout the research process. Participation was voluntary, and informed consent was obtained from all participants before data collection. Participants were informed about the purpose of the study and the confidentiality of the collected data. All data were handled confidentially and used solely for research purposes. Personal information that could identify individual participants was not disclosed in the publication.

Data Availability: The anonymized data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to applicable ethical and data confidentiality requirements.

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