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Impact of Agile Project-Based Learning: A Case Study of a PWM Inverter in Engineering Education

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Abstract: This study investigates the impact of integrating APBL with a PWM-controlled three-phase inverter project in vocational engineering education. This study was conducted across six vocational high schools in Indonesia and adopted a quasi-experimental, mixed-methods approach involving 223 students from the Industrial Electronics Engineering programs. The intervention was structured into sprint cycles, following APBL principles, which emphasized collaboration, iterative problem-solving, and hands-on experience. Data were collected through pre- and post-tests, student perception questionnaires, activity observations, product assessments, and semi-structured interviews. Results show a significant improvement in students' technical competencies, with average pretest and posttest scores rising from 59.2 to 83.7 and a mean N-Gain of 0.60, classified as moderate. The paired-sample t-test indicated a large effect size (Cohen's d = 2.03, p < 0.001). Students reported positive perceptions of motivation, teamwork, and problem-solving skills, supported by high mean activity observation and project assessment rubrics scores. The qualitative findings from the interviews highlighted enhanced engagement, collaboration, and autonomy. The study concludes that APBL is highly effective in bridging the gap between theory and practice in power electronics education when combined with technology-enhanced learning media. Recommendations for broader adoption and future research into long-term and scalable implementations of APBL in diverse educational contexts are provided.

Keywords: Agile project-based learning; PWM inverter; Engineering education; Technology-enhanced learning; Student competencies.

Introduction

The rapid advancement of industrial automation has significantly transformed engineering education. The integration of theoretical concepts with practical experience is now vital, especially for vocational students. However, vocational education institutions in many developing countries, including Indonesia, continue to face substantial challenges in providing relevant and effective practical learning. These challenges include limited access to modern laboratory equipment, outdated instructional approaches, and insufficient opportunities for students to engage in real-world engineering projects (Adeniji & Baker, 2023; Mukhadis et al., 2021).

Mastering three-phase induction motor control, which is vital in both manufacturing and process industries, is a key competency in the electrical engineering curriculum. Three-phase inverters with pulse-width modulation (PWM) techniques are an efficient method for controlling motor speed and torque (Tayal et al., 2021). Despite its importance, a significant gap remains between theory and practice, mainly due to inadequate training tools and facilities, resulting in

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limited student proficiency in modern motor control systems (Adeniji & Baker, 2023; Tayal et al., 2021).

A preliminary survey across six vocational schools in Indonesia revealed that more than 65% of students had never used a PWM-based three-phase inverter trainer in the laboratory, and only 28% of teachers reported having access to such trainers. Furthermore, conventional teacher-centered approaches still dominate classroom instruction in most schools. A large majority of students expressed a preference for project-based activities that promote hands-on and collaborative learning. Both teachers and students highlighted the urgent need for innovative, interactive training media and modern project-based learning models (Al-Kamzari & Alias, 2025).

Integration of Agile Project-Based Learning (APBL) into engineering education not only enhances students' technical competencies but also develops essential 21st-century skills such as collaboration, adaptability, and problem-solving (Dewantara et al., 2021; Nilsook et al., 2021). However, empirical research on the implementation and impact of Agile PBL in the context of advanced power electronics—specifically, PWM inverter projects—remains limited. Therefore, this study aims to implement and evaluate the use of a PWM-controlled three-phase inverter trainer within an Agile PBL framework across six vocational schools.

The novelty of this research lies in its systematic evaluation of the combined effects of APBL and advanced PWM inverter training media on students' technical proficiency, collaboration, and engagement within an Indonesian vocational context. This study provides empirical evidence of how APBL can bridge the persistent gap between theory and practice in power electronics education under real-world resource constraints, unlike previous studies that examined pedagogical models or technical media in isolation.

Method

Research Design

This study employed a quasi-experimental, one-group pretest-posttest design with a case study approach to examine the effects of Agile Project-Based Learning (APBL) on the technical competencies and collaborative skills of students during a PWM inverter project for induction motor control. A mixed-methods strategy was adopted, integrating quantitative data (pretest and posttest scores, questionnaires) and qualitative data (classroom observations, interviews, and project documentation) to provide a comprehensive evaluation of the effectiveness of the intervention in authentic classroom settings. The research was conducted in six vocational high schools in North Sumatra, Indonesia, each offering an IEE program. Participants, drawn from intact class groups, engaged in APBL-based activities centered on the design, assembly, and application of a PWM-controlled three-phase inverter trainer. The study measured the knowledge and skills of students before and after the intervention, enabling both outcome and process evaluation.

This research design was chosen based on three primary considerations: (1) the need to assess both learning outcomes and processes in real educational contexts, (2) the practical limitations that precluded the random assignment of participants, thus necessitating the use of existing classroom groups to maintain ecological validity, and (3) the value of triangulating multiple data sources to capture the complex, contextual factors that influence teaching and learning. Figure 1 illustrates the research workflow's main phases, including needs analysis, instrument development, pre-intervention assessment, APBL implementation, post-intervention assessment, and data analysis.

Figure 1. Research workflow and phases

Research Setting and Participants

This study was conducted in six vocational high schools in North Sumatra, Indonesia, each offering an IEE program. The schools are identified by initials (S1–S6) throughout the manuscript to maintain institutional confidentiality. The selection of these schools was purposeful, aiming to capture a broad range of geographic and demographic backgrounds to enhance the generalizability of the research findings.

The study population comprised 11th grade (second year) students enrolled in the Industrial Electronics Engineering program during the second semester of the 2024/2025 academic year. Across all six schools, the total student population consisted of 440 students (277 males and 163 females). Table 1 presents the distribution of students according to school, location, and gender.

Figure 2 displays the distribution of industrial electronics engineering students across the six schools, differentiated by gender, to further illustrate the demographic profile. This visual representation demonstrates that each participating school contributed both male and female students, supporting the study sample's proportional and inclusive nature.

Table 1. Distribution of participants by school, location, and gender

School Initial	Location	Male	Female	Total
S1	Simalungun	55	20	75
S2	Karo	45	35	80
S3	Batu Bara	38	17	55
S4	Dairi	32	38	70
S5	Medan	42	22	64
S6	Medan	65	31	96
Total		277	163	440

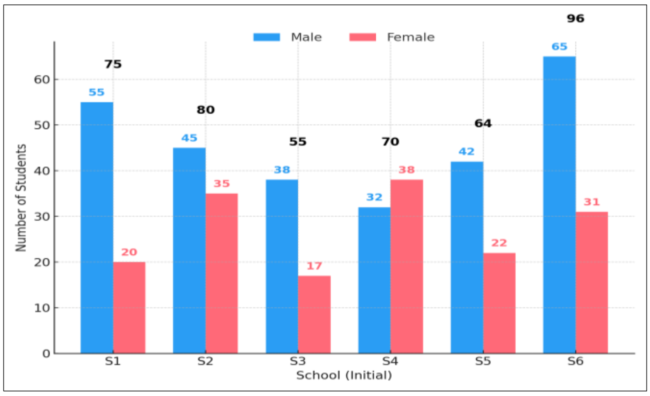

Figure 2. Distribution of industrial electronics engineering students by school and gender

Table 2. Sample distribution by school and gender

School (Initial)	Sampled Males	Sampled Females	Total Sample
S1	28	10	38
S2	23	18	41
S3	19	9	28
S4	16	19	35
S5	21	11	32
S6	33	16	49
Total	140	83	223

A proportional stratified random sampling technique was employed to select the research sample, ensuring balanced representation from each school and gender group. The sampling process was conducted in coordination with school administrators to maintain transparency and adhere to institutional guidelines. A total of 223 students (140 males and 83 females), representing approximately 50% of the overall population, were selected to participate in the study. Table 2 provides a summary of the sample by school and gender. All selected students voluntarily participated and provided written informed consent before the start of data collection, according to the ethical policies of each participating school.

Agile Project-Based Learning Implementation

The instructional approach in this study utilized Agile Project-Based Learning (APBL), which emphasizes collaboration, iteration, adaptability, and continuous problem-solving. APBL was selected to provide an authentic and contextual learning experience for students in the field of industrial electronics engineering, particularly in the development of a PWM-based three-phase inverter project for controlling induction motors.

Structure and APBL Sprint Cycle

APBL was implemented through a series of sprint cycles, with each sprint representing a focused period (typically one week) and comprising four distinct phases: planning, execution, review, and retrospective. Figure 3 illustrates the structure of a typical sprint cycle in the APBL process, highlighting how students and instructors collaboratively set objectives, perform tasks, review progress, and reflect on their learning in each cycle. This systematic approach was designed to foster authentic teamwork and continuous improvement throughout the project.

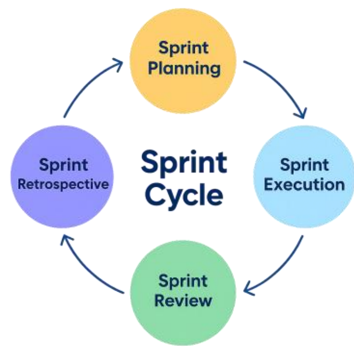

Figure 3. Agile project-based learning sprint cycle diagram

Sprint planning: at the beginning of each sprint, student teams and the instructor collaboratively defined short-term objectives, allocated tasks, and determined deliverables to be achieved by the end of the sprint. The roles and responsibilities were clarified to ensure the active involvement of all team members. Sprint execution: students worked in teams to accomplish the planned tasks, such as circuit design, hardware assembly, testing, and project-related activities. The instructor functioned as a facilitator, providing technical guidance and monitoring group dynamics. Sprint review: after each sprint, the teams presented their progress, demonstrated the outcomes, and discussed the challenges they had encountered. Peer and instructor feedback was provided to recognize achievements and identify areas for further improvement. Sprint retrospective: students engaged in reflective discussions and completed written reflections regarding their learning process, collaboration experiences, and effective strategies for the next sprint. This stage is essential for cultivating self-evaluation skills and adaptability.

Integration into Curriculum and Project Workflow

The APBL process was integrated into the curriculum over a period of 4–6 weeks, with each sprint focusing on a specific sub-task, such as circuit design, hardware assembly, programming, testing, and final integration. Formative assessments were conducted at the end of each sprint through observations, team presentations, and direct feedback.

Monitoring and Documentation

The teacher served as the primary facilitator (scrum master), ensuring that each team functioned effectively, facilitating communication, and addressing technical issues or group dynamics as needed. The entire sprint process was documented using project logs, student reflection notes, and team output records. Pretest and posttest results, along with student perception questionnaires, were used as the basis for evaluating the effectiveness of the APBL implementation.

Instruments and Data Collection

This study employed five primary instruments to comprehensively assess the effectiveness of Agile Project-Based Learning (APBL) in industrial electronics engineering education: (1) Pretest and Posttest, (2) Student Perception Questionnaire, (3) Student Activity Observation Sheet, (4) Project/Product Assessment Rubric, and (5) Interview Guidelines.

All instruments were subjected to rigorous content validation by a panel of experts, including two senior lecturers in electrical engineering education, one practitioner with extensive experience in power electronics, and one educational assessment expert. A structured review process was used to ensure clarity, relevance, and alignment with the competencies targeted by the research objectives. Feedback from these experts was incorporated iteratively, resulting in instruments that were deemed valid and reliable for capturing the intended data.

The pretest and posttest items were evaluated to confirm their representativeness of the targeted technical skills. The student perception questionnaire, observation sheet, and rubric were reviewed for clarity, comprehensibility, and relevance to Agile PBL outcomes. The interview guidelines were similarly validated to ensure that the questions were clear, unbiased, and comprehensive enough to meaningfully explore the participants' experiences and perspectives.
Through this validation process, the final instruments provided reliable measures for assessing both quantitative and qualitative aspects of student learning, engagement, and skill development within the APBL framework. This study employed five primary instruments to comprehensively assess the effectiveness of APBL in industrial electronics engineering education:

Pretest dan Posttest

The pretest and posttest assessments were designed to measure changes in the cognitive understanding and psychomotor skills of the students before and after the APBL intervention. The test items were developed based on key competency indicators, including open-ended questions and calculation tasks covering the working principles, circuit analysis, PWM calculations, troubleshooting, and practical assembly of the inverter system. Examples of the pretest and posttest items along with their corresponding competency indicators and maximum scores are presented in Table 3.

Table 3. Sample items and scoring scheme for pretest and posttest instruments

Competency Indicator	Question Type	Max Score
Explaining the working principle of an inverter	Essay	10
Analyzing a PWM circuit	Essay	10
Perform the PWM calculations	Calculation	10
Troubleshoot circuit problems	Essay	10
Assembling and testing the inverter	Practical	10

Student Perception Questionnaire (SPQ)

The Student Perception Questionnaire was developed to assess the views of students on key aspects of the APBL process, including motivation, teamwork, problem-solving, and overall learning satisfaction. The questionnaire consisted of statements rated on a five-point Likert scale (1 = strongly disagree; 5 = strongly agree) and several open-ended questions. Table 4 provides examples of items included in the SPQ.

Table 4. Sample items from the student perception questionnaire

Statement	Score (1-5)
I am motivated to participate in this project-based learning.	1 (Strongly Disagree)–5 (Strongly Agree)
I actively contribute to my team.	1 (Strongly Disagree)–5 (Strongly Agree)
I develop problem-solving skills.	1 (Strongly Disagree)–5 (Strongly Agree)

Student Activity Observation Sheet

Teachers and observers used the Student Activity Observation Sheet throughout each sprint to monitor students' participation, teamwork, application of concepts, creativity, and problem-solving. Each indicator was assessed using a five-point Likert scale, with higher scores indicating better performance. Table 5 lists the observation indicators and their corresponding Likert scale descriptions.

Table 5. Observation Indicators and Likert Scale Used in the Student Activity Observation Sheet

Statement	Likert Scale (1-5)
Student Engagement	1 (Poor)–5 (Excellent)
Teamwork	1 (Poor)–5 (Excellent)
Application of the Concepts	1 (Poor)–5 (Excellent)
Creativity and initiative	1 (Poor)–5 (Excellent)
Problem-solving	1 (Poor)–5 (Excellent)

Project/Product Assessment Rubric

The Project/Product Assessment Rubric was developed to evaluate the quality of the final inverter prototypes and project documentation. The rubric covered design accuracy, functionality, innovation, teamwork, and presentation. Each criterion was rated using a four-point scale to ensure an objective and comprehensive evaluation. Table 6 presents the assessment criteria and scoring scheme used in the evaluation of the project/product rubric.

Interview Guidelines

To gain deeper insights into the experiences of students during the implementation of the APBL, semi-structured interview guidelines were developed for use with selected participants. These interviews explored students' perceptions, challenges, collaborative processes, and suggestions for future improvement. Table 7 summarizes the main themes and sample questions used in the interview.

Table 6. Assessment criteria and scoring scheme for project/product evaluation rubric

Assessment Aspect	Score			
	1	2	3	4
Design/ Planning	Not feasible	Needs improvement	Good	Excellent
Prototype Function	Not working	Suboptimal	Working well	Optimal
Neatness	Not neat	Needs improvement	Neat	Immaculate and safe
Collaboration	Not active	Needs improvement	Active	Highly active
Innovation	None	Minimal	Innovative	Highly innovative
Report/ Presentation	Incomplete	Needs improvement	Complete	Complete and systematic

Table 7. Main themes and sample questions for student interview guidelines

Interview Question	Purpose
How did you experience participating in project-based learning using the Agile method?	Explore the overall experiences of students
What were the main benefits of teamwork during sprints?	Identifying the perceived advantages of collaboration
What challenges did you encounter and how did you address them?	Understand obstacles and problem-solving skills
How do you perceive the role of the teacher as a facilitator in this project?	Explore perceptions of the role of teachers

Data Analysis and Techniques

The data analysis in this study employed both quantitative and qualitative approaches to provide a comprehensive understanding of the effectiveness of APBL in the education of industrial electronics engineering.

Quantitative Analysis of Data

Descriptive statistics, including mean, percentage, and score distributions for pretest and posttest results, were used to summarize data characteristics. N-Gain calculation: The normalized gain (N-Gain) was calculated to measure instructional effectiveness using the Formula 1.

$$N - Gain = \frac{Posttest\ Score - Pretest\ Score}{Maximum\ Score - Pretest\ Score} \quad (1)$$

The N-Gain was interpreted based on the following categories: low (0.00–0.29), moderate (0.30–0.69), and ≥0.70 (high).

Inferential Statistics: Paired-sample t-tests were performed to determine the significance of differences between the pretest and posttest scores. Analysis of the student perception questionnaires: Questionnaire responses were analyzed by calculating mean scores for each item to determine trends in motivation, teamwork, satisfaction, and other measured constructs.

Qualitative Data Analysis

Thematic analysis: Qualitative data from observations, interviews, and project logs were thematically analyzed. The process involved careful reading, transcript coding, data grouping into central themes, and recurring pattern interpretation. The miles and huberman model: The analysis process consisted of three steps: data reduction, data display, conclusion drawing and verification. Validity of the qualitative data: Validity was enhanced through the triangulation of data sources and techniques, which involved comparing findings from observations, interviews, and project logs to ensure consistency and accuracy.

Results and Discussion

Pretest and Posttest

The distribution of pretest scores, as shown in Table 8, indicates that the majority of students (43.9%) scored between 60 and 69, with only 13.9% achieving scores of 70 or higher. This suggests that most students had only a moderate understanding of the fundamental concepts related to PWM inverter systems before the intervention.

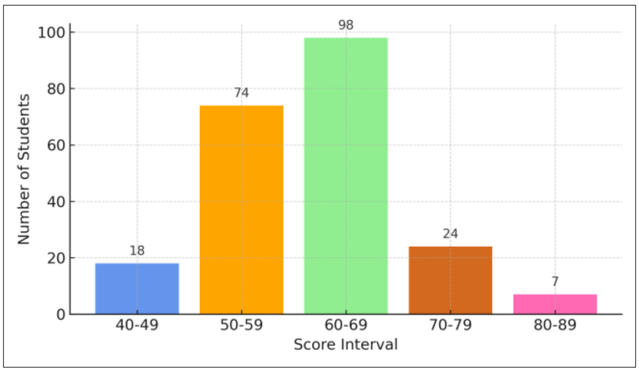

Figure 4. Distribution of students' pretest scores across score intervals

Figure 4 shows the distribution of the pretest scores across the defined score intervals. The majority of students (98 out of 223) achieved scores in the range of 60–69, while only a small proportion (7 students) scored above 80. This distribution suggests that most students had a moderate understanding of the basic concepts related to PWM inverter systems before the intervention, with relatively few demonstrating advanced proficiency at the outset. The bar chart provides a clear visual representation of the student cohort's baseline technical competence.

The posttest score distribution (Table 9) demonstrates that most students (65.0%) achieved scores within the 80–89 interval, while 23.3% of students obtained scores above 90. Only a small proportion of students (2.2%) scored below 70, indicating a significant improvement in overall proficiency following the APBL intervention.

Table 8. Distribution of the pretest scores

Score Interval	Number of students	Percentage (%)
40-49	18	8.1
50-59	74	33.2
60-69	98	43.9
70-79	24	10.8
80-89	7	3.1
Total	223	100

The posttest score distribution (Table 9) demonstrates that most students (65.0%) achieved scores within the 80–89 interval, while 23.3% of students obtained scores above 90. Only a small proportion of students (2.2%) scored below 70, indicating a significant improvement in overall proficiency following the APBL intervention.

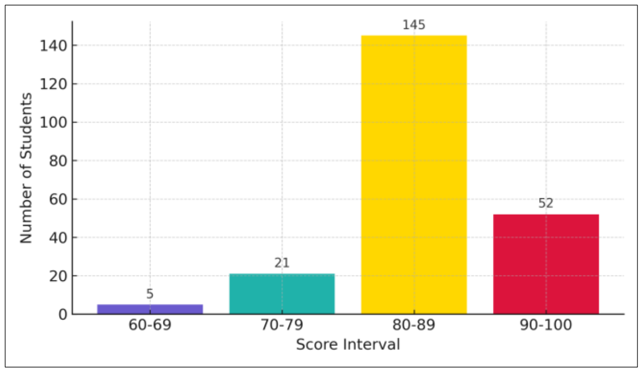

Figure 5. Distribution of students' posttest scores across score intervals

Figure 5 displays the distribution of posttest scores across defined intervals. The majority of students (145 out of 223, or 65.0%) achieved scores within the 80–89 interval, while 52 students (23.3%) obtained scores in the 90–100 range. Only a small proportion of students (2.2%) scored below 70 points. This marked improvement compared with the pretest results indicates that most students achieved a high level of proficiency in the subject matter following the APBL intervention. The bar chart provides a clear visual summary of the cohort's substantial gains in technical competence.

Table 9. Distribution of the posttest scores

Score Interval	Number of students	Percentage (%)
60-69	5	2.2
70-79	21	9.4
80-89	145	65
90-100	52	23.3
Total	223	100

N-Gain

The normalized gain (N-Gain) for each student was calculated using Equation 1 to measure the effectiveness of the APBL intervention. The analysis revealed an average N-Gain of 0.60 (standard deviation [SD] = 0.14), which falls into the "moderate" category according to Hake's classification. This result indicates that the majority of students experienced a substantial improvement in their technical competencies because of the intervention.

Table 10 presents the distribution of N-Gain values. The results show that 21.1% of students achieved a high N-Gain (≥0.70), 65.0% obtained a moderate N-Gain (0.30–0.69), and 13.9% fell into the low N-Gain category (≤0.29). These findings demonstrate the broad effectiveness of APBL in fostering significant learning gains across the student population.

Table 10. Distribution of students by n-gain category

N-Gain Category	Range	Number of students	Percentage (%)
High	≥ 0.70	47	21.1
Moderate	0.30–0.69	145	65.0
Low	≤ 0.29	31	13.9
Total		223	100

Paired-Sample t-test

A paired-sample t-test was conducted to assess the effectiveness of the Agile Project-Based Learning (APBL) intervention in improving students' technical competencies and compare students' pretest and posttest scores. This analysis aimed to determine whether the observed differences in student performance before and after APBL implementation were statistically significant.

Table 11. Paired-sample t-test results for pretest and posttest scores

	Mean	SD	t	df	p-value	Mean Difference (95% CI)
Pretest	59.2	8.7				
Posttest	83.7	7.4	28.46	222	<0.001	24.5 (22.5–26.6)

As shown in Table 11, the mean pretest score was 59.2 (SD = 8.7), whereas the mean posttest score increased substantially to 83.7 (SD = 7.4). The t-test yielded a t-value of 28.46 with a significance level of $p < 0.001$, indicating a highly significant improvement in student achievement following the APBL intervention. Furthermore, the effect size, as measured by Cohen's d (2.03), was categorized as large, reflecting the substantial magnitude of the intervention's impact on students' technical knowledge and skills (Georgiou & Ioannou, 2021).

These results provide robust evidence that the integration of APBL in the context of the PWM inverter project effectively enhanced the learning outcomes of students. The statistically significant gains in posttest scores suggest that APBL's hands-on, collaborative, and iterative nature can bridge the gap between theoretical understanding and practical application in vocational engineering education.

Student Perception Questionnaires

A Student Perception Questionnaire was administered at the end of the project to evaluate students' attitudes and perceptions toward the APBL intervention. The questionnaire assessed key aspects, including motivation, teamwork, problem-solving, learning satisfaction, and the learning approach's perceived benefits. Responses were collected using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Table 12 summarizes the descriptive statistics for each item in the SPQ, including the mean and standard deviation for all participating students.

Table 12. Descriptive statistics of the student perception questionnaire items

Statement	Mean	SD
I am motivated to participate in this project-based learning.	4.22	0.68
I actively contribute to my team.	4.09	0.72
I develop problem-solving skills.	4.15	0.70

As shown in Table 12, the descriptive analysis of the questionnaire results revealed that students responded very positively across all three domains. The mean score for the statement "I am motivated to participate in this project-based learning" was 4.22 (SD = 0.68), indicating a high level of motivation among the participants. The item "I actively contribute to my team" achieved a mean of 4.09 (SD = 0.72), reflecting strong engagement and active involvement in collaborative activities. The statement "I develop problem-solving skills" was rated with a mean of 4.15 (SD = 0.70), suggesting that students recognized significant improvement in their ability to address technical challenges through the APBL approach.

Overall, the questionnaire results indicate that students perceived the APBL environment as supportive and conducive to their learning. The integration of hands-on projects, collaborative activities, and iterative reflection cycles fostered a positive classroom atmosphere and increased the confidence of students in their technical abilities.

Observation of Student Activity

Teachers and observers employed a structured Student Activity Observation Sheet during each sprint cycle to gain a comprehensive understanding of students' engagement and participation throughout the APBL process. This instrument captured key indicators, including participation, teamwork, concept application, creativity, and problem-solving. Each aspect was rated using a five-point Likert scale, with higher scores indicating more desirable student behaviors. Table 13 presents the mean and standard deviation for each observation indicator across all student groups during the intervention.

As shown in Table 13, the descriptive analysis of the observation data revealed high levels of student participation and collaboration across all assessed domains. The mean score for student engagement was 3.56 (SD = 0.49), indicating that most students actively participated and demonstrated enthusiasm during the project activities. Teamwork received a mean score of 3.48 (SD = 0.52), reflecting strong group collaboration and open communication. The mean score for application of technical concepts was 3.42 (SD = 0.51), suggesting that students frequently and accurately applied theoretical knowledge to practical project tasks. Creativity and initiative were rated at a mean of 3.29 (SD = 0.58), while problem-solving ability achieved a mean score of 3.38 (SD = 0.53). These results suggest that the APBL framework effectively fostered a dynamic and collaborative classroom environment, encouraging active student participation and the development of critical skills essential for success in engineering education (Ariza, 2023).

Table 13. Descriptive statistics of the student activity observation sheet

Indicator	Mean	SD
Student Engagement	3.56	0.49
Teamwork	3.48	0.52
Application of the Concepts	3.42	0.51
Creativity and initiative	3.29	0.58
Problem-solving	3.38	0.53

Project/Product Assessment Rubric

A comprehensive Project/Product Assessment Rubric was employed to evaluate the quality and completeness of the final projects. This rubric encompassed several criteria, including design accuracy, circuit functionality, innovation, teamwork, and project documentation and presentation quality. Each criterion was scored using a four-point scale, with higher scores indicating superior performance and completeness. Table 14 presents the descriptive statistics for each criterion, including the mean and standard deviation for all student groups, assessed using the Project/Product Assessment Rubric.

Table 14. Descriptive statistics of the project/product assessment rubric criteria

Assessment Aspect	Mean	SD
Design/Planning	3.28	0.51
Prototype Function	3.34	0.57
Neatness	3.22	0.54
Collaboration	3.44	0.49
Innovation	3.15	0.60
Report/Presentation	3.29	0.52

As shown in Table 14, the majority of student teams achieved high scores across most assessment aspects. The mean score for design and planning was 3.28 (SD = 0.51), reflecting strong initial preparation and a systematic approach to project work. The prototype function received a mean of 3.34 (SD = 0.57), indicating that most teams successfully built and demonstrated optimally functioning PWM inverter systems. Neatness was rated at a mean of 3.22 (SD = 0.54), indicating attention to detail and safe construction practices. Collaboration yielded a mean of 3.44 (SD = 0.49), highlighting the team's highly cooperative and participatory nature. Innovation received a mean score of 3.15 (SD = 0.60), reflecting students' creativity in proposing solutions and project enhancements. Finally, the mean score for reporting and presentation was 3.29 (SD = 0.52), indicating that most groups delivered comprehensive and well-organized final documentation.

Overall, the high mean scores across all rubric dimensions demonstrate the effectiveness of the APBL approach in fostering not only technical proficiency but also essential project skills such as collaboration, innovation, and effective communication. The consistency of high scores in both technical and soft skill categories provides further evidence for the broad impact of Agile PBL in vocational and engineering education (Huang et al., 2023).

Interview

Semi-structured interviews were conducted with both students and teachers to gain deeper insight into their experiences, perceptions, challenges, and suggestions regarding the implementation of APBL.

Overall Experiences and Perceptions

Most students reported that participating in the APBL project was both engaging and transformative. They appreciated the opportunity to collaborate and apply technical concepts in a real-world context. One student remarked, “This was the first time I felt like I was working on something meaningful for my future career.” Teachers echoed these sentiments, noting that students became more autonomous and took greater responsibility for their learning (Chang et al., 2023; Retno et al., 2025).

Benefits of Teamwork

Students consistently highlighted teamwork as one of the most valuable aspects of the APBL experience. They reported that working in groups during sprint cycles encouraged open communication, idea sharing, and problem-solving. As one participant stated, “We learned to support each other and use everyone’s strengths to finish the project.” Teachers observed that the collaborative environment fostered leadership skills and a greater sense of accountability among students (Wu et al., 2023).

Challenges and Strategies Used

Some students and teachers acknowledged initial difficulties, particularly in adapting to the Agile methodology and managing project timelines. Challenges included balancing roles within the team and dealing with technical setbacks during prototype development. However, most students indicated that these obstacles were overcome through regular team meetings, guidance from teachers (as facilitators or scrum masters), and reflective review sessions at the end of each sprint. A teacher noted, “The iterative sprint process helped students learn from their mistakes and improve step by step.”

Perceptions of the role of teachers

Both students and teachers agreed that the teacher’s role as a facilitator (scrum master) was crucial to the project’s success. The students appreciated the guidance, encouragement, and problem-solving support provided by the teachers, especially when they faced technical or interpersonal challenges. Teachers felt that adopting a facilitative rather than a directive approach promoted greater independence and critical thinking among students (Hidayah et al., 2021).

Discussion

This study investigated the impact of integrating APBL with a PWM-controlled three-phase inverter project in vocational engineering education. The results provide compelling evidence that APBL significantly enhances the technical competencies, engagement, and collaborative skills of students (Affandy et al., 2024).

The substantial increase in posttest scores from a mean of 59.2 to 83.7, along with a moderate N-Gain of 0.60, strongly indicates a significant improvement in the technical understanding and practical abilities of the students following the APBL intervention. This finding is consistent with that of Chueh & Kao (2024), who reported that integrating agile and problem-based learning consistently yields significant improvements in professional competencies among engineering students. The large effect size (Cohen’s d = 2.03) further emphasizes the substantial impact of APBL on learning outcomes. This suggests that APBL’s hands-on, collaborative, and iterative nature effectively bridges the gap between theoretical understanding and practical application in vocational engineering education, which was identified as a key challenge in the introduction (Dori & Belcher, 2005).

The positive perceptions expressed by students regarding their motivation (mean = 4.22, SD = 0.68), teamwork (mean = 4.09, SD = 0.72), and problem-solving skills (mean = 4.15, SD = 0.70) in the perception questionnaire underscore a highly effective learning environment. These high scores are not merely superficial approvals; they are deeply rooted in the APBL sprint cycles’ practical experience. For instance, the iterative problem-solving inherent in APBL, where students repeatedly designed, assembled, tested, and troubleshooted the inverter system within short "sprints," directly contributed to the perceived development of problem-solving skills. As one student articulated, "We learned to support each other and use everyone’s strengths to finish the project". This qualitative insight demonstrates how structured collaboration within sprints fosters a sense of shared responsibility, enabling students to leverage diverse strengths and overcome technical challenges, thereby reinforcing problem-solving abilities. This aligns with Sukackė et al. (2022), who found that project-based approaches combined with agile methods effectively foster conceptual understanding and transversal skills, such as teamwork and adaptability (Schön et al., 2022).

The consistently high mean scores observed in student engagement (3.56, SD = 0.49) and teamwork (3.48, SD = 0.52) during the activity observations further substantiate the positive perceptions. The collaborative nature of the APBL framework, where students worked in teams to accomplish defined tasks in each sprint, created a dynamic and engaging learning environment. This direct engagement, in which students were actively involved in circuit design, hardware assembly, and testing, naturally increased their enthusiasm and participation. These observations are consistent with those of (Zhou et al., 2025), who indicated that students become more active and independent in project-based learning environments supported by interactive technological media.

The strong performance reflected in the Project/Product Assessment Rubric provides a clear link between the APBL methodology and tangible technical outcomes. The high mean score for "Prototype Function" (3.34, SD = 0.57) directly reflects the iterative "Sprint Execution" and "Sprint Review" phases of APBL. During Sprint Execution, students actively built and tested their prototypes, while peers and instructors provided immediate feedback during Sprint Review. This continuous feedback loop enabled students to promptly identify and rectify errors, resulting in significant improvements in the functionality of their PWM inverter systems. As a teacher noted, "The iterative sprint process helped students learn from their mistakes and improve step by step". This iterative refinement process, a core tenet of Agile, enabled students to progressively optimize their designs and constructions, directly translating into higher-quality, optimally functioning prototypes. Furthermore, the high mean score for the Collaboration criterion (3.44, SD = 0.49) on the rubric is a testament to the collaborative nature emphasized in APBL, where "roles and responsibilities were clarified to ensure the active involvement of all team members" during "Sprint Planning".

The teacher’s crucial role as a facilitator (scrum master) emerged as a significant factor in the success of APBL implementation. Both the students and teachers agreed on the importance of the students particularly valued the "guidance, encouragement, and problem-solving support" provided by teachers. Rather than a traditional teacher-centered approach, this facilitative approach empowered students to take greater ownership of their learning (Choi-Lundberg et al., n.d.). When students encountered technical setbacks or interpersonal issues, the teacher’s role in facilitating solutions and guiding reflective discussions during the Sprint Retrospective phase directly contributed to the positive perceptions of problem-solving skills and increased autonomy reported by the students. This contrasts sharply with the findings of the pre-intervention survey, in which 75% of teachers indicated that conventional, teacher-centered approaches dominated instruction, and 82% of students preferred project-based activities. The shift to a facilitative role directly addressed the identified need for innovative and interactive learning models (Barliana et al., 2020; Nurhidayah et al., 2021).

In comparison to existing literature, this study’s explicit integration of Agile methodology with PBL, specifically applied to PWM inverter technology in vocational education, provides novel empirical evidence for the combined effects of APBL and advanced PWM inverter training media. While studies by Awdaa et al. (2021); Mahbub (2021) focused on PWM inverter applications and reported improvements in students’ technical abilities through simulation and interactive media, this research systematically evaluates the combined effects within a real-world educational environment. The statistically significant gains in posttest scores, along with the qualitative insights, confirm that the hands-on, collaborative, and iterative nature of APBL effectively bridges the gap between theoretical understanding and practical application in VEE, addressing the previously identified lack of facilities and training tools (Guerra-Macías & Tobón, 2025).

Despite these promising results, this study has several limitations. First, the use of a quasi-experimental design without a control group may limit the generalizability of the findings and reduce the internal validity of the intervention. Second, the relatively short duration of APBL implementation (4–6 weeks) may not fully capture the long-term impact on the technical and soft skill development of students. Third, although the research involved six schools with diverse backgrounds, the geographical limitation (one region in Indonesia) may affect the generalizability of the results to other socio-cultural contexts. These limitations highlight avenues for future research to strengthen and broaden the APBL evidence base

Conclusion

This study demonstrated that integrating APBL with a PWM-controlled three-phase inverter project significantly enhances technical competencies, student engagement, and collaborative skills in vocational engineering education. The quasi-experimental, mixed-methods approach applied across six vocational high schools provided robust empirical evidence that APBL not only improved students’ cognitive and psychomotor abilities, as shown by substantial pretest-posttest gains and high effect sizes, but also fostered a highly motivating and collaborative learning environment. Based on these findings, it is strongly recommended that educational institutions and policymakers adopt and adapt APBL frameworks more broadly across different disciplines and academic settings, not only within vocational schools or power electronics but also in general STEM and technical training programs. Practitioners should ensure the systematic integration of APBL with hands-on projects, relevant technology-enhanced learning media, and ongoing professional development for teachers to maximize the benefits. We recommend conducting long-term and large-scale studies involving diverse educational and cultural contexts to further validate the effectiveness and scalability of APBL. Moreover, comparative studies with control groups and investigations into specific factors that may influence APBL outcomes (such as teacher facilitation styles, curriculum alignment, or resource availability) are encouraged. Such research efforts will help establish best practices for the widespread implementation of APBL and support continuous improvement in engineering and vocational education worldwide

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Author Contributions

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Conflicts of Interest

The authors declare no conflict of interest.

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