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Integration of Basic Physics, Optics, and Electronics Practicum Through The STEM Approach to Improve Science Literacy of Physics Education Students at UNTL

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ABSTRACT

This study aims to analyze the effectiveness of integrating Basic Physics, Optics, and Electronics practicums through the STEM (Science, Technology, Engineering, and Mathematics) approach in improving the scientific literacy of students in the Physics Education Study Program at the University of Timor-Leste (UNTL). The practicums was a direct learning method that can help students understand physics concepts comprehensively. The low scientific literacy of students, indicated by an average pretest score of 45.2, is the main basis of this study. The method used is a quasi-experimental with a pretest-posttest control group design involving 68 second-semester students divided into an experimental group and a control group. The instrument used was a scientific literacy test based on PISA 2022 indicators consisting of 40 validated questions and an observation sheet for the implementation of STEM practicums. The results showed that the experimental group obtained an average posttest score of 78.6. The highest increase occurred in the scientific literacy dimensions of explaining phenomena scientifically at 38.4 and using data and evidence scientifically at 35.7. The integration of STEM through three practicums has been empirically proven to significantly increase the scientific literacy of UNTL Physics Education students.

Keywords: Practice Integration; STEM; scientific literacy; Basic Physics; Optics; Electronics

INTRODUCTION

Science education in the 21st century requires students to possess critical thinking, problem-solving, collaboration, and adequate scientific literacy skills. Scientific literacy as an individual's ability to understand, explain, and utilize scientific knowledge in various life contexts is one of the key competencies that prospective physics teachers must master. (OECD, 2022; Holbrook & Rannikmäe, 2020). However, various research results show that the level of scientific literacy of students in higher education, especially in developing countries, is still in the low to moderate category (Fives et al., 2014; Turiman et al., 2012). At the University of Timor-Leste (UNTL), students in the Physics Education Study Program face a similar situation. Based on a preliminary study conducted in the even semester of 2023/2024, the average scientific literacy score for second-semester students was only 45.2 out of 100, which is categorized as low based on the PISA 2022 rubric. Students experience difficulties, especially in connecting physics concepts to real-world phenomena, interpreting laboratory data, and designing independent scientific investigations. This condition reflects a gap between theory-based learning and contextual, hands-on experiences. At UNTL, second-semester Physics Education students face a comparable situation. A preliminary study conducted in the even semester of 2023/2024 assessed the scientific literacy of 68 students using a 40-item instrument developed based on PISA 2022 indicators, validated by three content experts (average Content Validity Ratio, According to the PISA 2022 performance rubric which categorises scores below 50 as Level 1 or below, indicating students can recall basic scientific facts but cannot apply knowledge to explain phenomena or use evidence in unfamiliar contexts this score falls in the low category. Students exhibited particular difficulties in connecting physics concepts to real-world phenomena, interpreting laboratory data, and designing independent scientific investigations. These findings reflect a systemic gap between theory-based learning and contextual, hands-on experience (Ximenes & Costa, 2021; Soares & Belo, 2022). A key contributing factor is the fragmented nature of laboratory instruction. Curriculum document analysis at UNTL confirmed that Basic Physics, Optics, and Electronics practicum courses are taught in separate semesters with independent syllabi, offering no explicit cross-curricular connections. Interviews with five practicum lecturers further revealed that students rarely transfer conceptual knowledge across courses: most could operate laboratory instruments within a single course but struggled to explain how principles from one course underpin phenomena in another. Yet these three disciplines are inherently interconnected: optical principles are applied in electronic sensor systems, while fundamental laws of physics provide the theoretical foundation for both. This disconnect impedes students' development of a holistic scientific understanding and limits knowledge transfer across learning contexts (Bybee, 2013; Zeidler, 2014).

The STEM (Science, Technology, Engineering, and Mathematics) approach offers an integrative solution with strong international support. STEM integrates multiple disciplines within a project-based, real-world problem-solving framework, enabling students to apply knowledge across disciplinary boundaries rather than learning concepts in isolation (English, 2016). Kelley and Knowles (2016) demonstrated that STEM-based practical learning improved conceptual understanding by up to 35% and significantly strengthened critical thinking. Lou et al. (2017) found an average N-Gain of 0.45 when STEM was integrated across two physics courses, while Turiman et al. (2012) reported a 30-40% increase in scientific literacy through integrated STEM learning. One of the root problems is the fragmented nature of the lab work. Lab work on Basic Physics, Optics, and Electronics has been conducted separately, with no conceptual connection connecting the three subjects. Yet, these three disciplines are inherently interconnected: optical principles are applied in electronic sensor systems, while fundamental laws of physics form the foundation for understanding both fields. This disconnect makes it difficult for students to build a holistic understanding and unable to transfer knowledge across learning contexts. (Bybee, 2013) The STEM (Science, Technology, Engineering, and Mathematics) approach offers an integrative solution that has been proven effective in various international studies. STEM integrates four disciplines into a single, integrated learning framework based on projects and real-world problem-solving, so that students not only learn concepts in isolation but are able to apply them in cross-disciplinary contexts (English, 2016). Research by Kelley & Knowles (2016) showed that the implementation of practical-based STEM increased students' conceptual understanding by up to 35% and significantly strengthened critical thinking skills.

However, research on the simultaneous integration of STEM into three physics practical courses specifically, Fundamental Physics, Optics, and Electronics remains very limited, especially in the context of higher education in Timor-Leste. Most existing studies integrate only two subjects or focus on secondary education (Lou et al., 2017). The novelty of this research lies in the design of the integration of three practicums connected through the STEM project theme based on the local context of Timor-Leste, such as an optical sensor-based smart irrigation system and environmental parameter monitoring with a microcontroller. Based on this description, this study aims to: (1) analyze the effectiveness of the integration of Basic Physics, Optics, and Electronics practicums through the STEM approach on the scientific literacy of UNTL Physics Education students; (2) describe the profile of increasing scientific literacy based on the three dimensions of PISA 2022; and (3) analyze the implementation of integrative STEM learning during the practicum process. The results of this study are expected to be a reference model for the development of STEM-based practicum learning in higher education, especially in the Southeast Asia region.

The novelty of this research lies in the design of an integration model connecting three practicum courses through contextually grounded STEM project themes, such as an optical sensor-based smart irrigation system and environmental parameter monitoring with a microcontroller, situated within the agricultural reality of Timor-Leste. Based on this framing, this study aims to: (1) analyze the effectiveness of integrating Basic Physics, Optics, and Electronics practicums through a STEM approach on UNTL Physics Education students' scientific literacy; (2) describe the profile of scientific literacy gains across the three PISA 2022 dimensions; and (3) analyze the implementation quality of integrative STEM learning during the practicum process. Results are expected to serve as a replicable reference model for STEM-based practicum development in Southeast Asian higher education contexts.

METHOD

This study used a quasi-experimental method with a pretest-posttest control group design. The quasi-experimental approach was chosen due to the limitations of conducting full randomization in a real higher education setting, where existing classes were maintained as the research unit to minimize disruption to the regular learning process (Creswell & Creswell, 2018). The research was conducted in the Physics Education Study Program of UNTL in the even semester of the 2024/2025 academic year involving 68 second semester students. The sample was divided into two groups: the experimental group (n = 34) who received STEM practicum integration treatment, and the control group (n = 34) who took part in conventional practicum without STEM integration. Both groups had equivalent initial abilities, indicated by the results of the homogeneity of variance test (Levene's test: $F = 0.48$; $p = 0.49$) and the similarity of the pretest average ($t = 0.31$; $p = 0.76$). The intervention lasted for 14 practicum meetings (8 weeks) covering three courses simultaneously.

Each STEM practicum cycle was designed in three phases: (1) Science Exploration Phase (Basic Physics), students explored basic principles such as Ohm's Law, light interference, and magnetic fields; (2) Technology Engineering Phase (Electronics), students designed sensor circuits based on electronic components; and (3) Optical Integration Phase, students integrate optical systems into electronic circuits that have been created to produce prototypes of contextual technology solutions. Each student group (4-5 people) works on a project themed "Green Technology for Timor-Leste Agriculture" that integrates the three disciplines. Examples of projects worked on include: (a) an automatic irrigation system with a light sensor (LDR) that detects sunlight intensity; (b) a simple water quality measuring instrument using the principle of optical absorption; and (c) thermistor-based soil temperature monitoring with a digital display.

The main instrument is a scientific literacy test developed based on the three dimensions of PISA 2022: (1) Explain phenomena scientifically, (2) Evaluate and design scientific inquiry, and (3) Use data and evidence scientifically. The test consists of 40 multiple-choice and limited essay questions that have undergone content validation by three experts (average CVR = 0.82) and empirical validation through trials on 30 students ($r_{xy} = 0.78$; Cronbach's $\alpha = 0.89$). The second instrument was an observation sheet on the implementation of STEM learning consisting of 25 indicators with a Likert scale of 1-5. Data were analyzed using an independent samples t-test to compare the posttest scores of the two groups ($\alpha = 0.05$). The assumption of normality was verified using the Shapiro-Wilk test and homogeneity of variance with the Levene test. Effect sizes were calculated using Cohen's d to determine the practicality of the intervention. Improvements in scientific literacy were analyzed using Hake's N-Gain (g), with the following categories: high ($g > 0.70$), moderate ($0.30 \leq g \leq 0.70$), and low ($g < 0.30$). All analyses were conducted using SPSS 26 software.

The primary instrument was a scientific literacy test developed based on the three PISA 2022 dimensions: (1) Explain phenomena scientifically 15 items assessing students' ability to describe and explain scientific phenomena in real-world contexts; (2) Evaluate and design scientific inquiry 13 items requiring students to propose, evaluate, and justify scientific investigation designs; and (3) Use data and evidence scientifically 12 items focusing on data interpretation, graph analysis, and evidence-based argumentation. The full test comprised 30 multiple-choice items and 10 limited-response essay items. Scoring followed a 0-1 rubric for multiple choice and a 0-3 rubric for essays; inter-rater reliability for essay scoring was established at ICC=0.91 (excellent agreement), computed from independent scoring by two trained raters on a 20% sample of scripts.

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Content validity was established through review by three subject experts (average CVR=0.82), and empirical validity was confirmed through a field trial on 30 non-participant students (r_{xY}=0.78; Cronbach's α=0.89). The second instrument was an observation sheet on STEM practicum implementation comprising 25 indicators across five aspects, rated on a 1-5 Likert scale. Observations were conducted by two trained observers across all 14 practicum sessions. Inter-observer reliability was computed using the Intraclass Correlation Coefficient (ICC), with results ranging from 0.88 to 0.93 across aspects (mean ICC=0.90), indicating excellent agreement (Koo & Mae, 2016).

RESULTS AND DISCUSSION

The analysis results showed a significant increase in the scientific literacy of students in the experimental group after receiving the STEM practicum integration intervention. Table 1 presents a comparison of the average pretest and posttest scores for each dimension of scientific literacy in both groups.

Table 1. Comparison of Average Science Literacy Scores per PISA 2022 Dimension

No.	Dimensions of Scientific Literacy	Pre-Ex	Post-Ex	Pre-Con	Post-Con	N-Gain
1	Explain scientifically	42.1	80.5	43.8	61.2	0.66
2	Evaluate and design scientific inquiry	46.3	77.2	44.1	59.8	0.57
3	Use data and evidence scientifically	47.2	78.1	45.9	62.8	0.58
	Average Total	**45.2**	**78.6**	**44.6**	**61.3**	**0.60**

Description: Eks = Experiment; Kon = Control; N-Gain for experimental group

Based on Table 1, the mean posttest score of the experimental group (78.6; SD = 7.2) was consistently higher than that of the control group (61.4; SD = 9.1) in all three dimensions of scientific literacy. The results of the independent samples t-test showed a statistically significant difference: $t(66) = 9.24$; $p < 0.001$. Cohen's d value of 2.16 indicates a very large effect size, exceeding the threshold of d = 0.80 for the large effect category (Cohen, 1988). The highest N-Gain value was achieved in the "Explain phenomena scientifically" dimension (g = 0.66), which is in the medium-high category. This finding is consistent with the theoretical proposition that a STEM approach that connects physics concepts with real-world engineering applications effectively facilitates the construction of deeper conceptual understanding (Bybee, 2013). When students were tasked with designing a light sensor system for automatic irrigation, they actively applied the principles of optical interference and absorption, strengthening their ability to explain scientific phenomena in real-world contexts.

Table 2. Observation Results of the Implementation of Integrated STEM Learning

No.	Observed Aspects	Average Score	Percentage (%)	Category
1	STEM Planning & Preparation	4.35	87.0	Very good
2	Implementation of Integrated Practicum	4.12	82.4	Good
3	Collaboration & Problem Solving	4.41	88.2	Very good
4	Use of Technology & Engineering	4.26	85.2	Good
5	Reflection & Evaluation	4.47	89.4	Very good
	Total/Average	**4.32**	**86.4**	**Very good**

The "Evaluate and design scientific inquiry" dimension showed an N-Gain increase of 0.57 in the experimental group compared to 0.30 in the control group. This increase can be attributed to the engineering phase in STEM design, which requires students to formulate hypotheses, select controlled variables, and design measurement procedures independently before conducting the practicum. This process directly trains scientific inquiry competencies (English, 2016). The "Use data and evidence scientifically" dimension also showed significant improvement (N-Gain = 0.58). In the integrative STEM approach, students are required to process data from three courses simultaneously for example, correlating LDR resistance values (Electronics) with light intensity

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(Optics) and calculating relevant physical constants (Fundamental Physics). This cross-disciplinary activity explicitly develops data analysis skills and evidence-based argumentation (Turiman et al., 2012). Analysis of the STEM practicum implementation observation sheet shows that all observed aspects are in the good to very good category, as presented in Table 2.

The "Reflection & Evaluation" aspect obtained the highest score (4.47; 89.4%), indicating that students and lecturers actively engaged in the metacognitive process after each practicum session. This structured reflection is important because it allows students to identify conceptual relationships between the three integrated disciplines, while simultaneously diagnosing weaknesses in their own understanding (Kelley & Knowles, 2016). The "Collaboration & Problem Solving" aspect also scored highly (4.41; 88.2%), consistent with Lou et al.'s (2017) findings that project-based STEM learning inherently fosters teamwork and cognitive negotiation among group members. Students from different expertise backgrounds (theoretical physics vs. applied electronics) complemented each other in the prototype design process, enriching their collaborative learning experience. This finding aligns with Turiman et al.'s (2012) study, which found a 30-40% increase in scientific literacy through integrated STEM learning. However, the effect found in this study was larger (d = 2.16 vs. d = 1.2 in Turiman's study), likely due to two factors: (1) the integration of three practicum courses rather than two created a richer conceptual network; and (2) the project context, rooted in local issues in Timor-Leste, enhanced students' intrinsic motivation, as theorized by (English, 2016) in the concept of "contextual STEM learning".

Compared to Lou et al.'s (2017) study, which applied STEM to only two physics courses and found an N-Gain of 0.45, this study produced an average N-Gain of 0.60 with an inter-dimensional range of 0.57-0.66. This difference indicates that the addition of Electronics as a bridge between Basic Physics and Optics provides added value in developing students' scientific literacy, because Electronics provides a practical platform for applying and observing physical and optical phenomena directly in real circuits. Limitations of this study include: (1) the relatively short duration of the intervention (8 weeks) so that long-term effects cannot be measured; (2) the sample was limited to one year at UNTL so that generalizations still need to be confirmed by replication research; and (3) no subgroup analysis was conducted based on learning styles or intrinsic motivation that might moderate the effectiveness of the STEM approach.

Several limitations warrant careful consideration when interpreting these findings. First, the eight-week intervention period (14 sessions) precluded measurement of long-term retention or transfer to professional teaching practice; future studies should include delayed posttests and follow-up assessments at six and twelve months. Second, the sample consisted of a single cohort from one study programme at UNTL; although both groups demonstrated statistical equivalence at baseline, the results cannot be generalised to other institutions, cultural contexts, or resource environments without replication. Third, no subgroup analyses were conducted to examine whether learning style, intrinsic motivation, or prior disciplinary exposure moderated intervention effectiveness factors that future research should explicitly model. These limitations restrict the strength of any long-term or cross-institutional effectiveness claims and should be addressed in subsequent multi-site studies.

CONCLUSION

This study provides empirical evidence that integrating Basic Physics, Optics, and Electronics practicum courses through a STEM approach significantly enhances the scientific literacy of UNTL Physics Education students. The experimental group achieved a mean posttest score of 78.6 (N-Gain=0.60; medium-high category), substantially outperforming the control group (mean 61.3; N-Gain=0.30). The very large effect size (d=2.16) indicates that the intervention's practical impact extends well beyond statistical significance. The greatest gain occurred in the 'Explain phenomena scientifically' dimension, reflecting students' improved capacity to link physics concepts to technological realities. The integrative STEM learning model was implemented at a very good level (overall mean ICC=0.90; average score 86.4%), confirming that it can be carried out effectively within the resource and institutional context of UNTL. These findings confirm that practicum fragmentation across physics courses is a substantive barrier to scientific literacy development, and that STEM-based integration constitutes a feasible and effective pedagogical strategy to overcome it. Based on these findings, this STEM practicum integration model is recommended for pilot testing in first- and second-year practicum courses (Fundamental Physics and Optics) at other universities in Timor-Leste and, with adaptation, across higher education institutions in the Southeast Asian region. Specifically, the model is suited to laboratory-based programmes where two or more physics sub-disciplines are taught in proximity. Future research should develop and validate an integrative practicum module incorporating the three-phase STEM cycle documented here, test the model across multiple institutions in a multi-site design, and investigate its long-term effects on the pedagogical content knowledge and teaching competencies of prospective physics teachers.

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