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The Impact of Laboratory Management Module on Students' 4C Competencies in Physics Education

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Abstract – *In today's rapidly changing world, higher education is expected to equip students with the essential skills to thrive in global competition. Among these, the four core (4C) competencies—critical thinking, creativity, communication, and collaboration — are considered fundamental for success. Science laboratories hold great potential to cultivate these skills by providing students with direct, hands-on learning experiences. Yet, the benefits are often limited when laboratory activities are not supported by effective management. To respond to this challenge, this study explored how a laboratory management module influences students' 4C skills. Using a quantitative survey design, data were collected from 142 undergraduates drawn from a total population of 208, with the sample size determined through the Isaac and Michael table. Two Likert-scale questionnaires measured students' perceptions of the module and their mastery of the 4C skills. Data analysis employed Structural Equation Modeling with Partial Least Squares (SEM-PLS), enabling rigorous tests of validity, reliability, and causal relationships. The results indicate that the laboratory management module had a significant and positive impact on critical thinking and creativity, but no notable effect on communication and collaboration. This finding highlights the novelty of distinguishing between cognitive and interpersonal outcomes within laboratory management. The study concludes that structured laboratory management can serve as a powerful tool to enhance higher-order thinking, while additional strategies are needed to strengthen communication and teamwork. This study contributes to physics education by providing empirical evidence that structured laboratory management can effectively foster students' critical and creative thinking skills. It also highlights the need to integrate collaborative and communication-focused strategies into laboratory practices.*

Keywords: *communication skill; collaboration skill; creative thinking; critical thinking; laboratory management module*

I. INTRODUCTION

The 21st century is marked by unprecedented technological advances, global interconnectedness, and rapid socio-economic transformations that demand a new set of competencies from future graduates. Educational institutions worldwide are therefore under increasing pressure to align their curricula with the skills necessary for success in an evolving knowledge-based society. Scholars consistently highlight that higher education should not only impart disciplinary knowledge but also foster transferable competencies that prepare students to adapt, innovate, and collaborate within complex real-world contexts (Grinin et al., 2021; Kaya et al., 2025; Zoidze et al., 2025). Among these, the so-called "4C skills" critical thinking, creative thinking, communication, and collaboration are widely regarded as the cornerstone of twenty-first-century learning (Amalia & Siburian, 2025). These competencies are essential not only for academic success but also for global competitiveness, as industries increasingly demand graduates who can solve ill-structured problems, generate original ideas, communicate effectively, and work productively in teams (Usman et al., 2024; Kadarisman, 2017).

Research across various domains confirms that cultivating these 4C skills significantly contributes to improved learning outcomes and employability. For example, critical thinking empowers learners to analyze, evaluate, and synthesize information beyond surface-level comprehension, a necessity in a world saturated with complex and often contradictory data (Lespita et al., 2023). Creative thinking, on the other hand, enables the generation of novel and practical solutions to emerging global challenges (Leasa et al., 2025). Communication is equally vital, as it underpins collaboration, cross-cultural understanding, and the dissemination of knowledge in both academic and professional settings (Makmuri & Harun, 2024). Lastly, collaboration skills promote collective intelligence and shared responsibility, fostering the ability to achieve goals that extend beyond individual capacities (Rachma et al, 2025). The integration of these skills into higher education is no longer optional but an imperative aligned with international educational frameworks such as the UNESCO 2030 Agenda for Sustainable Development and various national education policies worldwide (Hujjatusnaini et al., 2022; Mirici & Kızılışıkoğlu, 2025).

Despite this recognition, numerous studies indicate that higher education institutions continue to struggle with embedding the 4C competencies systematically into the curriculum. Traditional pedagogies, which predominantly emphasize rote memorization and lecture-based instruction, often fall short in cultivating the higher-order thinking and interpersonal abilities demanded by the twenty-first century (Stevens, 2012). The gap between theoretical knowledge and practical application remains significant, particularly in science education, where laboratory activities should ideally function as sites for experiential and collaborative learning (Cahyani, 2022; Lutfhianti et al., 2024). However, poor laboratory management, insufficient training modules, and limited opportunities for structured student participation frequently hinder the development of critical, creative, communicative, and collaborative proficiencies (Napsawati & Kadir, 2022). This reality points to a pressing challenge: while science laboratories hold immense potential to develop students' 4C skills, their impact is often undermined by systemic inefficiencies.

The central problem, therefore, lies in the underutilization of laboratories as effective learning environments. Empirical evidence suggests that without well-structured management systems, even well-equipped laboratories fail to yield substantial improvements in student outcomes (Nurhadi, 2018; Nurdiana et al., 2024). Issues such as inadequate procurement processes, lack of proper storage and maintenance, and ineffective scheduling often disrupt practicum activities and compromise the overall quality of science education (Irawandi & Saputra, 2025; Nurmadiah, 2018). These inefficiencies not only waste valuable resources but also weaken the opportunities for students to actively engage in critical inquiry, collaborative problem-solving, and effective communication. Furthermore, the absence of pedagogically oriented laboratory guidelines creates inconsistent practices, leaving students with fragmented experiences that neither maximize the potential of laboratory-based learning nor address the holistic demands of twenty-first-century education (Agustina, 2018; Laeli & Maryani, 2020).

To address these challenges, a growing body of research has advocated for structured modules that guide laboratory management in ways that explicitly align with twenty-first century learning outcomes. Laboratory management modules are designed to provide systematic instructions on procurement, storage, inventory, and maintenance of laboratory resources, while simultaneously embedding pedagogical principles that promote student engagement (Septia et al., 2018; Mardiah et al., 2025). Such modules represent more than administrative tools; they function as pedagogical instruments that support both educators and students in optimizing laboratory experiences. By formalizing processes and clarifying expectations, laboratory management modules enable students to actively participate in laboratory activities that develop critical and creative thinking while also offering opportunities for communication and collaboration.

Evidence from recent studies underscores the effectiveness of structured laboratory management in improving academic performance and fostering essential competencies. For instance, Girma and Geletu (2024) demonstrated that laboratory practical work, when supported by effective management systems, significantly increased student engagement and enhanced the quality of science learning. Similarly, Rachma et al. (2025) showed that integrating structured digital laboratories within hybrid problem-based learning contexts strengthened students' higher-order thinking skills. Other scholars argue that management modules serve as a bridge between resource optimization and pedagogical innovation, ensuring that laboratory activities not only meet curricular objectives but also prepare students for professional demands (Bahtiar & Azmar, 2022; Lespita et al., 2023). Collectively, these findings highlight the promise of laboratory management modules as scalable and effective interventions to enhance student learning in higher education.

Nevertheless, current research still reveals notable gaps. While previous studies have largely focused on the effect of laboratory management on cognitive outcomes and overall performance, relatively few have examined its direct influence on the development of the 4C skills. For instance, existing works acknowledge that laboratories can foster collaboration and communication, but empirical evidence often remains fragmented or anecdotal (Makmuri & Harun, 2024; Leasa et al., 2025). Additionally, while modules may effectively improve resource efficiency and critical or creative thinking, their capacity to cultivate interpersonal competencies such as teamwork and communication remains underexplored. This suggests that while laboratory management modules hold significant promise, more empirical studies are required to evaluate the extent to which they contribute to comprehensive twenty-first-century skill development (Munifah et al., 2019; Prastowo et al., 2019).

Building on this context, the present study seeks to address these gaps by empirically examining the effect of a laboratory management module on the four pillars of twenty-first-century competencies: critical thinking, creative thinking, communication, and collaboration. Unlike previous works that primarily investigated resource optimization or academic achievement, this research emphasizes the holistic outcomes of laboratory management by explicitly measuring its influence on the 4C skills among undergraduate students of science education. The novelty of this study lies in its integration of partial least squares structural equation modeling (PLS-SEM) to rigorously analyze causal relationships between laboratory management practices and twenty-first-century skills. This methodological approach provides robust evidence regarding which competencies are significantly impacted by structured laboratory management and which remain unaffected. By addressing the intersection of laboratory management and twenty-first-century pedagogy, this study contributes to the international discourse on how higher education can better prepare graduates to meet the demands of an increasingly complex and interconnected world.

II. METHODS

This study adopted a quantitative approach with a survey design in order to analyze the influence of the laboratory management module on students' twenty-first-century skills, particularly the four core competencies of critical thinking, creative thinking, communication, and collaboration. Quantitative approaches are widely recognized as suitable for measuring the strength and direction of relationships between variables and for ensuring replicability of results in educational research (Eveland et al., 2024). The survey method, in particular, is considered appropriate for gathering data from relatively large populations in a standardized form, thereby allowing for meaningful statistical analysis and generalization (Schubring et al., 2016). The context of this study was the undergraduate Natural Sciences Education Study Program at the State Islamic Institute Kediri, Indonesia, where the laboratory serves as a central component of the science education curriculum.

The research population comprised all active students enrolled in the Natural Sciences Education Study Program, totaling 208 individuals. From this population, a representative sample of 142 students was selected by referring to the Isaac and Michael sampling table with a 5% margin of error. The use of this table ensured that the sample size was statistically adequate to represent the population and reduce sampling bias, while also remaining practical for data collection and analysis (Munifah et al., 2019). The selected students were considered appropriate respondents, as they had direct experience with laboratory practices and exposure to the laboratory management module being evaluated.

The variables under investigation were categorized into exogenous and endogenous constructs. The exogenous latent variable was the laboratory management module, while the endogenous latent variables included critical thinking skills, creative thinking skills, communication skills, and collaboration skills. The relationships between these constructs were conceptualized as causal, consistent with the SEM paradigm that allows for the simultaneous assessment of direct and indirect effects among multiple variables (Prastowo et al., 2019). This research framework is illustrated in Figure 1, which presents the hypothesized structural relationships between the exogenous and endogenous variables.

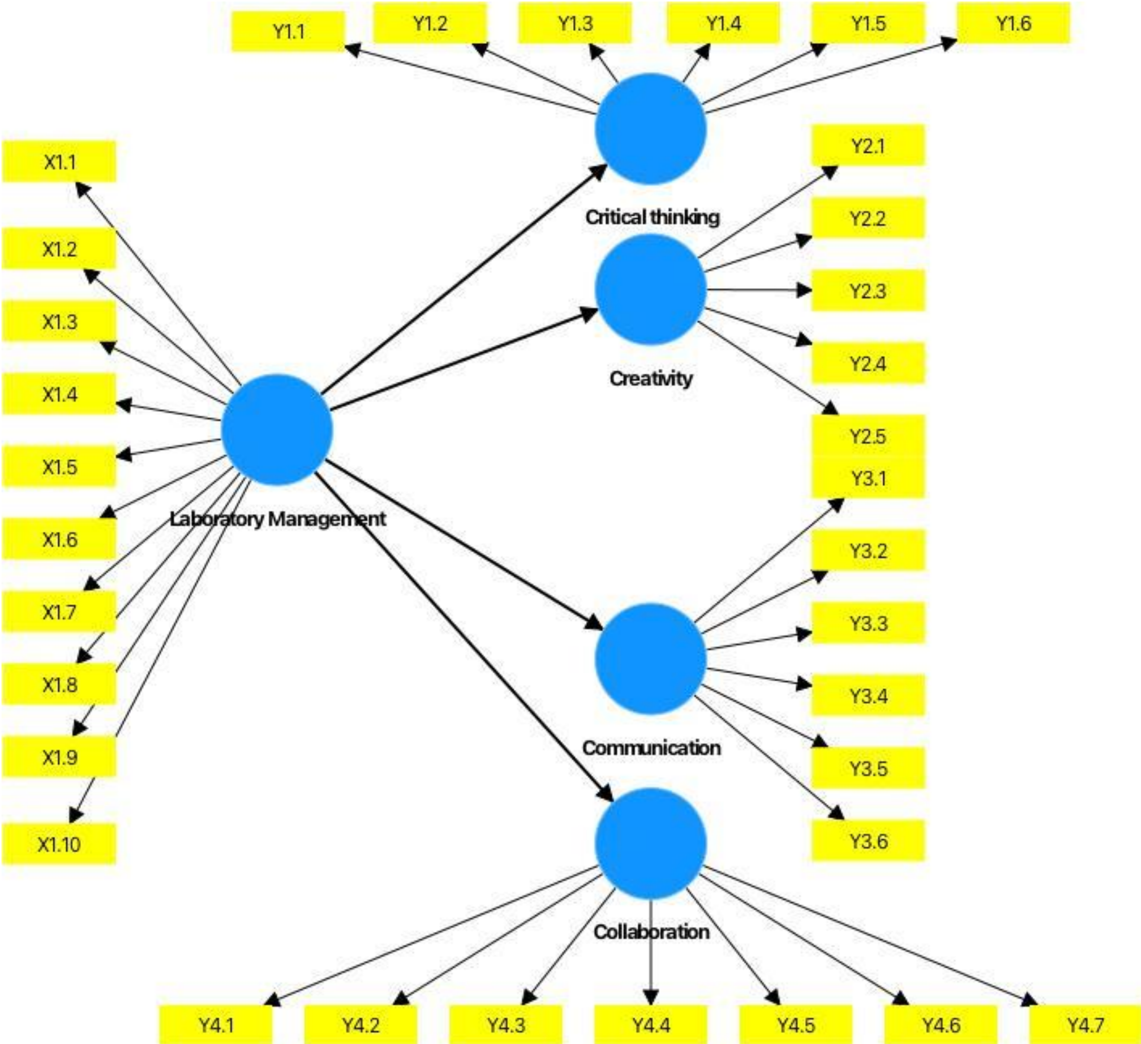

Figure 1. Relationship between exogenous and endogenous variables

Data collection employed a structured questionnaire developed to capture both the implementation of the laboratory management module and the extent of students' mastery of the 4C skills. The instrument was designed in two complementary parts. The first questionnaire focused on the implementation of the laboratory management module. It consisted of statements relevant to students' experiences with laboratory management procedures, such as procurement, storage, inventory, and maintenance of equipment and materials. Respondents were asked to indicate their level of agreement with each statement using a five-point Likert scale, ranging from "strongly disagree" (1) to "strongly agree" (5). The Likert scale has been widely applied in educational measurement for its ability to capture attitudinal and perceptual data in a quantifiable manner (Cahyani, 2022; Napsawati & Kadir, 2022).

The second questionnaire was designed to measure students' mastery of the 4C skills. It was organized into four sections, each corresponding to one of the competencies. The items within each section were adapted from validated indicators of twenty-first-century skills, ensuring content validity and alignment with existing frameworks (Lespita et al., 2023; Makmuri & Harun, 2024). Respondents rated their skills on a scale ranging from "very poor" to "very good," thus enabling the researchers to classify students' self-reported abilities across the four domains. This self-reporting method is commonly used in skill-assessment research, although it was complemented by statistical validation techniques to minimize subjectivity (Hujjatusnaini et al., 2022).

The analytical method employed was PLS-SEM. This method was chosen because it is particularly suited for exploratory and predictive research involving complex models with latent variables measured through multiple indicators (Schubring et al., 2016). Compared to covariance-based SEM, PLS-SEM is less demanding with respect to sample size and data distribution assumptions, making it highly appropriate for educational contexts with moderate sample sizes such as the present study (Eveland et al., 2024). Through this approach, the study was able to simultaneously evaluate measurement models assessing the reliability and validity of constructs and structural models, which test the hypothesized relationships among variables.

The evaluation of the measurement model involved examining convergent validity, discriminant validity, and reliability. Convergent validity was assessed by inspecting factor loadings and the Average Variance Extracted (AVE) for each construct, with values above 0.5 indicating satisfactory validity (Bahtiar & Azmar, 2022). Discriminant validity was tested by comparing AVE values with inter-construct correlations, ensuring that constructs were empirically distinct (Girma & Geletu, 2024). Reliability was established using Cronbach's alpha, with thresholds above 0.7 considered acceptable (Rachma et al., 2025). These evaluations ensured that the indicators used in the study accurately measured the intended constructs.

The structural model was then evaluated using R^2 values, which indicate the proportion of variance in endogenous variables explained by the exogenous construct. Values closer to 1 signify greater explanatory power (Prastowo et al., 2019). Additionally, bootstrapping procedures were conducted to test the significance of path coefficients by generating t-statistics and p-values for each hypothesized relationship. Bootstrapping is widely recognized for its robustness in addressing non-normal data distributions, a common characteristic in survey research (Eveland et al., 2024). By combining these methods, the analysis provided rigorous evidence regarding the extent to which the laboratory management module influenced students' critical thinking, creative thinking, communication, and collaboration skills.

III. RESULTS AND DISCUSSION

The analysis began with an assessment of the measurement model to ensure that the indicators reliably captured the constructs under study. Convergent validity was first examined by evaluating the correlation between item loadings and their respective latent variables. As illustrated in Figure 1, the results of the PLS-SEM computation indicated that all items had standardized factor loadings greater than 0.50. This threshold is commonly accepted in measurement literature. Thus, all indicators demonstrated satisfactory convergent validity, which justified proceeding to the assessment of discriminant validity.

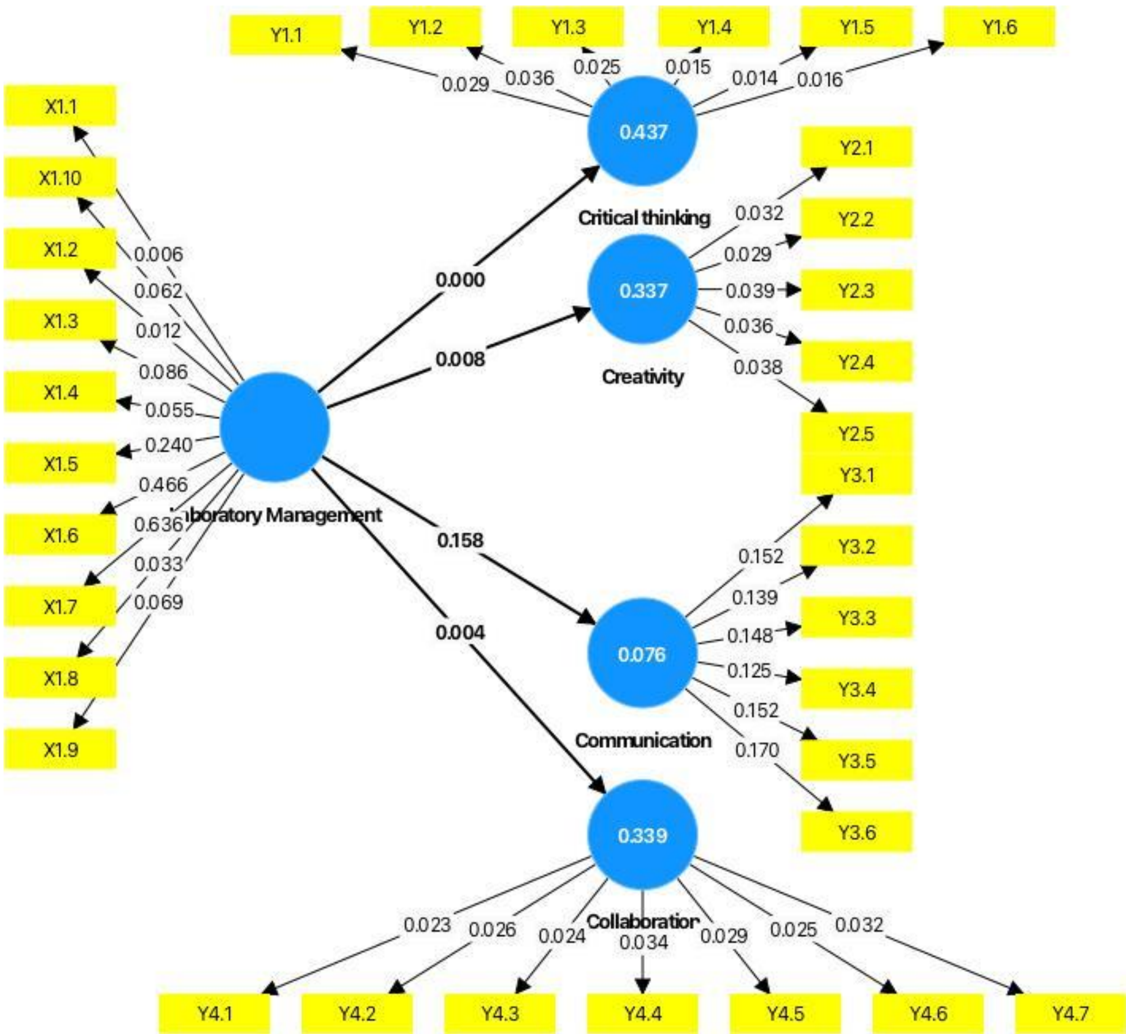

Figure 2. Cross-loading and discriminant validity results of the structural measurement model

The discriminant validity of the constructs was subsequently analyzed to determine whether each construct was empirically distinct from the others. According to the cross-loading results depicted in Figure 2, every indicator exhibited stronger loadings on its assigned construct compared with cross-loadings on other constructs. This finding confirms that the constructs-maintained discriminant validity.

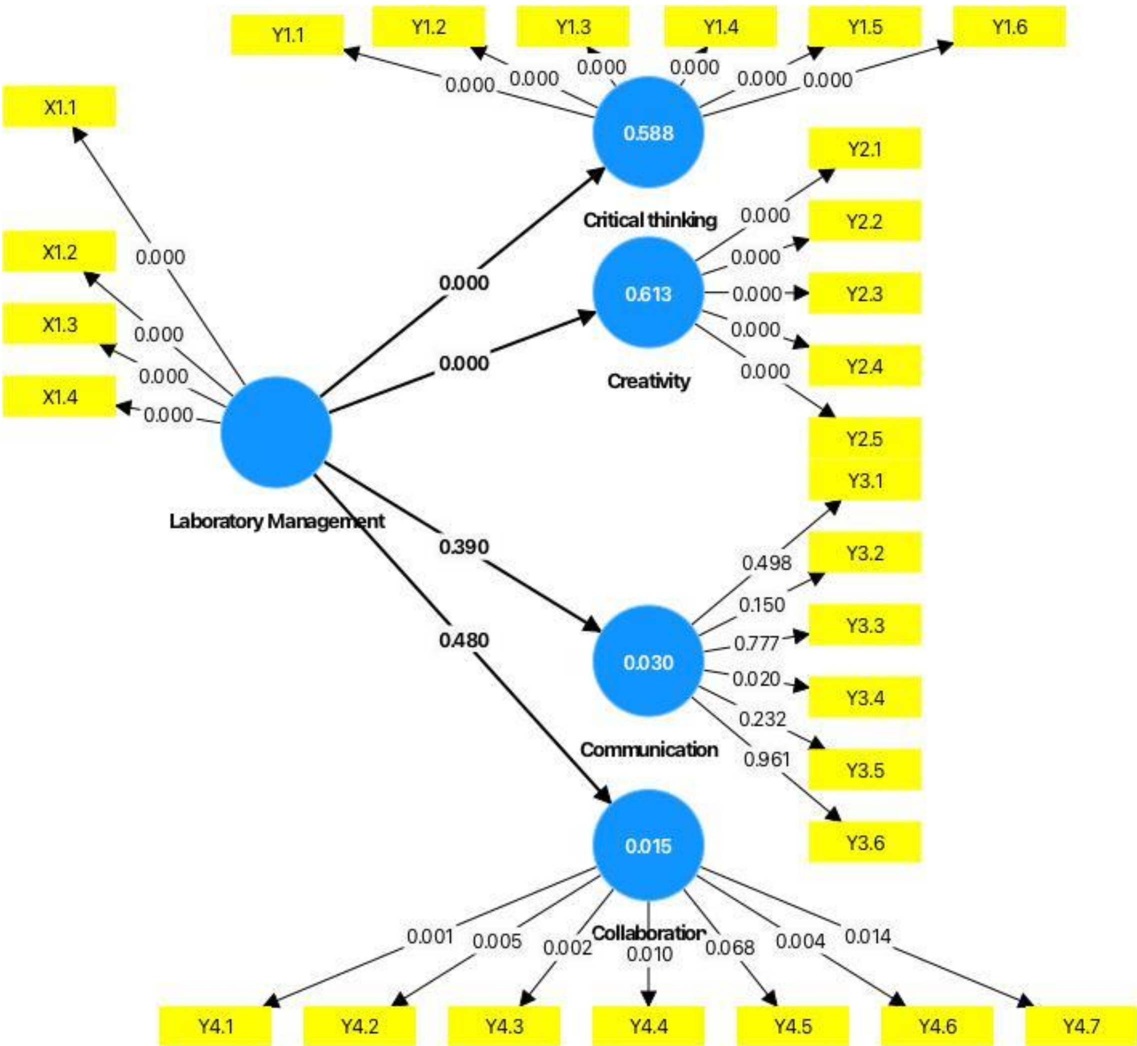

Figure 3. Bootstrapping results of the PLS-SEM analysis showing path coefficients and significance levels

Further evidence of discriminant validity was obtained by comparing the AVE for each construct with inter-construct correlations. As reported in Table 1, all AVE values exceeded the 0.50 threshold, ranging from 0.532 to 0.620. These results affirm that more than half of the variance of the indicators were explained by the constructs, thereby satisfying the criteria for discriminant validity.

Table 1. The AVE values for each construct

Variable	Skor AVE
Laboratory management	0.550
Critical thinking	0.532
Creativity	0.620
Communication	0.550
Collaboration	0.548

Reliability was then evaluated using Cronbach's alpha. As shown in Table 2, the Cronbach's alpha coefficients for all constructs were above 0.70, with values ranging from 0.727 for the laboratory management construct to 0.886 for collaboration. These findings surpass the minimum recommended threshold. This indicates strong internal consistency among the indicators for each latent construct (Rachma et al., 2025). The reliability results reinforce the stability of the measurement model, thereby ensuring confidence in subsequent structural analyses.

Table 2. Cronbach's alpha values for the latent constructs

Variable	Cronbach alpha
Laboratory management	0.727
Critical thinking	0.827
Creativity	0.850
Communication	0.871
Collaboration	0.886

The structural model was assessed through three main indices: the coefficient of determination (R^2), predictive relevance (Q^2), and effect size (f^2). R^2 values indicate the extent to which the variance of endogenous constructs can be explained by exogenous variables. As presented in Table 3, the R^2 value for critical thinking was 0.588, while creativity recorded an R^2 value of 0.613. Both values exceed the threshold of 0.25, suggesting medium predictive accuracy (Prastowo et al., 2019). In contrast, communication and collaboration yielded very low R^2 values (0.030 and 0.015, respectively), indicating that laboratory management contributed little to explaining these competencies. This finding suggests that while laboratory management practices substantially explain variance in higher-order thinking skills, they are less predictive of interpersonal skills.

Table 3. R^2 squared values for endogenous constructs

Exogenous versus endogenous variables	R square	R square customized	Level of determination
Laboratory management → critical thinking	0.588	0.585	Medium
Laboratory management → creativity	0.613	0.610	Medium
Laboratory management → communication	0.030	0.023	Low
Laboratory management → collaboration	0.015	0.008	Low

To test the significance of the hypothesized relationships, bootstrapping procedures with resampling were performed. Bootstrapping reduces bias associated with non-normal data distributions and provides robust estimates of path coefficients. The results, shown in Figure 3 and summarized in Table 4, provide a detailed overview of the direct effects between the laboratory management construct and each of the 4C skills. The standardized path coefficient from laboratory management to critical thinking was 0.767, with a t-value of 20.569 and a p-value of <0.001. Similarly, the path from laboratory management to creativity was 0.783, with a t-value of 26.325 and a p-value of <0.001. Both results indicate statistically significant positive effects, thereby supporting the hypotheses that laboratory management enhances students' critical and creative thinking.

By contrast, the paths from laboratory management to communication and collaboration did not achieve statistical significance. The path to communication yielded a coefficient of 0.172 with a t-value of 0.859 (p = 0.390), while the path to collaboration showed a coefficient of 0.121 with a t-value of 0.707 (p = 0.480). Since both p-values were above the 0.05 threshold, the results indicate that laboratory management did not have a direct effect on communication or collaboration skills among the respondents.

Table 4. Bootstrapping results of the relationships between laboratory management and 4C skills

No	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T Statistic (O/STDEV)	P values	Relationship
Laboratory management → collaboration	0.121	0.120	0.172	0.707	0.480	not available
Laboratory management → communication	0.172	0.012	0.201	0.859	0.390	not available
Laboratory management → creativity	0.783	0.791	0.030	26.325	0.000	available
Laboratory management → critical thinking	0.767	0.768	0.037	20.569	0.000	available

Hypothesis testing was also conducted using the t-statistic values compared with the critical t-table value of 1.684 (df = 40; α = 0.05, one-tailed test). The results, summarized in Table 5, corroborate the bootstrapping outcomes. The hypotheses proposing positive effects of laboratory management on critical thinking and creativity were supported, as indicated by calculated t-values of 20.569 and 26.325, respectively, both exceeding the critical threshold. Conversely, the hypotheses linking laboratory management to communication and collaboration were rejected, as their t-values (0.859 and 0.707) fell below the threshold.

Table 5. Hypothesis testing results using t-statistics

No	Original sample (O)	T statistics (O/STDEV)	Hypothesis decision	Relationship
Laboratory management → collaboration	0.121	0.707	Accept Ho	not available
Laboratory management → communication	0.172	0.859	Accept Ho	not available
Laboratory management → creativity	0.783	26.325	Reject Ho	available
Laboratory management → critical thinking	0.767	20.569	Reject Ho	available

The findings of this study provide important insights into the role of structured laboratory management modules in developing twenty-first-century skills, specifically the 4C competencies of critical thinking, creativity, communication, and collaboration. The results of the PLS-SEM analysis confirmed that the laboratory management module had a significant and positive effect on students' critical thinking and creativity but did not exert a statistically significant influence on communication and collaboration skills. This outcome highlights both the strengths and limitations of the laboratory management module as an educational intervention.

The positive effect on critical thinking aligns with the broader literature emphasizing the role of structured learning environments in enhancing students' analytical and evaluative capacities. Critical thinking is a skill that thrives in contexts where learners are required to engage systematically with tasks, evaluate evidence, and make decisions based on empirical data (Lespita et al., 2023; Grinin et al., 2021). The laboratory management module, with its emphasis on procurement, inventory, and structured experimental procedures, appears to create such an environment by encouraging students to engage in careful planning, problem identification, and evaluation of outcomes. This finding resonates with prior research showing that well-organized laboratory activities contribute to deeper conceptual understanding and strengthen students' ability to apply scientific reasoning (Cahyani, 2022; Lutfhianti et al., 2024).

Similarly, the strong effect of laboratory management on creativity reflects the capacity of structured laboratory practices to promote divergent thinking and innovative problem-solving. By providing students with clear guidelines and access to properly maintained resources, the module reduces logistical barriers and enables students to focus their cognitive efforts on generating novel ideas and exploring alternative solutions. This finding is consistent with studies demonstrating that laboratory-based and project-based learning environments foster creative thinking by combining hands-on engagement with opportunities for reflection and experimentation (Leasa et al., 2025; Fajri et al., 2023). As highlighted by Rachma et al. (2025), integrating structured laboratory experiences into hybrid or problem-based learning models significantly enhances students' higher-order thinking, including creativity, by situating learning in authentic and exploratory contexts.

On the other hand, the lack of significant effects on communication and collaboration underscores an important limitation in the current design of the laboratory management module. Although laboratory activities inherently involve group work, the module as implemented in this study did not explicitly incorporate mechanisms or structured prompts to train communication and collaborative practices. The findings suggest that while laboratory organization facilitates cognitive processes, interpersonal skills such as teamwork, negotiation, and effective articulation require additional pedagogical interventions beyond laboratory management per se. Prior literature supports this interpretation, noting that communication and collaboration are best cultivated through instructional strategies such as cooperative learning, peer feedback, and collaborative project design, rather than through resource management alone (Makmuri & Harun, 2024; Hujjatusnaini et al., 2022).

The low R^2 values observed for communication and collaboration further reinforce the notion that laboratory management, although effective for cognitive outcomes, does not sufficiently account for the development of interpersonal skills. This resonates with studies by Girma and Geletu (2024) and Bahtiar and Azmar (2022), who found that laboratory experiences enhance engagement and motivation but do not automatically translate into improvements in teamwork or communication unless complemented by explicit pedagogical strategies. The implication is that laboratory modules should be redesigned to integrate cooperative tasks, role distribution, and communication checkpoints if the aim is to holistically develop all four dimensions of twenty-first-century skills.

These results also contribute to theoretical discussions on the multidimensionality of the 4C framework. While critical thinking and creativity are often regarded as cognitive dimensions, communication and collaboration are more social and affective in nature (Amalia & Siburian, 2025; Kaya et al., 2025). The fact that the laboratory management module significantly influenced the cognitive but not the social dimensions suggests that different instructional approaches may be required to address these domains. Laboratory management may serve as a foundational structure for cognitive development, but the enhancement of interpersonal skills requires integration with pedagogical models such as problem-based learning, collaborative inquiry, or team-based projects (Mirici & Kızılışıkoğlu, 2025).

From a practical perspective, the findings indicate that higher education institutions seeking to strengthen students' twenty-first-century competencies should consider combining laboratory management modules with other instructional strategies that target communication and collaboration explicitly. For example, integrating the module with structured peer interactions, reflective group discussions, and collaborative project assessments may provide opportunities for students to practice and refine interpersonal skills. This integrated approach would align with recommendations from UNESCO's 2030 education agenda, which emphasizes the need to develop both cognitive and socio-emotional competencies for sustainable development (Grinin et al., 2021; Zoidze et al., 2025).

Finally, the novelty of this study lies in its empirical demonstration of the differentiated effects of laboratory management on the four skill domains. While previous research has acknowledged the importance of laboratory management for student achievement and engagement (Agustina, 2018; Laeli & Maryani, 2020; Septia et al., 2018), few studies have directly measured its impact on the 4C framework using advanced statistical modeling. By employing PLS-SEM, this research provides robust evidence that laboratory management modules are effective for fostering critical and creative thinking but insufficient for advancing communication and collaboration. This contribution highlights the need for a more nuanced understanding of how different instructional interventions align with distinct dimensions of twenty-first-century competencies.

IV. CONCLUSION AND SUGGESTION

The present study investigated the effect of a laboratory management module on the development of students' twenty-first-century skills, focusing on critical thinking, creativity, communication, and collaboration. The findings revealed that the implementation of the module had a significant and positive impact on critical thinking and creative thinking, as evidenced by strong path coefficients and high explanatory power in the structural model. Conversely, no significant direct effects were observed on communication and collaboration skills, suggesting that the module is more effective in fostering cognitive competencies than interpersonal ones. These results affirm the pedagogical value of structured laboratory management in supporting analytical and innovative capacities in science education.

Despite these promising results, the study has several limitations. First, the use of self-reported questionnaires may introduce subjective bias, as students' perceptions of their skills may not fully align with their actual performance. Second, the research was conducted in a single institutional context, which may limit the generalizability of findings across different educational settings. Future research should therefore incorporate multiple institutions, utilize mixed-method approaches such as classroom observations or performance-based assessments, and explore complementary instructional strategies that explicitly promote communication and collaboration. Nonetheless, this study contributes to the field of physics education by providing empirical evidence, using advanced PLS-SEM analysis, that laboratory management modules can serve as effective tools for enhancing critical and creative thinking. It also highlights the need for integrated pedagogical frameworks that combine structured resource management with collaborative learning designs, thereby advancing the broader agenda of preparing students for the complex challenges of the twenty-first century.

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