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4C Competencies of Laboratory Assistants: A Catalyst for Improved Experimental Comprehension in Physics Education

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Abstract: This study addresses a pressing issue in physics education: the underutilization of laboratory assistants as facilitators of conceptual learning, particularly in experimental settings. Despite their vital role, the impact of their 21st century competencies, known as the 4C skills on students' experimental comprehension remains underexplored. This study investigates the influence of laboratory assistants' 4C competencies on Students' Experimental Comprehension (SEC) in Basic Physics Practicum I and II at the Physics Education Study Program, UIN Sunan Gunung Djati Bandung. Employing a quantitative quasi-experimental approach, data were collected from 29 laboratory assistants and 401 students between 2020 and 2024. Validated instruments, including written tests, structured observation sheets, and documentation of practicum results, ensured methodological rigor. Multiple linear regression analysis revealed that the 4C competencies significantly predicted SEC (R^2 = 0.869), with creativity (β = 0.461) and critical thinking (β = 0.350) emerging as the most influential dimensions. Pearson correlation further confirmed strong positive relationships between each competency and SEC. The findings highlight the critical role of soft skills in laboratory-based science education and suggest that structured training in 4C competencies can substantially enhance experimental learning outcomes. This research provides new insights for curriculum developers, educational policymakers, and laboratory supervisors seeking to improve practicum quality by empowering laboratory assistants as active pedagogical agents.

INTRODUCTION

Education is a holistic process that goes beyond acquiring knowledge to include the development of skills, values, attitudes, and the ability to apply knowledge critically and ethically in real-life situations (Chang et al., 2022). Learning can be achieved through various approaches, depending on the context, learning goals, and student needs. Two common but distinct strategies are conceptual learning, which typically takes place in classrooms and focuses on theoretical understanding, and laboratory-based learning, which emphasizes hands-on, experiential activities (Agustina et al., 2024). In addition to these, other pedagogical models, such as project-based learning, problem-based learning, inquiry-based learning, and online or blended learning have also been shown to enhance student engagement and deepen understanding (Almulla, 2020). Laboratory-based learning is especially important in science education because it helps students connect theory to practice, develop scientific reasoning, and construct knowledge actively. However, it is not inherently more effective than conceptual learning, so its success depends on how well it is integrated with other instructional methods and aligned with specific learning objectives (Reyes et al., 2024).

Laboratory activities are vital in science education, allowing students to apply theory through hands-on practice while developing analytical and problem-solving skills (Castro & Morales, 2017; Kumari et al., 2024). In Indonesia, limited lecturer availability often leads to reliance on laboratory assistants typically senior students or recent graduates who support instruction, ensure safety, and guide experiments (Malik & Ubaidillah, 2021). Assistants with strong soft skills, especially the 4C competencies can significantly enhance student engagement and learning outcomes (Herro et al., 2021; Sarvary et al., 2025). These skills are essential for guiding teamwork, solving problems, and adapting to diverse needs in inquiry-based learning environments (Dirgantara et al., 2024; Purnama et al., 2021). To build these competencies, training should include methods like scenario-based problem solving, collaborative microteaching, design thinking, reflective journaling, and mentorship (Geraets et al., 2021; Zheng et al., 2024). Evidence shows that such training boosts assistant confidence, improves student interaction, and leads to better learning outcomes (Williams et al., 2023), making 4C-focused preparation essential for high-quality science education.

Despite the central role of laboratory activities in science education, limited research has examined how laboratory assistants' competencies, especially 4C skills affect student learning outcomes. Most studies focus on infrastructure or teaching methods, often neglecting the assistants' instructional impact, particularly in Indonesia where assistants frequently lead lab sessions (Junaidi et al., 2024). Many lack structured training or pedagogical support, leading to procedural teaching that limits student understanding (Rini et al., 2024; Walsh et al., 2022). Without strong 4C skills, even well-planned experiments may not foster meaningful learning (Agustina & Putra 2022). Moreover, assistants are often viewed as technical staff rather than educators, resulting in minimal training and support (Sastria, 2024). Educational policies should address this by providing formal training, certification, and supervision (Kayal & Khalife, 2025). Studies show that assistants with strong 4C skills enhance student engagement, inquiry, and problem-solving (Gudyanga & Jita, 2019; Parmar et al., 2024), making it essential to explore and strengthen these competencies through evidence-based programs.

Although laboratory activities are a key part of science education, limited research has explored how laboratory assistants' competencies directly influence student learning. Most existing studies focus on infrastructure, teaching methods, or student motivation, often overlooking the assistants' instructional role. In Indonesia, laboratory sessions are frequently led by assistants, making their impact especially significant (Junaidi et al., 2024). However, as noted by Marisda et al., (Marisda et al., 2022), these assistants may not always use strategies that support student understanding, potentially reducing the effectiveness of laboratory learning. This challenge is compounded by a lack of structured training and pedagogical support for assistants in many Indonesian institutions (Rini et al., 2024). Agustina and Putra (2022) emphasize that 4C skills are crucial for effective knowledge transfer. Without these skills, even well-designed experiments may fail to promote deep understanding. The current lack of empirical studies linking assistants' 4C competencies to students' experimental comprehension (SEC) highlights a critical gap in science education research.

Neglecting the teaching competencies of laboratory assistants can result in lab sessions that are procedural rather than inquiry-based, limiting students' development of scientific reasoning and experimental skills (Walsh et al., 2022). To address this, educational policies should promote formal training programs focused on 4C competencies, pedagogical certification, and ongoing supervision (Kayal & Khalife, 2025). In many Indonesian institutions, assistants are still seen mainly as technical staff, which leads to limited training and minimal involvement in teaching (Sastria, 2024). This underuse of their potential weakens the overall effectiveness of laboratory instruction, which depends on active, real-time support (Gudyanga & Jita, 2019; May et al., 2023). Studies show that when assistants possess strong 4C skills, they enhance student engagement, inquiry, and problem-solving during lab work (Parmar et al., 2024). Understanding the impact of these competencies is therefore essential for developing evidence-based training programs that strengthen the educational role of laboratory assistants.

This study is grounded in several learning theories that highlight the active role of students and the supportive role of laboratory assistants in enhancing learning. Constructivist theory emphasizes that students learn more effectively through hands-on activities, problem-solving, and social interaction rather than passive observation (Efgivia et al., 2021). Vygotsky's Zone of Proximal Development (ZPD) supports this by stressing the importance of guidance from more knowledgeable individuals such as lab assistants who provide scaffolding until students can perform tasks independently (Cooper et al., 2024; Ness, 2023). The effectiveness of these assistants is enhanced by 4C competencies, including clear communication, creativity, and critical thinking, which help address student misconceptions and adapt instruction (Agustian et al., 2022). Social Learning Theory further suggests that students learn by observing and imitating assistants' behavior, such as safe lab practices and problem-solving strategies (Bandura, 1999; Ilmiani et al., 2021). Finally, Cognitive Load Theory (CLT) highlights the need to manage students' mental effort in complex lab tasks by simplifying instructions, using demonstrations, and offering guided practice (Makransky et al., 2019; Sweller, 2022). Together, these theories frame laboratory assistants as essential mediators of learning whose impact is maximized through strong 4C skills.

Based on the background and theoretical framework, this study investigates the impact of laboratory assistants' 4C competencies on Students' Experimental Comprehension (SEC) in Basic Physics Practicum I and II at UIN Sunan Gunung Djati Bandung. Using validated instruments such as surveys, structured observations, and student feedback, the study offers empirical evidence that can inform future research in science education, especially in lab-based learning environments where assistants support instruction. Although external factors like institutional policies, lab facilities, or prior student knowledge were not included, the findings highlight the importance of developing assistants' soft skills. The study recommends that institutions incorporate structured 4C skill training, adjust assistant selection criteria to emphasize teaching potential, and implement regular evaluations. These steps can enhance instructional quality and serve as a model for improving laboratory education in other physics programs.

METHOD

This study used a quantitative, quasi-experimental design to examine the impact of laboratory assistants' 4C competencies on Students' Experimental Comprehension (SEC). Data were collected throughout the entire practicum period to capture a complete picture of student learning. To control for potential confounding factors, such as differences in student backgrounds, teaching environments, or assistant-student interactions, several statistical tests were applied. These included classical assumption tests for normality, multicollinearity, and heteroscedasticity to ensure the validity of the regression analysis. A purposive sampling method and the use of consistent assessment tools across cohorts further enhanced the reliability and comparability of the results.

This study involved laboratory assistants and first-semester students from the Physics Education Study Program at UIN Sunan Gunung Djati Bandung, spanning cohorts from 2020 to 2024. Participants were selected through purposive sampling based on specific criteria: assistants were 5th-semester students who had completed required courses and were actively assisting in Basic Physics Practicum I, while student participants were those enrolled in the same course. To enhance representativeness, factors such as age, academic performance, and prior lab experience were considered. A total of 29 lab assistants participated, with the highest number recorded in 2024. Student numbers varied each year, with 2022 showing the largest cohort. Full participant details are presented in Table 1.

Table 1. Participants Description

Period	Participant	
	Laboratory Assistant	Undergraduate Students
2020	4	62
2021	4	92
2022	4	96
2023	7	75
2024	10	76

The period in Table 1 is the year of the class, so this study does not use the same student sample in each year. In terms of the number of laboratory assistant participants, the number is the same, but the laboratory assistants are different participants in each year, so this study can be better illustrated because the laboratory assistants will have different characteristics in their 4C skills. The instrument used in this study was to conduct observations on participants, both laboratory assistants and students and it is believed that observations were carried out accurately and measurably. In terms of assessment, researchers assessed participants through 4C skills that have certain indicators, and can be seen in Table 2.

Table 2. 4C Indicators Used

Skills	Reference	Indicators	Sub-Indicators
Critical Thinking	(Ennis, 1993)	Providing a Simple Explanation	Focusing Arguments. Analyzing Arguments.
		Basic Skills Construction	Determine how to handle the problem.
		Trial Interference in Conclusion	Deduce and consider a deduction. Induce and consider an induction.
		Making in Further Explanation	Defining terms in the problem. Identifying assumptions.
		Strategy and Tactics	Communicate with colleagues about the results found.
Creative Thinking	(D J Treffinger, 2002)	Originality	The originality of the experimental series idea. The originality of the answers given.
		Fluency	Giving ideas in arguments.
		Flexibility	Complete data processing correctly. Complete calculations correctly. Complete data analysis correctly.
		Elaboratioin	Completeness of laboratory activity modules in groups. Completeness of presentation of laboratory activity results in groups.
Collaborative	(Hesse et al., 2015)	Teamwork & Cooperation	Ability to support and assist teammates. Open-mindedness to different perspectives. Ability to adapt to team roles and responsibilities.
		Conflict Resolution	Mediate disputes constructively. Professionalism.
		Accountability & Responsibility	Complete assigned tasks on time. Hold team members accountable in a respectful manner. Be reliable for group success.
		Adaptability & Flexibility	Willingness to accept and implement change. Adapt to different work styles within the team. Handle unexpected challenges without disrupting teamwork.
Communication	(Afriani et al., 2019)	Oral Communication	The volume of the voice given is clear, and the intonation is appropriate. Attractive in two-way communication.
		Reseptive Communication	Ability to identify and summarize the main ideas to be conveyed. Delivery without reading the text repeatedly, and without stuttering.
		Understanding	Able to translate messages well.
		Attitude	Co mmunicate with appropriate language.

Skills	Reference	Indicators	Sub-Indicators
		Clarity	Accept questions well. Accept differences of opinion in communication. Understanding the purpose of scientific communication. The language used in writing is in accordance with Operational Verbs and Adjusted Spelling (EYD)
		Careness	Calmness and accuracy in responding to the audience in a presentation.

The instruments used in this study align with those specified in Table 2, ensuring researchers clearly understand the assessment criteria for students. Laboratory assistants, who had previously been evaluated using the same Table 2 indicators and sub-indicators by the recruiting lecturer, had their 4C competencies assessed through a combination of written tests, observation sheets, and performance tasks. Critical thinking (ALCri) was measured via pretests and posttests employing essays, multiple-choice questions, and observation sheets. Creative thinking (ALCre) was evaluated using questions embedded within the practicum module alongside observations during lab activities. Communication skills (ALCom) were assessed through presentations, lab reports, and researcher observations. Collaboration skills (ALCol) were measured via structured observations based on the indicators in Table 2. To ensure consistency and reliability, identical questions and assessment criteria were applied across all participants, with all instruments having undergone prior validity and reliability testing to guarantee the accuracy and credibility of the collected data.

This quantitative study examined the relationship between laboratory assistants' 4C competencies and students' experimental comprehension (SEC). The 4C skills were assessed via observations, written tests, and practical tasks using Listiawati's (2022) method, while SEC was measured through final practicum grades (lab reports, midterm, and final exams). Multiple linear regression analyzed both individual and combined effects of the 4C competencies on SEC, supplemented by Pearson's correlation to measure relationship strength/direction. Classical assumption tests (Kolmogorov-Smirnov normality, multicollinearity, heteroscedasticity) were conducted per parametric guidelines (Kumar, 2018; Pandey & Pandey, 2021), confirming all assumptions were met (Table 3), thereby validating the regression results (Mishra et al., 2019).

Table 3. Normality Test Hypothesis Making

Decision	Description
Sig. < 0.05	Do not Reject H_0: The data used is not normally distributed.
Sig. > 0.05	Reject H_0: The data used is normally distributed.

Classical assumption tests ensured regression validity. Multicollinearity (Tolerance > 0.05; VIF < 5) and heteroscedasticity (Glejser test, Sig > 0.05) were confirmed (Kim, 2019; Kumar, 2018; Berenguer-Rico & Wilms, 2021). These validated the multiple linear regression model testing four variables' influence on SEC. Pearson's correlation (Berman, 2016) supplemented this by assessing individual 4C-SEC relationships.

Table 4. Pearson's Test Correlation Level Scale

Pearson's Value (r)	Correlation
$\|r\| = 0$	No Correlation
$0 < \|r\| < 0.25$	Very Weak Correlation
$0.25 < \|r\| < 0.5$	Weak Correlation
$0.5 < \|r\| < 0.75$	Strong Correlation
$0.75\ \|r\| < 1$	Very Strong Correlation
$\|r\| = 1$	Perfect Correlation

Table 4 shows the interpretation scale for Pearson's correlation coefficient (r), which measures the strength and direction of a linear relationship between two continuous variables. The value of r ranges from 0 to 1 in absolute terms, where 0 indicates no correlation and 1 indicates a perfect correlation. Values between 0 – 0.25 are considered very weak, 0.25 – 0.5 weak, 0.5 – 0.75 strong, and 0.75 – 1 very strong. A perfect correlation (r = 1) means both variables change exactly together. This scale helps interpret the practical significance of relationships in quantitative research. In this study, Pearson's correlation was visualized using a Taylor diagram generated with OriginLab 2024 and MATLAB 2021 Update 7.

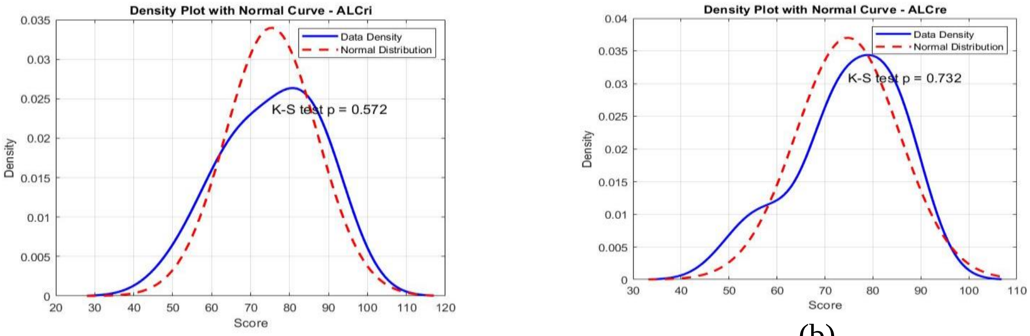
RESULT AND DISCUSSION

This study collected data on laboratory assistants' 4C skill scores and students' Experimental Comprehension (SEC), as shown in Table 1. To ensure accuracy and objectivity, both assistants and researchers independently assessed students using standardized rubrics with validated criteria. The assessments were then cross-checked and averaged using inter-rater agreement to generate a single SEC score per student. These scores were further averaged to represent each laboratory assistant's overall SEC impact. Although the sample included participants from five academic years, it was limited to one institution, which may affect the generalizability of the findings. However, the data are sufficient to explore trends within the program. The normality test results are shown in Figure 1, and descriptive statistics are provided in Table 5.

Tabel 5. Primary Data Descriptive

Variable	Minimum	Maximum	Mean	Std. Dev
ALCri (X_1)	52	93	75.38	11.743
ALCre (X_2)	50	90	74.76	10.776
ALCol (X_3)	54	93	74.14	11.109
ALCom (X_4)	56	92	75.90	9.634
SEC (Y)	66	95	79.83	8.933

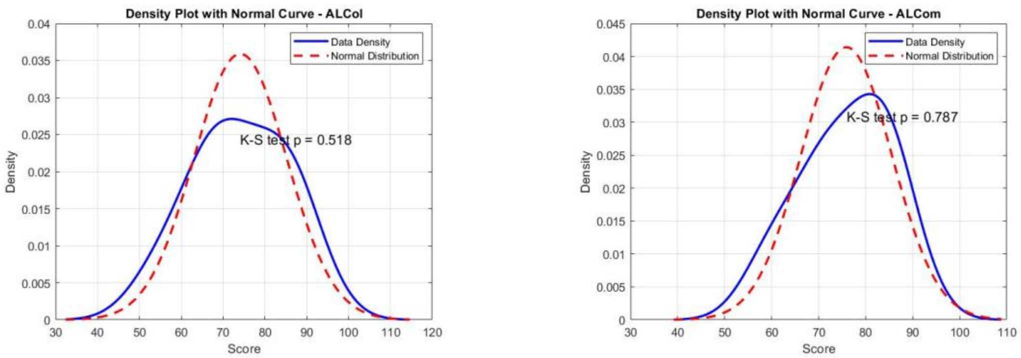
Table 5 shows lab assistants' 4C competency scores (74.14–75.90; 'Good' per Coe et al., 2021). Communication scored highest (75.90), collaboration lowest (74.14), indicating needs for group-work training. SEC averaged 79.83, reflecting effective support. Critical thinking had highest variability (SD=11.743), communication the lowest (SD=9.634). Normality (Figures 1–3) supports result reliability.



(a) (b)

Figure 1. Normality Test Results on; (a) ALCri; and (b) ALCre.

Figure 1 presents the results of the normality tests for two key variables, for ALCri, ALCre using the KS test. The density plots compare the observed data distribution (blue solid line) with the expected normal distribution (red dashed line). For ALCri (Figure 1a), the KS test yielded a p-value of 0.572, while for ALCre (Figure 1b), the p-value was 0.732. Since both p-values are greater than the threshold of 0.05, the null hypothesis of normality is accepted for both variables, indicating that the data are normally distributed. This supports the suitability of using parametric statistical techniques such as multiple linear regression and Pearson correlation in further analysis. The visual alignment of the observed data with the normal curve reinforces the conclusion that there are no significant deviations from normality in these variables.



(a) (b)

Figure 2. Normality Test Results on; (a) ALCol; and (b) ALCom.

Figure 2 displays the results of the normality test for the remaining two 4C skill variables, for ALCol and ALCom using the KS test. In Figure 2a, the collaboration skill scores yielded a KS p-value of 0.518, while in Figure 2b, the communication skill scores produced a p-value of 0.787. Both p-values exceed the significance threshold of 0.05, indicating that the data distributions for these variables do not significantly deviate from normality. This is further supported by the visual alignment between the observed data density (solid blue line) and the expected normal distribution (dashed red line) in both plots. The confirmation of normality for ALCol and ALCom supports the appropriateness of subsequent parametric statistical analyses, such as regression and correlation, and adds credibility to the consistency and reliability of the measurement instruments used in evaluating laboratory assistants' competencies.

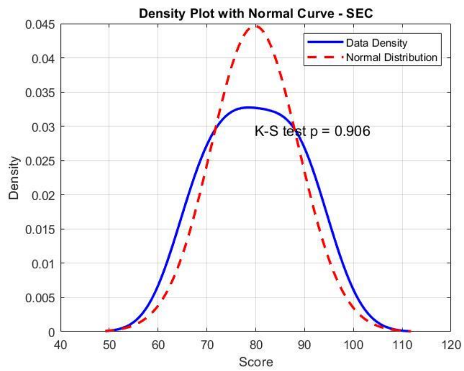


Figure 3. Normality Test Results on SEC

The density plot presented for the SEC variable illustrates the results of the KS normality test. The plot compares the observed data distribution (solid blue line) with the theoretical normal distribution (dashed red line). The KS test yielded a p-value of 0.906, which is well above the 0.05 threshold, indicating that the SEC scores are normally distributed. This strong alignment between the actual and expected distributions confirms that the SEC variable meets the assumption of normality required for parametric statistical tests. The result further supports the validity of using regression and correlation analyses to explore the relationship between laboratory assistants' 4C competencies and student experimental understanding. After the normality test was carried out, the results of the multicollinearity test can be seen in Table 6.

Table 6. Multicollinearity Test Results

Variable	Collinearity Statistics	
	Tolerance	**VIF**
ALCri	.389	2.571
ALCre	.638	1.567
ALCol	.778	1.285
ALCom	.452	2.211

The results presented in Table 6 indicate that all independent variables, such ALCri, ALCre, ALCol, and ALCom passed the multicollinearity test, as evidenced by their Tolerance values being greater than 0.05 and their Variance Inflation Factor (VIF) values being well below the commonly accepted threshold of 10 (Kim, 2019). Specifically, ALCri had a Tolerance of 0.722 and VIF of 1.385, ALCre showed a Tolerance of 0.641 and VIF of 1.561, ALCol had a Tolerance of 0.695 and VIF of 1.438, while ALCom recorded a Tolerance of 0.768 and VIF of 1.302. The absence of multicollinearity implies that each 4C skill variable contributes uniquely to the model and does not distort the estimation of the regression coefficients. Following the multicollinearity test, the study also conducted a heteroscedasticity test using the Glejser method, the results of which are illustrated in Figure 4. Ensuring the fulfillment of both these classical assumption tests strengthens the reliability and validity of the regression analysis, allowing for more accurate interpretation of how laboratory assistant competencies influence students' experimental comprehension.

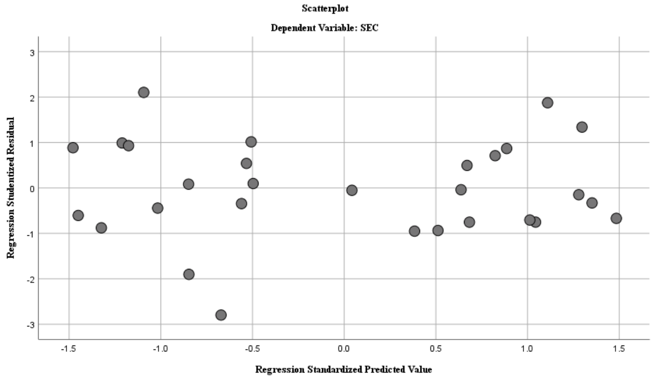


Figure 4. Heteroscedasticity Test Results

The Glejser heteroscedasticity test results as seen in Figure 4 demonstrated that residual values for all independent variables were randomly scattered around the Y=0 axis without a discernible pattern, indicating an absence of heteroscedasticity. This random distribution suggests that the variance of the residuals was consistent across all levels of the independent variables. A reliable regression model presupposes homoscedasticity, so it means error terms possess constant variance, as violations can result in inefficient estimators and dubious significance tests (Berenguer-Rico & Wilms, 2021). The lack of residual clustering near the zero line further affirmed that they were not biased or influenced by the magnitude of the predictors. Consequently, this validated the application of ordinary least squares (OLS) regression, as the assumption of constant error variance was met (Đalić & Terzić, 2021). With all classical assumptions fulfilled, the study proceeded to an inferential analysis using a multiple linear regression model. This model was employed to assess the predictive power of laboratory assistants' 4C competencies on students' experimental comprehension (SEC), with the results presented in Figure 5.

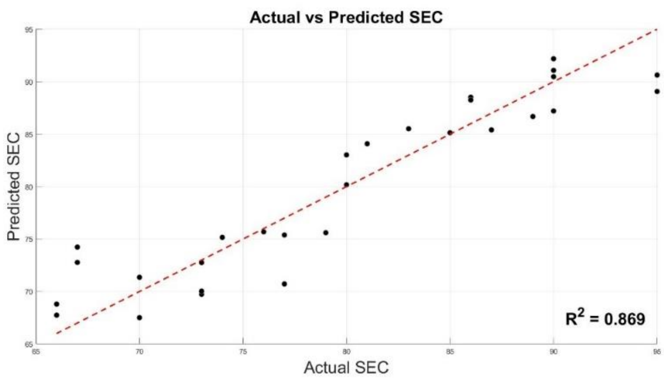


Figure 5. Multiple Linear Regression Test Results Using Scatter Plot

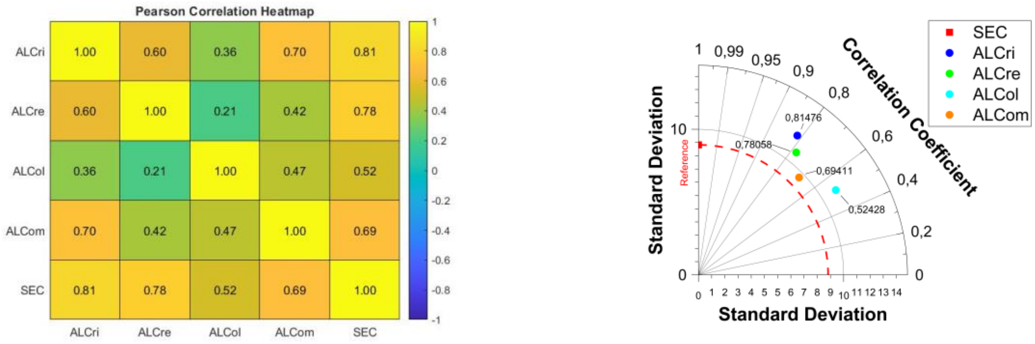
Figure 5's scatter plot compares predicted versus actual Students' Experimental Comprehension (SEC) scores, based on a multiple linear regression model of laboratory assistants' four 4C competencies (ALCri, ALCre, ALCol, and ALCom). A high R-squared value (R2=0.869) signifies that these competencies explain 86.9% of SEC variance, representing a strong effect size (Zhang, 2017). This result supports constructivist learning theory on the importance of interactive, scaffolded learning environments (Efgivia et al., 2021) and aligns with prior studies indicating that assistants possessing strong 4C skills enhance student learning outcomes (Sarvary et al., 2025). The close alignment of data points with the regression line demonstrates the model's accurate predictive capability for student outcomes. Minor deviations are within acceptable limits and, as common small residuals, do not compromise model reliability (Mertler, 2024), these differences may stem from unmeasured variables such as students' prior knowledge or motivation (Brod, 2021; Simonsmeier et al., 2022). The absence of systematic error patterns further supports the model's validity. In conclusion, the 4C competencies of laboratory assistants significantly and reliably contribute to students' experimental comprehension, highlighting the need for institutions to develop training programs that integrate these essential soft skills.

Laboratory assistants at UIN Sunan Gunung Djati Bandung's Physics Education Study Program (2020-2024), who met specific inclusion criteria such as active involvement in Basic Physics Practicum I and II, were purposively sampled and paired with first-semester student cohorts; this approach ensured consistency and yielded insights applicable to similar undergraduate science programs. The 4C competencies of these assistants were evaluated using a combination of validated instruments, including written tests, observation sheets, and practicum performance documentation, all confirmed for reliability and validity (Cohen et al., 2017). Limitations of the study include its single-institution setting, which may constrain the generalizability of findings, and the exclusion of potential moderating factors like student motivation, prior knowledge, and laboratory infrastructure (Mertler, 2024). Despite these limitations, the findings strongly advocate for structured training programs focused on 4C skill development, particularly critical thinking and creativity, identified as key predictors of student success to enhance student engagement, comprehension, and preparedness in laboratory settings. The results also support redefining the role of laboratory assistants from technical support staff to active pedagogical facilitators. Investing in assistants' soft skills can thereby improve science education quality, promote active learning, and align with 21st-century educational demands (Herro et al., 2021). These outcomes resonate with constructivist and socio-cultural learning theories that endorse collaborative, skill-enriched, and guided learning environments (Herro et al., 2021). Ultimately, this research provides a foundation for educational reforms that integrate soft skills into laboratory instruction to enhance teaching effectiveness and student learning outcomes in experimental science.

Table 7. Partial Multiple Linear Regression Test Results

Variabel	Standarized Coefficient Beta	Sig.
Constant	6.922	.282
ALCri	.350	.007
ALCre	.461	<.001
ALCol	.235	.010
ALCom	.146	.022

The analysis in Table 7 shows that all four 4C competencies significantly influence SEC, with p-values below 0.05. ALCre has the strongest impact ($\beta = 0.461$, $p < 0.001$), highlighting the value of creative teaching strategies, such as using everyday materials or simulations to simplify complex concepts (Hakim et al., 2022; Kaplan, 2019). ALCri follows as the second most influential factor (β = 0.350, p = 0.007), showing that assistants who encourage inquiry and reasoning improve student understanding. While ALCol and ALCom have smaller effects (β = 0.235, p = 0.010; β = 0.146, p = 0.022), they remain significant and should be developed through peer activities and feedback (Hargreaves, 2021; Priadi, 2020). Correlation analysis (Figure 6) and Taylor diagram results confirm that ALCri and ALCre align most strongly with positive student outcomes (r = 0.81 and r = 0.78), emphasizing their critical role in effective lab instruction. These findings support the need for training programs that strengthen all 4C skills and suggest that institutions and policymakers should recognize assistants as key contributors to STEM education (Herro et al., 2021; Zheng et al., 2024).



(a) (b)

Figure 6. Pearson Correlation Based on; (a) Heatmap; and (b) Taylor Diagram

Figure 6 reveals a strong and positive correlation between each of the 4C competencies of laboratory assistants and students' experimental understanding (SEC), as shown through both the Pearson correlation heatmap and Taylor diagram. Among these, ALCri shows the highest correlation with SEC (r = 0.81), followed closely by ALCre with r = 0.78. These results are consistent with the regression analysis, in which ALCre had the highest standardized beta coefficient (β = 0.461), followed by ALCri (β = 0.350), both statistically significant at $p < 0.01$. This indicates that laboratory assistants with strong critical and creative thinking skills tend to significantly enhance students' ability to comprehend and engage with experimental concepts. Supporting this, Alsaleh (2020) argues that educators with critical thinking skills are more adept at identifying and resolving instructional challenges, while Zamzam et al., (2023) emphasize that creativity enables educators to generate effective strategies for simplifying complex ideas.

To strengthen the validity of the correlations found in this study, future research should consider accounting for other potential influencing factors, such as student motivation, prior academic performance, or laboratory resources. Using advanced methods like structural equation modeling (SEM) or including relevant control variables can help isolate the unique impact of laboratory assistants' 4C competencies on students' experimental comprehension (Hair Jr et al., 2021). Additionally, longitudinal or mixed-method research designs are recommended to explore causal relationships and determine whether improvements in these competencies lead to long-term student gains (Waller et al., 2021). While this study provides valuable insights, its generalizability is limited due to its single-institution scope. Expanding the research to multiple institutions, regions, and scientific disciplines, such as biology, chemistry, and engineering can help validate whether the influence of critical and creative thinking holds across diverse educational contexts (Heitzmann et al., 2021). Practically, these findings support the inclusion of 4C-focused modules in assistant training programs, including real-world experiment design and inquiry-based learning for creativity, as well as reflective practices and problem-solving simulations to enhance critical thinking (Cooper et al., 2024; Dirgantara et al., 2024).

The study also found that while ALCol and ALCom had weaker statistical effects compared to critical thinking and creativity, they still showed significant positive associations with student comprehension—$\beta = 0.235$ ($p = 0.010$) and $\beta = 0.146$ ($p = 0.022$), respectively with Pearson's r values of 0.69 and 0.52. These results suggest that although these competencies contribute less directly, they remain essential for fostering effective laboratory instruction. Training programs should therefore include communication workshops, collaborative simulations, and role-play scenarios that encourage peer discussion, teamwork, and problem-solving (Lorencová et al., 2019). Moreover, communication and collaboration are often most impactful when integrated with critical and creative thinking, as effective dialogue typically arises from strong analytical reasoning, and collaboration is enhanced by creative input (Cáceres et al., 2020). However, the relationships between competencies such as critical thinking and communication may be influenced by unmeasured variables like pedagogical skills, teaching experience, or familiarity with student-centered instruction (Kuloğlu & Karabekmez, 2022). Future research should adopt more comprehensive models or longitudinal methods to clarify these dynamics (Waller et al., 2021). While this study is limited to the Physics Education Study Program at UIN Sunan Gunung Djati Bandung, its findings provide strong support for the broader integration of 4C skill development in laboratory assistant training across STEM education settings.

Figure 7. Laboratory Activities Process as Long on Data Acquisition

Creativity and critical thinking are essential for laboratory assistants to enhance student collaboration and communication. Creative assistants design engaging, student-centered activities that go beyond routine procedures, such as modifying experiments with everyday materials or integrating real-world problems (Kaplan, 2019; Paek & Sumners, 2019). Creativity also supports scaffolding within the ZPD, encouraging active participation and shared problem-solving (Ness, 2023). Technological tools like virtual labs and digital platforms (e.g., Google Jamboard, Gather Town) further enrich these experiences (Agustina et al., 2024), while creative use of storytelling and visuals aids in simplifying complex concepts (Fardhila & Istiyono, 2019). Evaluating creativity involves performance assessments and rubrics measuring originality, fluency, and flexibility (Treffinger et al., 2023). Meanwhile, critical thinking helps assistants address classroom dynamics, assess participation, and implement inclusive strategies such as rotating group roles (Bezanilla et al., 2019). It also strengthens communication by enabling assistants to pose reflective questions that connect theory with practice (Fisher, 2014), fostering dialogue and deeper understanding (Royce et al., 2019). Together, creativity and critical thinking make laboratory learning more interactive, inclusive, and inquiry-driven (Cooper et al., 2024; Cremin & Chappell, 2021).

Creativity and critical thinking, when intentionally integrated, empower laboratory assistants to communicate and collaborate more effectively. Creative thinking introduces imagination, flexibility, and empathy into the learning process, helping assistants design engaging and adaptive learning experiences. In contrast, critical thinking offers the structure, logic, and evaluation needed to ensure these experiences are pedagogically sound and aligned with learning goals. To balance the two, laboratory assistants can use planning tools such as instructional design frameworks or reflection journals that help them evaluate whether their creative ideas are also purposeful, feasible, and aligned with intended outcomes. For example, when planning an open-ended physics experiment, an assistant might creatively present a real-world challenge, e.g., designing a low-cost water filtration system, and then apply critical thinking to ensure the procedures, data collection, and assessment criteria are valid and achievable. This synergy enables them to act as facilitators of collaborative inquiry, designing rich, hands-on tasks (creativity), guiding structured reflection and problem-solving (critical thinking), communicating expectations clearly, and fostering peer learning. The impact of this dual competency can be measured through student artifacts such as lab reports or project prototypes, peer and self-assessments, and longitudinal tracking of student growth in areas like scientific reasoning, teamwork, and communication. Additionally, classroom observations and qualitative interviews can capture how students respond emotionally and cognitively to these experiences over time. Ultimately, by blending creativity with critical thinking, laboratory assistants not only enhance the immediate learning environment but also support students' long-term development in both cognitive and social-emotional domains.

CONCLUSION

This study provides strong empirical evidence that laboratory assistants' 4C competencies significantly enhance students' experimental understanding in physics practicum settings. Multiple linear regression analysis showed that these four competencies collectively accounted for 86.9% of the variance in Students' Experimental Comprehension ($R^2 = 0.869$). Creativity ($\beta = 0.461$, $p < 0.001$) and critical thinking ($\beta = 0.350$, $p = 0.007$) were the most influential factors, followed by collaboration ($\beta = 0.235$, *p* = 0.010) and communication (β = 0.146, *p* = 0.022). These findings highlight that effective laboratory instruction goes beyond technical support and requires pedagogical expertise and social responsiveness. However, the study faced limitations, including variability in student engagement and a restricted sample drawn from a single institution, which may limit the generalizability of the findings. Future research should include multiple universities and additional variables such as student motivation, learning preferences, and laboratory infrastructure. Longitudinal studies are also recommended to examine the lasting impact of 4C competencies on student outcomes and attitudes toward science.

From a practical perspective, the results emphasize the need to reconceptualize laboratory assistants as co-educators who support inquiry-based and collaborative learning environments. Institutions should implement structured, long-term training programs focused on cultivating the 4C competencies through workshops, microteaching, role-playing, and live practicum simulations accompanied by feedback and reflection. Evaluation methods such as peer reviews, student feedback, and performance rubrics should be used to monitor their development. In recruiting lab assistants, universities should consider not only academic performance and technical skills but also candidates' potential in communication, critical thinking, and teamwork assessed through behavioral interviews and practical teaching demonstrations. Supervisors should actively mentor lab assistants by offering regular guidance, collaborative planning, and opportunities for reflective dialogue. Ultimately, this study underscores that the 4C competencies are essential, not optional in transforming laboratory environments into dynamic, student-centered spaces that promote scientific thinking and holistic learning.

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