

Bilingual STEM Workshop Assisted by PhET Simulations to Improve Hooke's Law Understanding and 21st-Century Skills among High School Students in a Border Region

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Abstrak

Sekolah di wilayah perbatasan Indonesia masih menghadapi tantangan dalam meningkatkan literasi sains, keterampilan abad ke-21 (4C), dan kemampuan bahasa Inggris secara bersamaan. Lebih lanjut, pembelajaran fisika masih didominasi oleh hafalan rumus sehingga siswa cenderung memandang konsep sains sebagai sesuatu yang abstrak dan jauh dari kehidupan nyata. Kegiatan pengabdian masyarakat ini bertujuan untuk mengkaji efektivitas Workshop Bilingual STEM yang mengintegrasikan simulasi virtual PhET dan aktivitas eksperimen dalam meningkatkan pemahaman konsep Hukum Hooke serta mengembangkan keterampilan abad ke-21 siswa. Program ini menggunakan pendekatan mixed-methods dengan desain explanatory sequential, melibatkan 15 siswa kelas X SMAIT Ibnu Sina Boarding School Nunukan. Workshop dilaksanakan dengan menggunakan prinsip *Content and Language Integrated Learning* (CLIL), dengan bahasa Inggris sebagai bahasa pengantar selama kegiatan pembelajaran. Data kuantitatif diperoleh melalui pre-test dan post-test yang dianalisis menggunakan rumus Normalized Gain (N-Gain). Sementara itu, data kualitatif diperoleh melalui observasi *Direct Performance Assessment* yang berfokus pada 4 aspek utama, yaitu kolaborasi, berpikir kritis, kreativitas, dan komunikasi. Hasil penelitian menunjukkan adanya peningkatan signifikan dalam pemahaman konsep siswa. Hal ini ditunjukkan oleh kenaikan rata-rata skor dari 42,6 (pre-test) menjadi 81,3 (post-test) serta nilai rata-rata N-Gain sebesar 0,68 yang termasuk kategori sedang menuju tinggi. Hasil observasi juga menunjukkan perkembangan positif pada keterampilan abad ke-21 siswa. Kegiatan ini menyimpulkan bahwa integrasi pembelajaran bilingual dengan STEM berbantuan simulasi PhET merupakan strategi potensial untuk meningkatkan pembelajaran fisika dan keterampilan abad ke-21 dalam konteks pendidikan di wilayah perbatasan. Selain itu, pembelajaran bilingual berbasis simulasi dapat menjadi model pembelajaran yang praktis dan mudah diterapkan di sekolah dengan keterbatasan fasilitas laboratorium.

Kata Kunci: Bilingual STEM, simulasi PhET, Hukum Hooke, Keterampilan Abad 21, CLIL, pendidikan wilayah perbatasan

Abstract

Schools in Indonesia's border regions continue to face challenges in improving scientific literacy, 21st – century skills (4C), and English proficiency simultaneously. Furthermore, physics learning is still largely dominated by formula memorization. It causes students to perceive scientific concepts as abstract and disconnected from real-life contexts. This community service program aimed to examine the effectiveness of a Bilingual STEM Workshop integrating PhET virtual simulations and experimental activities in improving students' understanding of Hooke's Law concepts and developing their 21st – century skills. The program employed a mixed-methods approach with an explanatory sequential design and involved 15 Grade 10 students from SMAIT Ibnu Sina Boarding School, Nunukan. The workshop was implemented using the principles of Content and Language Integrated Learning (CLIL). It functions as the medium of instruction during learning activities. Quantitative data were collected through pre-test and post-test assessments and analyzed using the Normalized Gain (N-Gain) formula. Meanwhile, qualitative data were obtained through Direct Performance Assessment observations focused on four major aspects of collaboration, critical thinking, creativity, and

communication. The findings revealed a significant improvement in students' conceptual understanding. This was indicated by the increase in the mean score from 42.6 (pre-test) to 81.3 (post-test), as well as the average N-Gain score of 0.68. It was categorized as moderate to great improvement. Observation results also demonstrated positive development in students' 21st – century skills. The study concludes that integrating bilingual learning with STEM supported by PhET simulations represents a promising strategy for improving physics learning and 21st–century skills in border-region educational contexts. In addition, simulation-based bilingual learning can serve as a practical and accessible instructional model for schools with limited laboratory facilities.

Keywords: Bilingual STEM, PhET simulation, Hooke's Law, 21st – century skills, CLIL, border-region education

1. Introduction

Schools in Indonesia's border regions face structural challenges in producing globally competitive graduates. There are three main challenges in strengthening 21st–century skills (4Cs) alongside foreign language proficiency, namely limited access to resources, exposure to innovative pedagogical practices, and learning environments. One of the schools located on the Indonesia-Malaysia border, known as SMAIT Ibnu Sina Boarding School in Nunukan regency, offers a strategic advantage through its extended learning time within a boarding school system. However, subjects related to science, especially Physics, remain theoretically and mathematically oriented. It has a strong emphasis on just formula memorization. This approach limits students' ability to connect physics to real-world phenomena. Therefore, it will lead to the perception of Physics as an abstract and difficult subject. An Applied Physics approach is proposed to enhance students' engagement through hands-on experimentation in mechanics and fluid concepts, addressing the issue. At the same time, the demands of globalization position English as a critical competency. Therefore, integrating science and language learning through a Bilingual STEM approach can be a potential solution. This approach uses English as the medium of instruction for specific experiments, enabling students to develop both scientific literacy and language proficiency simultaneously.

Recent studies in science education have explored various approaches to enhancing students' conceptual understanding through the integration of technology and innovative pedagogies. The use of interactive simulations has been widely recognized for its effectiveness in visualizing abstract scientific concepts (Wieman et al., 2008). Zacharia and Olympious (2011) also highlighted that combining virtual simulations with physical experimentation leads to more comprehensive learning outcomes. Moreover, the integration of language and content learning has gained increasing attention through the bilingual education model (for instance, Content and Language Integrated Learning, known as CLIL). Coyle (2007) emphasized that language functions as a medium for knowledge construction. Nikula et al. (2013) also supported the argument by showing that language use significantly shapes students' cognitive engagement in content-based instruction, making it relevant to STEM learning contexts. However, the existing studies tend to address virtual simulations, hands-on experimentation, and bilingual learning separately. The potential of integrating conceptual understanding, practical skills, and language development remains underexplored, particularly in authentic learning contexts.

Although research on STEM education and the integration of virtual simulations is emerging, recent studies still indicate a dominant trend toward enhancing students' conceptual competencies. Empirical studies on PhET-based learning over the last five years consistently report a significant increase in students' conceptual understanding and critical thinking (Tanzillal et al, 2026; Fadillah et al., 2026). Moreover, STEM-based learning is supported by PhET simulations, which have been proven to enhance students' engagement and HOTS in science learning (Ikhsan et al., 2025; Buhera et al., 2024). Nevertheless, these studies largely emphasize cognitive outcomes. It has a limited attention

to the development of hands-on experimental skills and authentic scientific practices. The recent research has acknowledged the importance of integrating virtual simulation with inquiry-based or STEM approaches. However, the implementation often remains confined to simulation-centered activities or digital worksheets. Studies conducted in Indonesia demonstrate that PhET-assisted STEM learning improves students' conceptual understanding and engagement, but it still relies heavily on virtual environments and does not systematically incorporate physical experimentation (Eliansi et al., 2023; Buhera et al., 2024). This indicates that students need to develop procedural skills through direct practice with real physical instruments.

At the same time, the integration of bilingual approaches in STEM education is a rarely explored topic in recent empirical research, especially in science learning contexts involving experimental activities. Recent empirical work in science classrooms tends to treat language as an auxiliary component rather than an integral part of experimental learning design. It contrasts with previous studies on bilingual or CLIL-based instruction by emphasizing the role of language in shaping cognitive processes. As a result, the potential of using English as a medium for conducting scientific experiments has not been sufficiently investigated. A notable gap exists in border-region education. Additional challenges include limitations in resources, access to laboratory facilities, and exposure to global academic practices. Previous studies in Indonesian science education contexts have primarily focused on improving conceptual understanding through technology-enhanced learning. There is still minimal attention to integrating bilingual instruction with authentic experimentation in geographically constrained settings (Pratama et al, 2025; Tanzillal et al, 2026). Moreover, evidence on how an integrated approach combining virtual simulations, physical experiments, and bilingual instruction can enhance students' applied physics literacy.

Therefore, the authors identify three critical gaps. First, recent studies tend to prioritize conceptual outcomes over the integration of procedural and contextual learning in science education. Second, there is limited implementation of instructional designs that systematically combine virtual simulations and physical experiments as complementary learning strategies. Third, empirical research integrating bilingual STEM approaches within authentic experimental contexts, especially in border-region schools, is rarely explored. Based on the framework, the author designed a program entitled "Bilingual STEM Workshop" targeting the Grade 10 students. It integrates PhET virtual simulations with hands-on measurement activities using physical instruments, where virtual simulations facilitate conceptual understanding through visualization, and real tools enhance students' technical skills. SMAIT Ibnu Sina Boarding School's environment also supports the approach by fostering intensive interaction and collaboration among students.

2. Method

The community service program employed a mixed-methods approach using an explanatory sequential design. Quantitative data were collected in the initial phase to measure students' learning outcomes. Qualitative data is used to provide deeper insights into students' performance during the learning process. The program was held at SMAIT Ibnu Sina Boarding School in Nunukan in May 2026. It involves 15 Grade 10 students as participants. The students are selected as they establish foundational scientific reasoning before entering more specialized academic tracks.

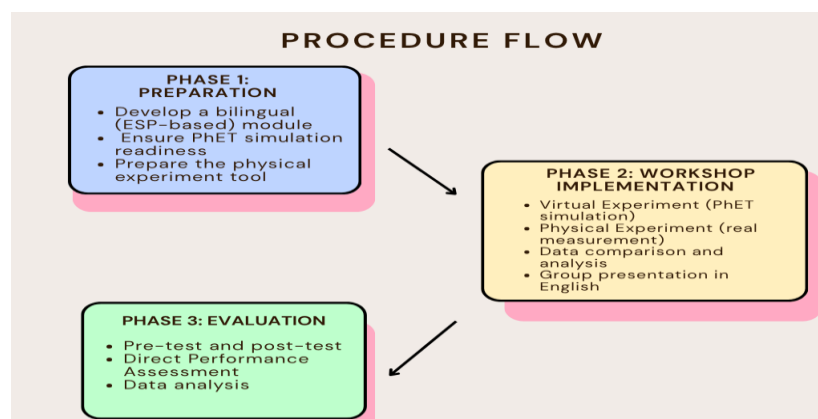


Figure 1. The Procedure Flow

The implementation of the program was structured into three main phases, namely preparation, workshop execution, and evaluation. The first phase involved preparation. The team developed bilingual instructional modules based on English for Specific Purposes (ESP) principles and ensured the functionality of PhET Interactive Simulations. In addition, a simple experimental apparatus for Hooke's Law was prepared to facilitate hands-on measurement activities. The second phase consisted of a one-day intensive workshop integrating virtual simulations and physical experimentation under the principles of CLIL. English is the primary medium of instruction used during all experimental activities. Students worked in small groups and engaged in a two-stage experimental process.

In the first stage, students explored Hooke's Law concepts using PhET simulations by manipulating variables. It allows them to visualize the relationship between applied force and displacement. They conducted a physical experiment using a real apparatus in the second stage, measuring the spring's extension under varying loads. Later, they recorded data and compared the results from the virtual simulation with those from the physical experiment. The comparative process was designed to strengthen both conceptual understanding and procedural skills. At the end of the session, each group presented its findings in English (focusing on both scientific explanation and communication clarity).

The third phase is the evaluation and reflection. Two primary instruments were used to assess the program's effectiveness. First, a written test (pre-test and post-test) was administered to measure students' conceptual understanding of Hooke's Law. Second, a Direct Performance Assessment rubric with a four-point scale was used to evaluate students' performance during both virtual and physical experimental activities. The rubric assessed four aspects aligned with 21st-century skills (4Cs), namely collaboration, critical thinking, communication, and creativity.

Quantitative data from written tests were analyzed using the Normalized Gain (N-Gain) formula to determine students' learning improvement.

$$g = \frac{Post-Pre}{100-pre}$$

Qualitative data from the observation sheets were analyzed descriptively to identify patterns in students' 4C skill development during the experimental process. The results from both analyses were then integrated to provide a comprehensive evaluation of the program's effectiveness.

3. Result and Discussion

The community service program was successfully implemented with the participation of 15 grade 10 students from SMAIT Ibnu Sina Boarding School, Nunukan. The experimental focus was on spring systems and Hooke’s Law. It utilizes the Masses and Springs feature in PhET virtual simulations developed by Carl Wieman. All instructional materials and the simulation interface were delivered in English. It aims to align with the principles of bilingual STEM learning. Through the simulation, students observed how the spring constant, applied mass, and gravitational force influence a spring’s displacement in a dynamic, visual manner.



Figure 2. The implementation of the Workshop at SMAIT Ibnu Sina

To evaluate the intervention’s impact on students’ conceptual understanding, a pre-test and a post-test were administered. The maximum score for both tests was 100. The results were analyzed using the Normalized Gain (N-Gain) to determine the level of improvement.

$$g = \frac{Post-Pre}{100-pre}$$

Table 1. The summary of students’ performance

Assessment Indicator	Minimum Score	Maximum Score	Mean Score
Pre-test	30	55	42.6
Post-test	70	95	81.3
N-Gain Score	0.57	0.88	0.68
Category	-	-	Moderate

As shown in Table 1, the initial mean score of 42.6 indicates that students possessed limited conceptual understanding of Hooke’s Law. Observations during the initial phase revealed that students could recall the mathematical formula but struggled to interpret its physical meaning. This finding supports the view that students rely heavily on memorization rather than conceptual reasoning, a common issue in physics learning.

After engaging with the PhET simulation, students’ mean score increased significantly to 81.3 with an average N-Gain of 0.68. It is categorized as moderate to high. The result aligns with previous findings that interactive simulations effectively enhance understanding through visual representations of abstract concepts (Wieman et al, 2008; Rutten et al., 2012). More importantly, students demonstrated the ability to relate variables such as spring stiffness and displacement. It indicates a shift from procedural memorization to conceptual comprehension.

Beyond cognitive outcomes, students’ 21st-century skills (4Cs) were assessed using a Direct Performance Assessment rubric with a scale of 1 (poor) to 4 (excellent). The students were divided into five groups of 3 members each.

Table 2. The results

4C Skills Aspect	Mean Score (1–4)	Category
Collaboration	3.7	Excellent
Critical Thinking	3.4	Excellent
Creativity	3.2	Good
Communication	3.1	Good

The highest score was observed in collaboration (3.7). It highlights that students were able to distribute tasks effectively within their groups. The boarding school environment likely influences the outcome. It aims to foster strong peer interaction and teamwork. Students naturally adopted different roles, such as operating the simulation, recording data, and interpreting English instructions.

The elements of critical thinking (3.4) show that students demonstrated analytical reasoning when modifying variables in the simulation. They inferred that gravitational force affects the spring's weight, which in turn influences its displacement. This indicates that the simulation supported inquiry-based exploration and reasoning process. Creativity (3.2) was reflected in students' initiative to explore additional features within the simulation. The behavior, such as activating the energy graph without explicit instruction, suggests that the learning environment encouraged curiosity and independent exploration. Communication (3.1) shows the lowest outcomes. During the group presentation, students were required to explain their findings in English. Despite grammatical inaccuracies and limited fluency, students can still convey key scientific concepts. It demonstrates that language was used functionally as a tool for communication rather than as an isolated subject of assessment.

These findings support the effectiveness of the Bilingual STEM approach. It is particularly within the framework of CLIL proposed by Do Coyle (2007). He argued that language is the medium of instruction to build understanding and knowledge. Thus, the use of English integrated into science experimental activities can reduce students' anxiety towards the foreign language. It can also enhance their self-esteem in expressing scientific ideas. Overall, the results indicate that integrating virtual simulations with bilingual instruction improves conceptual understanding and facilitates the development of 21st-century skills. However, the findings are limited to a small sample size and short intervention duration. This may affect the generalizability of the results.

4. Conclusion

It can be concluded that the bilingual STEM workshop, supported by PhET virtual simulations, had a positive impact on students' learning in physics. The implementation of a virtual Hooke's Law experiment resulted in a moderate-to-great improvement. The N-Gain score of 0.68 is highlighted among 15 participants from SMAIT Ibnu Sina Boarding School. In addition to cognitive gains, the approach contributed to the development of 21st – century skills, particularly in collaboration and critical thinking. It also reduces students' anxiety in communicating scientific ideas using basic English during group presentations. From a pedagogical perspective, the study highlights the potential of integrating virtual simulations and bilingual approaches within STEM learning. Especially when it is implemented in resource-constrained and geographically remote contexts.

The use of PhET simulations provides an accessible alternative to traditional laboratory limitations. Meanwhile, the CLIL-based approach enables the simultaneous development of content knowledge and language skills. This integrated model offers a practical framework for educators seeking to address multiple learning objectives within a single instructional design. However, the study still has limitations. The relatively small sample size and short duration of the intervention restrict the generalizability of the findings. In addition, although the study emphasizes an integrated approach, the implementation was still predominantly simulation-based. It may lead to a limitation of hands-on

experimental skills development. Therefore, future studies are recommended to incorporate more extensive physical experimentation to examine the sustainability of learning outcomes. In conclusion, the study contributes to the growing body of research on STEM education by demonstrating that a Bilingual STEM approach supported by interactive simulations can serve as an effective strategy to enhance both conceptual understanding and 21st-century skills. More importantly, it provides empirical evidence from a border-region educational context. It remains underrepresented in the literature, thereby offering both theoretical and practical implications for future instructional innovation.

5. Reference

- Astuti, I. D., Toto, T., & Yulisma, L. (2019). Model Project-Based Learning (PjBL) Terintegrasi STEM untuk Meningkatkan Penguasaan Konsep dan Aktivitas Belajar Siswa. *Jurnal Pendidikan dan Biologi*, 11(2), 93–98.
- Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Computers & Education*, 87, 218–237. <https://doi.org/10.1016/j.compedu.2015.07.003>
- Carloni, G. (2019). Digital Pedagogy and CLIL for the Development of Intercultural Dimensions. In M. E. Hughes & D. Lindmeier (Eds.), *Educating the Global Citizen* (pp. 145–160). München: LMU Press.
- Coyle, D. (2007). Content and language integrated learning: Towards a connected research agenda for CLIL pedagogies. *International Journal of Bilingual Education and Bilingualism*, 10(5), 543–562. <https://doi.org/10.2167/beb459.0>
- Coyle, D., Hood, P., & Marsh, D. (2010). *CLIL: Content and Language Integrated Learning*. Cambridge: Cambridge University Press.
- Eliansi, E., et al. (2023). STEM learning assisted by PhET simulation to improve students' conceptual understanding in physics learning. *Journal of Science Education Research*, 7(2), 115–124.
- Fadillah, N., et al. (2026). The effectiveness of PhET-assisted physics learning on students' conceptual understanding and critical thinking skills. *Jurnal Pendidikan Fisika Indonesia*, 22(1), 45–56.
- Ikhsan, M., et al. (2025). STEM-based learning using PhET simulations to improve higher-order thinking skills in science education. *Jurnal Pendidikan IPA Indonesia*, 14(2), 210–221.
- Kolb, D. A. (2014). *Experiential Learning: Experience as the Source of Learning and Development* (2nd ed.). New Jersey: Pearson FT Press.
- Nikula, T., Dalton-Puffer, C., Llinares, A., & Lorenzo, F. (2013). More than content and language: The complexity of integration in CLIL and bilingual education. *Journal of Immersion and Content-Based Language Education*, 1(2), 236–256. <https://doi.org/10.1075/jicb.1.2.06nik>
- PhET Interactive Simulations. (2026). Masses and Springs. Available from <https://phet.colorado.edu/en/simulations/masses-and-springs> (accessed 1 April 2026).
- Pratama, R., et al. (2025). Technology-enhanced science learning in border-region schools: Challenges and opportunities in Indonesian education. *Jurnal Pendidikan Sains Indonesia*, 13(1), 55–67.
- Prihatiningtyas, S., Shofiyah, N., Yunus, S. R., dkk. (2025). Transforming Physics Education in Boarding Schools: Development of STEM-Q-Based E-Modules to Improve Science Literacy. *Jurnal Pendidikan Fisika Indonesia*, 21(1), 69–85.
- Rutten, N., van Joolingen, W. R., & van der Veen, J. T. (2012). The learning effects of computer simulations in science education. *Computers & Education*, 58(1), 136–153. <https://doi.org/10.1016/j.compedu.2011.07.017>
- Sari, N., Sunarno, W., & Sarwanto, S. (2018). Analisis Motivasi Belajar Siswa Dalam Pembelajaran Fisika Sekolah Menengah Atas. *Jurnal Pendidikan dan Kebudayaan*, 3(1), 17–32.

- Tanzillal, M., et al. (2026). Interactive simulation-based learning and its impact on students' conceptual understanding in physics education. *Jurnal Penelitian Pendidikan IPA*, 12(1), 88–99.
- Widana, I. W., & Septiari, K. L. (2021). Kemampuan Berpikir Kreatif dan Hasil Belajar Matematika Siswa Menggunakan Model Pembelajaran Project-Based Learning Berbasis Pendekatan STEM. *Jurnal Elemen*, 7(1), 209–220.
- Wieman, C. E., Adams, W. K., & Perkins, K. K. (2008). PhET: Simulations that enhance learning. *Science*, 322(5902), 682–683. <https://doi.org/10.1126/science.1161948>
- Zacharia, Z. C., & Olympiou, G. (2011). Physical versus virtual manipulative experimentation in physics learning. *Learning and Instruction*, 21(3), 317–331. <https://doi.org/10.1016/j.learninstruc.2010.03.001>