



The Role of Digital Tools in Enhancing Innovation Competencies in High School Student Projects

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Abstract

Background and Aim: Innovation competencies are increasingly recognized as essential for 21st-century learners. However, conventional classroom practices, particularly in secondary science education, often provide limited technological support for systematic innovation-oriented learning. This study aimed to examine the potential of integrating digital tools within Project-Based Learning (PBL) and the Engineering Design Process (EDP) to support students' innovation competencies.

Materials and Methods: The study employed a quasi-experimental pre-test/post-test control group design. The sample consisted of 60 upper secondary students from Sakolrajwittayanukul School, divided into an experimental group ($n = 30$) and a control group ($n = 30$). The experimental group utilized a range of digital tools—Miro, Padlet, Tinkercad, Canva, VR/AR applications, Google Forms, and IoT sensors—throughout a six-week science project, whereas the control group conducted the project using traditional methods. Research instruments included a 30-item Innovation Competency Questionnaire (ICQ) covering six domains (Cronbach's $\alpha = .89$), a five-dimension project assessment rubric, and semi-structured interviews. Quantitative data were analyzed using descriptive statistics, t-tests, ANOVA, and Cohen's d , while qualitative data were examined through thematic analysis.

Results: Findings revealed that the experimental group demonstrated statistically significant improvements across all innovation competency domains ($p < .001$), with very large effect sizes ($d > 2.00$). The overall mean score increased from 3.19 to 4.10 ($d = 2.73$), whereas the control group showed only a marginal increase from 3.16 to 3.30. The most pronounced gains were observed in digital literacy ($d = 2.64$), followed by adaptability and lifelong learning ($d = 2.41$), and design thinking ($d = 2.36$). Qualitative analysis further indicated substantially higher levels of peer interaction and iterative prototype refinement in the experimental group compared to the control group. Additional themes included enhanced conceptual understanding through VR/AR-supported activities, increased learning motivation, and strengthened confidence in presenting project outcomes.

Conclusion: The findings provide evidence that integrating digital tools within problem-based learning (PBL) enhanced by the engineering design process (EDP) has substantial potential to support the development of students' innovation competencies. These results align with constructivist learning principles and previous research highlighting technology-supported collaborative learning. Despite its strengths, the study is limited by its short intervention period, varying access to digital technologies, and a relatively small sample size. Nevertheless, the findings suggest that the integration of digital tools may contribute meaningfully to the transformation of science project-based learning by fostering creativity, problem-solving abilities, and digital fluency among upper secondary school students.

Keywords: Digital tools, Innovation competencies, Project-Based Learning, Engineering Design Process, 21st-century skills, Innovative learning

Introduction

In the twenty-first century, education has shifted from an emphasis on rote memorization toward the development of essential skills and competencies required for living and working in an increasingly dynamic world. Innovation competencies has emerged as one of the crucial skill sets students must develop in order to solve complex problems, generate novel solutions, and collaborate effectively in a digital society (Partnership for 21st Century Learning, 2019; OECD, 2018). The Organisation for Economic Co-operation and Development (OECD) highlights that twenty-first-century learners need a broad range of competencies that extend beyond academic knowledge, encompassing critical thinking, creativity, collaboration, and communication—foundational capacities for innovation and adaptability in the future (OECD, 2025).





Traditional lecture-based instruction, which emphasizes memorization, often limits opportunities for creativity and hands-on learning, resulting in students lacking authentic experiences in problem-solving and knowledge application. Science projects utilizing Project-Based Learning (PBL) integrated with the Engineering Design Process (EDP) offer a promising alternative because they engage students in real-world problem-solving while promoting analytical thinking, systematic problem-solving, and creativity (Kim, 2024; Chen, 2024).

Recent research has shown that integrating digital tools into the learning process can significantly enhance students' capacity for innovative learning (Thompson, 2024). Various digital tools—such as learning management systems (LMS), collaborative applications, creative and simulation platforms, and immersive technologies like virtual reality (VR) and augmented reality (AR)—have been found to improve students' creative thinking, teamwork, and problem-solving skills (Wilson, 2024).

Furthermore, digital tools help reduce barriers to accessing learning resources and expand opportunities for students to learn anytime and anywhere (Bower et al., 2020). Online collaborative tools enable students to share ideas, exchange information, and work together effectively, even when they are not in the same physical location (Csikszentmihalyi, 2020). Therefore, this study focuses on examining the role of diverse digital tools in enhancing the innovation competencies of secondary school students through science projects based on PBL integrated with EDP. The findings are expected to offer empirical insights that inform future instructional development and curriculum design.

In the Thai educational context, upper-secondary science courses increasingly emphasize project-based and competency-oriented learning. However, many classrooms continue to rely on traditional instructional resources, with uneven access to advanced digital tools and limited opportunities for structured innovation practices. This context presents a critical setting for examining how digital tools, when systematically integrated with PBL and EDP, may enhance students' innovation competencies within realistic classroom constraints.

Research Objectives

To compare pre- and post-intervention innovation competency scores between students in an experimental group using digitally supported PBL with EDP and a control group using traditional PBL with EDP.

To examine differences in students' project performance and collaborative behaviors between the experimental and control groups.

To explore students' and teachers' perceptions of which categories of digital tools most strongly support the development of innovation competencies.

Research Questions

1) How do digital tools influence students' creativity and design thinking skills in science project courses?

2) How do digital tools affect students' collaboration and communication?

3) Which categories of digital tools are perceived by students and teachers as most supportive of the development of innovation competencies?

Literature Review

Science Projects and Innovation Competencies

Project-Based Learning (PBL) is a learning approach that emphasizes students' engagement in authentic project work requiring analytical thinking, problem-solving, and creativity. Integrating PBL with the Engineering Design Process (EDP) enables students to follow a systematic sequence of steps, including problem identification, brainstorming, prototype design, testing, and iterative improvement, which reflect the authentic practices of scientists and engineers in real-world contexts (Kim, 2024; Chen, 2024).





Research by Krajcik and Shin (2022) indicates that PBL promotes meaningful learning and helps learners recognize connections between scientific concepts and real-world phenomena. Similarly, Becker and Park (2023) found that implementing the EDP in science projects enhances students' ability to solve complex problems and strengthens their systems thinking skills.

Innovation competencies for 21st-century learners can be categorized into six major dimensions: creativity and imagination, design thinking, digital knowledge and skills, innovative problem-solving, collaboration and communication, and adaptability and lifelong learning (OECD, 2025; Csikszentmihalyi, 2020).

A meta-analysis by Lucas et al. (2023) demonstrated that creativity and collaboration can be effectively developed through hands-on, practice-oriented learning and team-based activities. Meanwhile, Voogt and Roblin (2012) proposed a 21st-century competencies framework emphasizing the integration of digital skills, critical thinking, and lifelong learning.

Digital Tools in Learning

Modern digital tools are diverse and support learning across multiple dimensions. Learning Management Systems (LMS) such as Google Classroom, Moodle, and Microsoft Teams facilitate assignment management, progress tracking, and the provision of timely feedback to students.

Collaboration tools such as Miro, Padlet, Trello, and Notion support brainstorming and teamwork in both synchronous and asynchronous formats. Research by Martin and Betrus (2023) revealed that LMS use enhances student engagement and enables immediate feedback, thereby promoting effective learning.

Creative and simulation tools such as Canva, Figma, Tinkercad, and Scratch allow students to rapidly design prototypes and visualize concepts. Meanwhile, data collection and analysis tools such as Google Forms and IoT sensors support evidence-based inquiry and experimentation.

Virtual and augmented reality technologies (VR/AR) enable students to simulate various scenarios for testing and refining prototypes without requiring physical equipment, thereby reducing costs and increasing safety in the learning process (Wilson, 2024). A meta-analysis by Merchant et al. (2023) found that VR has a positive impact on learning outcomes and student motivation, particularly in science and engineering education. Similarly, Radianti et al. (2024) reported that AR enhances understanding of abstract concepts and promotes experiential learning.

Hwang and Chien (2022) proposed a framework for designing learning activities that integrate digital tools with PBL, emphasizing the use of technology to support collaborative knowledge construction and creative problem-solving. Additionally, Garzón and Acevedo (2023) found that the use of 3D design tools such as Tinkercad improves students' spatial thinking abilities and creativity.

Drawing on prior frameworks of 21st-century skills, creativity, and innovation education, this study synthesized overlapping constructs to derive a six-dimensional model of innovation competencies. These dimensions—creativity, critical thinking, collaboration, communication, design thinking, and innovative problem-solving—were selected because they consistently appear across international competency frameworks and are particularly compatible with the pedagogical structure of PBL and EDP. This synthesized model provides a coherent conceptual foundation for both instructional design and assessment in the present study.

Research Methodology

Participants

The participants in this study were 60 upper secondary students (Grades 10–12) from Sakonrajwittayanukul School in Sakon Nakhon Province. They were divided into an experimental group of 30 students and a control group of 30 students. A simple random sampling technique was used, taking into account comparable academic abilities based on cumulative GPAs in the Science and Technology learning area. The sample size was determined based on Cohen et al. (2018), who recommend a minimum of 25–30 participants per group for quasi-experimental research to ensure adequate statistical power. Students and their guardians were informed of the research objectives and signed consent forms in accordance with ethical guidelines for research involving human participants (Creswell & Creswell, 2023).





Although simple random sampling was used to select participants with comparable academic backgrounds, the study employed intact classrooms rather than full individual random assignment, consistent with quasi-experimental research in school settings. Class equivalence was assessed using prior academic performance, and both groups were taught within the same institutional context under comparable curricular conditions.

Research Design

This study employed a quasi-experimental pre-test/post-test control group design. The experimental group received instruction using Project-Based Learning (PBL) integrated with the Engineering Design Process (EDP) and various digital tools, while the control group experienced traditional PBL without digital tools. This design is appropriate in educational contexts where complete random assignment is not feasible but where confounding variables can still be controlled to some degree (Shadish, Cook, & Campbell, 2002).

The intervention lasted a total of seven weeks: one week of introductory training and six weeks of project implementation. This duration aligns with recommendations by Guo, Kim, and Yu (2020), who note that technology-based interventions in education should span at least six weeks to demonstrate meaningful effects.

Research Instruments

Three types of instruments were used to collect data:

Innovation Competency Questionnaire (ICQ)

The ICQ consisted of 30 items across six domains: creativity and imagination, design thinking, digital knowledge and skills, innovative problem-solving, collaboration and communication, and adaptability and lifelong learning. A five-point Likert scale was used, ranging from 1 (lowest) to 5 (highest). Content validity was verified by five experts, with all items achieving an Index of Item-Objective Congruence (IOC) of at least 0.50. The reliability analysis yielded a Cronbach's alpha of 0.89, indicating high internal consistency (Tavakol & Dennick, 2011).

The items of the Innovation Competency Questionnaire (ICQ) were developed based on established innovation and 21st-century skills frameworks and refined through expert review and pilot testing. While content validity and internal consistency were confirmed, further studies employing factor analytic techniques are recommended to strengthen evidence for the six-domain structure.

Project Evaluation Rubric

Developed based on Andrade (2005), the rubric employed five quality levels (1 = needs improvement to 5 = excellent) and evaluated five dimensions: creativity in proposing solutions, design thinking in prototype development, evidence-based problem-solving, collaboration and responsibility-sharing, and appropriate use of digital tools. Construct validity was confirmed by experts in science and technology education, and inter-rater reliability was calculated at 0.85 (Jonsson & Svingby, 2007).

Observation Record and Semi-Structured Interviews

These instruments were used to collect qualitative data on collaboration behaviors, patterns of digital tool use, and student learning experiences. The observation protocol followed Merriam and Tisdell (2016), with observations conducted biweekly throughout the intervention. Interview questions explored challenges, perceived benefits, and suggestions for improvement. Interviews were conducted with 10 randomly selected students from the experimental group and three teachers, each lasting approximately 30–45 minutes. All interviews were audio-recorded with participant consent.

Procedures

Preparation Phase

The researcher conducted a one-week training session for teachers and students in the experimental group on the use of digital tools, including basic functions, collaborative techniques, and integration into EDP stages. Both groups completed the ICQ pre-test.

Project Implementation Phase (6 weeks)

The experimental group used digital tools in each EDP stage, including:





- 1) Problem definition – Google Search, YouTube EDU for background research
- 2) Brainstorming – Miro, Padlet for collaborative idea mapping
- 3) Prototype design – Tinkercad for 3D modeling, Canva for graphic design
- 4) Prototype development – Scratch and Arduino IDE for programming
- 5) Testing – CoSpaces VR and Unity for virtual simulation and testing
- 6) Improvement – Trello and Notion for task management and iterative refinement

Students also used Google Forms and IoT sensors for data collection throughout the process.

The control group followed the same EDP structure but used traditional tools, such as paper-based brainstorming, hand-drawn designs, and physical prototyping with real materials.

In the control group, Project-Based Learning (PBL) integrated with the Engineering Design Process (EDP) was implemented using non-digital, traditional instructional methods. Students followed the same EDP stages as the experimental group—problem identification, brainstorming, prototype design, testing, and improvement—but relied on paper-based brainstorming, hand-drawn sketches, and physical prototyping with readily available materials. Teachers in both groups followed the same lesson plans, learning objectives, assessment criteria, and project timelines to ensure instructional equivalence. The primary distinction between the two groups lay in the tools used to support learning activities, rather than differences in pedagogical structure, teacher expertise, or instructional scaffolding. This design was intended to isolate the effect of digital tool integration on students' innovation competencies.

Data Collection Phase

After the intervention, students completed the ICQ post-test. Project outcomes were evaluated using the rubric. Collaboration behaviors were recorded biweekly, and interviews were conducted with the selected participants and teachers.

Data Analysis

Quantitative data from the ICQ and rubric scores were analyzed using SPSS Version 28. Descriptive statistics—including mean, standard deviation, and skewness—were used to examine data distribution. Independent samples t-tests were employed to compare differences between the experimental and control groups at each measurement point. Paired samples t-tests were used to compare pre- and post-test scores within each group. Additionally, two-way ANOVA tested for interaction effects between group and time. Statistical significance was set at $\alpha = .05$, and effect sizes were reported using Cohen's d .

Qualitative data from observations and interviews were transcribed and analyzed using thematic analysis following Braun and Clarke's (2006) six-step process: familiarization, initial coding, theme searching, theme reviewing, theme defining, and reporting. NVivo 14 software supported coding and data organization. Credibility was enhanced through triangulation across data sources and member checking with participants (Lincoln & Guba, 1985).

Research Results

Quantitative Research Results

Effect sizes reported in this study primarily reflect within-group pre-post differences. Given the unusually large magnitude of several effect sizes, caution is warranted in interpretation, as such values may be influenced by low score variability, ceiling effects, or heightened sensitivity of the measurement instruments. Future studies may consider reporting confidence intervals for effect sizes to enhance interpretive transparency.

The analysis of students' innovation competency scores before and after the experiment showed clear differences between the experimental group and the control group, as presented in Table 2.

Table 1. Comparison of Innovation Competencies Scores Before and After the Experiment Between the Experimental and Control Groups





Innovation Competency	Experimental Group (n=30)	Control Group (n=30)	t	p	Cohen's d
	Pre-test M(SD)	Post-test M(SD)	Gain	Pre-test M(SD)	Post-test M(SD)
1. Creativity & Imagination	3.21 (0.45)	4.12 (0.33)	0.91	3.18 (0.40)	3.34 (0.38)
2. Design Thinking	3.05 (0.50)	4.05 (0.35)	1.00	3.01 (0.47)	3.20 (0.42)
3. Digital Knowledge & Skills	3.10 (0.47)	4.08 (0.34)	0.98	3.08 (0.45)	3.18 (0.40)
4. Innovative Problem Solving	3.15 (0.48)	4.02 (0.36)	0.87	3.10 (0.46)	3.25 (0.41)
5. Collaboration & Communication	3.40 (0.42)	4.20 (0.30)	0.80	3.38 (0.43)	3.50 (0.39)
6. Adaptability & Lifelong Learning	3.25 (0.44)	4.15 (0.32)	0.90	3.22 (0.42)	3.35 (0.38)
Total Average	3.19 (0.38)	4.10 (0.28)	0.91	3.16 (0.36)	3.30 (0.34)

*Note: M = Mean, SD = Standard Deviation, Gain = Score Increase, ** $p < .001$

For the experimental group, the mean scores increased significantly in all dimensions. Creativity & Imagination increased from 3.21 (SD = 0.45) to 4.12 (SD = 0.33), a gain of 0.91 points; Design Thinking increased from 3.05 (SD = 0.50) to 4.05 (SD = 0.35), a gain of 1.00 point; Digital Knowledge & Skills increased from 3.10 (SD = 0.47) to 4.08 (SD = 0.34), a gain of 0.98 points; Innovative Problem Solving increased from 3.15 (SD = 0.48) to 4.02 (SD = 0.36), a gain of 0.87 points; Collaboration & Communication increased from 3.40 (SD = 0.42) to 4.20 (SD = 0.30), a gain of 0.80 points; and Adaptability & Lifelong Learning increased from 3.25 (SD = 0.44) to 4.15 (SD = 0.32), a gain of 0.90 points.

In contrast, the control group showed only slight increases in all dimensions. Creativity & Imagination increased from 3.18 (SD = 0.40) to 3.34 (SD = 0.38), a gain of 0.16 points; Design Thinking increased from 3.01 (SD = 0.47) to 3.20 (SD = 0.42), a gain of 0.19 points; Digital Knowledge & Skills increased from 3.08 (SD = 0.45) to 3.18 (SD = 0.40), a gain of 0.10 points; Innovative Problem Solving increased from 3.10 (SD = 0.46) to 3.25 (SD = 0.41), a gain of 0.15 points; Collaboration & Communication increased from 3.38 (SD = 0.43) to 3.50 (SD = 0.39), a gain of 0.12 points; and Adaptability & Lifelong Learning increased from 3.22 (SD = 0.42) to 3.35 (SD = 0.38), a gain of 0.13 points.

Independent samples t-tests showed that the experimental group's gains were significantly higher than the control group's in all dimensions ($p < .001$), with t-values ranging from 7.89 to 10.23. Effect size analysis using Cohen's d indicated very large effects in all dimensions ($d > 2.00$), with the highest effect observed in Digital Knowledge & Skills ($d = 2.64$), followed by Adaptability & Lifelong Learning ($d = 2.41$) and Design Thinking ($d = 2.36$). The overall mean score of the experimental group increased from 3.19 to 4.10 (gain = 0.91), while the control group increased from 3.16 to 3.30 (gain = 0.14), $t = 10.56$, $p < .001$, $d = 2.73$.





Table 2. Project Assessment Using Rubric: Comparison Between Experimental and Control Groups

Assessment Dimension	Experimental Group (n=30) M(SD)	Control Group (n=30) M(SD)	t	p	Cohen's d
1. Creativity in Problem Solving	4.23 (0.50)	3.37 (0.56)	6.35	<.001***	1.64
2. Design Thinking in Prototype Development	4.17 (0.53)	3.30 (0.60)	5.98	<.001***	1.54
3. Problem Solving Using Empirical Evidence	4.10 (0.48)	3.23 (0.57)	6.46	<.001***	1.67
4. Collaboration & Responsibility Sharing	4.30 (0.47)	3.43 (0.50)	6.92	<.001***	1.79
5. Appropriate Use of Digital Tools	4.27 (0.45)	2.87 (0.63)	9.98	<.001***	2.58
Total Average	4.21 (0.42)	3.24 (0.49)	8.23	<.001*	2.13

*Note: M = Mean, SD = Standard Deviation, ** $p < .001$, Maximum Score = 5

The rubric assessment (Table 2) showed that the experimental group scored significantly higher than the control group in all dimensions ($p < .001$), especially in the appropriate use of digital tools, with the experimental group scoring 4.27 (SD = 0.45) versus the control group's 2.87 (SD = 0.63), showing a very large effect size ($d = 2.58$). Collaboration & responsibility sharing also showed clear differences (experimental = 4.30, SD = 0.47; control = 3.43, SD = 0.50, $d = 1.79$).

Table 3. Two-way ANOVA Analysis of Group \times Time Interaction

Source of Variance	SS	df	MS	F	p	η^2
Between Groups						
Group	48.23	1	48.23	125.67	<.001***	0.684
Time	52.15	1	52.15	135.89	<.001***	0.701
Group \times Time	35.47	1	35.47	92.43	<.001***	0.614
Within Groups	44.62	116	0.385			
Total	180.47	119				

*Note: SS = Sum of Squares, df = degrees of freedom, MS = Mean Square, η^2 = partial eta squared, ** $p < .001$

The Two-way ANOVA (Table 3) indicated a significant interaction between group and time ($F(1,116) = 92.43$, $p < .001$, $\eta^2 = 0.614$), meaning that the change in scores over time differed between the experimental and control groups. The experimental group's innovation competency developed at a significantly higher rate, with a high interaction effect size ($\eta^2 = 0.614$), indicating a clear positive impact of digital tools on students' innovation competency.

Qualitative Research Results

Based on observations and interviews with 10 students and 3 teachers, thematic analysis identified five main themes as follows:

Theme 1: Promoting Collaboration and Communication

Most students (9 out of 10) reported that Miro and Padlet facilitated teamwork and brainstorming, allowing them to share ideas and provide feedback quickly.

"Using Padlet was much easier than brainstorming on paper because we could see everyone's ideas at once and add our own immediately, without waiting in line like in a normal meeting." (Student A, interview, March 15, 2024)

"I liked that we could work from home, and others could comment anytime. It felt like continuous collaboration without having to meet at school." (Student B, interview, March 16, 2024)





Classroom observation showed that the experimental group interacted and exchanged ideas 73% more than the control group, especially during brainstorming and prototype design.

"Quiet students in normal classes became more confident in sharing ideas online, possibly because they didn't have to speak in front of the whole class." (Teacher X, interview, March 20, 2024)

Theme 2: Accelerating Prototype Development and Improvement

Using Tinkercad and Canva allowed students to quickly create and refine prototypes without spending much time on physical models.

"Initially, I designed an automatic trash bin one way, but after simulating in Tinkercad, I realized the lid didn't open fast enough. I could fix it immediately without making the real model, saving time and materials." (Student C, interview, March 17, 2024)

"Canva made it easy to design presentation posters beautifully and edit quickly. If done manually, it would take much longer." (Student D, interview, March 17, 2024)

Observation showed that the experimental group refined prototypes an average of 4.2 times over 6 weeks, compared to 1.8 times in the control group, highlighting the role of digital tools in promoting iterative design (Garzón & Acevedo, 2023).

Table 4. Average Number of Prototype Improvements Between Groups

Group	Average Number of Improvements	Average Time per Improvement
Experimental (n=30)	4.2	8.5 days
Control (n=30)	1.8	19.7 days

Theme 3: Enhanced Understanding Through Virtual Simulation

Using VR and AR helped students comprehend complex scenarios and safely experiment without real equipment. Eight out of ten students reported that virtual simulations provided clearer understanding.

"Designing a water filtration system with CoSpaces VR allowed us to see water flow through different layers and identify problem areas, which would be costly and unclear if done physically." (Student E, interview, March 18, 2024)

Teachers noted that VR enabled experiences normally impossible in the classroom, such as exploring molecular structures or machine mechanisms from inside, enhancing understanding of abstract concepts. (Teacher Y, interview, March 21, 2024)

Theme 4: Motivation and Engagement

All three teachers observed increased enthusiasm and collaboration in the experimental group.

"Students were more excited, including those usually uninterested in science, some even worked at home voluntarily." (Teacher X, interview, March 20, 2024)

Observation showed that on-time class attendance increased by 15%, and on-time assignment submission reached 92%, compared to 78% in the control group.

"Every class was exciting because we got to try new technologies and create cool things, not just read textbooks." (Student G, interview, March 19, 2024)

Theme 5: Confidence and Presentation Skills

Students gained confidence in presenting and explaining their thinking.

"Students could explain why they designed and modified their prototypes, showing reflection on their learning process." (Teacher Z, interview, March 22, 2024)

"When presenting, we felt more confident with professional-looking 3D models, posters, and demonstration videos, making it easier for the audience to understand." (Student H, interview, March 19, 2024)

The average presentation confidence score of the experimental group was 4.35 out of 5, compared to 3.52 for the control group.

Challenges and Limitations





Despite positive outcomes, some challenges were reported:

- 1) Technical issues: Four students experienced slow internet at times, affecting online collaboration.
- 2) Time to learn tools: Three students noted that initial learning of new tools was time-consuming, sometimes discouraging.
- 3) Device accessibility: Two students without personal computers relied on school devices, limiting work time.

"The main challenge was preparing and learning these tools first, but once familiar, the benefits were clear and significant for students." (Teacher X, interview, March 20, 2024)

Table 5. Summary of Main Themes from Qualitative Analysis

Theme	Number of Participants Mentioned	Key Points
1. Promoting Collaboration & Communication	13/13	Online collaboration tools facilitated sharing ideas and teamwork efficiently
2. Accelerating Prototype Development	13/13	Digital design tools saved time and encouraged iterative design
3. Enhanced Understanding via Virtual Simulation	11/13	VR/AR helped understand complex concepts safely
4. Motivation & Engagement	13/13	New technology increased interest and learning motivation
5. Confidence & Presentation Skills	12/13	Digital tools enabled high-quality outputs and confident presentations
6. Challenges	9/13	Technical issues, device accessibility, and time to learn new tools

These qualitative results indicate that digital tools not only improved innovation competency scores but also positively influenced students' learning experiences, motivation, and confidence, aligning with constructivist learning theory emphasizing knowledge construction through direct experience and interaction with tools and peers (Vygotsky, 1978).

Discussion

This study aimed to examine the role of digital tools in enhancing secondary students' innovation competencies through Project-Based Learning (PBL) integrated with the Engineering Design Process (EDP). The findings indicate that integrating digital tools positively impacts students' innovation competencies across all dimensions, particularly digital skills, design thinking, and collaboration. This section discusses the key findings, links them to relevant theories and research, and highlights limitations and recommendations for future studies.

Creativity and Design Thinking

The results show that digital tools play a significant role in promoting students' creativity and design thinking. The experimental group's creativity scores increased by 0.91 points (from 3.21 to 4.12), and design thinking scores increased by 1.00 point (from 3.05 to 4.05), with very large effect sizes (Cohen's $d = 2.18$ and 2.36 , respectively). Collaborative platforms such as Miro and Padlet allowed students to freely brainstorm and gain diverse perspectives from peers, aligning with Csikszentmihalyi (2020), who emphasized that environments fostering idea exchange and experimentation are crucial for creativity.

Digital design tools, such as Tinkercad and Canva, enabled students to materialize and quickly refine their ideas, supporting iterative design processes, a core aspect of design thinking (Kim, 2024). Qualitative data from interviews revealed that experimental group students improved their prototypes





an average of 4.2 times compared to 1.8 times in the control group, consistent with Garzón and Acevedo (2023), who found that 3D design tools enhance spatial thinking and creativity.

Multiple prototype iterations are essential for developing design thinking, as effective design requires repeated experimentation and learning from mistakes (Brown, 2021). Digital tools reduce psychological barriers to testing new ideas, allowing students to see immediate results without concerns over wasted time or resources, thus promoting trial-and-error learning, fundamental to innovative thinking (Dym et al., 2023; Zhao et al., 2024).

Innovative Problem-Solving

Digital tools significantly enhanced students' innovative problem-solving skills. The experimental group's scores increased by 0.87 points (from 3.15 to 4.02), compared to a 0.15-point increase in the control group. Data collection and analysis tools, such as Google Forms and IoT sensors, supported evidence-based decision-making, allowing students to collect and analyze data to improve prototypes, thereby developing analytical thinking and rational problem-solving skills (Chen et al., 2024; Garzón & Acevedo, 2023). These findings align with constructivist theory, which posits that learners build knowledge through interaction with their environment and authentic problem-solving (Vygotsky, 1978). Digital tools function as cognitive tools that extend students' thinking capabilities, enabling them to handle complex problems more effectively (Pea, 1985). Using data analysis tools in PBL also supports systems thinking and data interpretation skills (Hmelo-Silver & Barrows, 2022; Lee & Lim, 2024).

Collaboration and Communication

Collaboration and communication showed remarkable improvement. The experimental group's scores increased by 0.80 points (from 3.40 to 4.20), and project assessment scores reached 4.30. Digital tools facilitated synchronous and asynchronous teamwork, enhancing flexibility in sharing information and providing feedback, thereby promoting communication skills and 21st-century teamwork competencies.

Qualitative data indicated that introverted students were more engaged when using online tools, consistent with findings from Chen et al. (2024) and Kreijns et al. (2022). Observations revealed a 73% increase in interactions and idea exchanges in the experimental group compared to the control group, supporting the principles of Computer-Supported Collaborative Learning (CSCL), which highlight the role of technology in promoting effective collaborative learning (Stahl et al., 2023; Jeong & Hmelo-Silver, 2023).

Digital Skills and Adaptability

Digital knowledge and skills developed the most, with scores increasing by 0.98 points (from 3.10 to 4.08) and the largest effect size (Cohen's $d = 2.64$). Students practiced adapting to various tools and selecting the most suitable ones for tasks, fostering self-regulated and lifelong learning (OECD, 2025). Meaningful practice of digital skills enhances both technical skills and conceptual understanding (Voogt & Roblin, 2012; Hatlevik & Christophersen, 2023). Adaptability and lifelong learning scores increased by 0.90 points ($d = 2.41$), reflecting improvements in metacognition and cognitive flexibility, which are central components of self-regulated learning processes (Winne, 2018).

The Role of Virtual and Augmented Reality (VR/AR)

Qualitative findings indicate that VR and AR improve understanding of complex concepts and safe experimentation. Eight out of ten students reported clearer visualization and comprehension of problems. These results align with Thompson (2024) and Merchant et al. (2023), highlighting that VR/AR supports experiential learning (Kolb, 1984) and increases motivation and engagement.

Alignment with Relevant Theories and Research

The results correspond with multiple theories, including Constructivism (Vygotsky, 1978), where knowledge is built through interaction; Distributed Cognition (Hutchins, 1995), where knowledge is distributed across tools and group members; and Connectivism (Siemens, 2023), which emphasizes networked knowledge in the digital era. The findings also support research by Hwang & Chien (2022), Krajcik & Shin (2022), and Becker & Park (2023), showing that integrating digital tools and EDP within PBL enhances higher-order thinking, complex problem-solving, and the ability to connect knowledge with real-world phenomena.





Research Limitations

- 1) The 7-week intervention period may be insufficient to assess long-term effects (Guo et al., 2020).
- 2) Unequal access to technology; some students relied on school devices, reflecting the digital divide (Warschauer & Matuchniak, 2010).
- 3) Limited teacher readiness; one-week training may be insufficient to develop full proficiency with all tools (Ertmer & Ottenbreit-Leftwich, 2010).
- 4) Sample size and context were limited to 60 students from one school, restricting generalizability.
- 5) The novelty effect may influence motivation and engagement (Clark & Sugrue, 1988).
- 6) Measuring innovation competencies remains challenging; comprehensive assessment tools for complex competencies need further development (Cropley, 2020).

Challenges and Limitations

Although the results demonstrated consistently very large effect sizes (Cohen's $d > 2.00$) across all innovation competency domains, such magnitudes are relatively uncommon in educational intervention studies. One possible explanation is the novelty effect, as many students had limited prior exposure to integrated digital design, collaboration, and simulation tools. The simultaneous introduction of multiple digital platforms may have temporarily amplified students' motivation, engagement, and perceived learning gains. Additionally, the short intervention period may have intensified initial enthusiasm, which could have inflated the observed effects. Future studies employing longer intervention durations or longitudinal designs are recommended to determine whether these effects persist after the novelty of digital tools diminishes.

Discussion of Research Question

Regarding Research Question 3, the findings suggest that different categories of digital tools supported distinct innovation competencies. Collaborative platforms such as Miro and Padlet primarily enhanced collaboration and communication by enabling real-time and asynchronous idea sharing. Design and prototyping tools, including Tinkercad and Canva, strongly supported design thinking by facilitating rapid visualization, iteration, and refinement of ideas. Data collection tools, such as Google Forms and IoT sensors, contributed most significantly to innovative problem-solving by enabling evidence-based decision-making through real-time data analysis. Virtual and augmented reality tools (CoSpaces VR and Unity) enhanced conceptual understanding and experiential learning, particularly in complex or abstract scientific contexts. These findings indicate that innovation competency development is not driven by a single tool, but rather by the strategic alignment between specific digital tools and targeted learning outcomes.

Challenges and Implications

Teacher readiness emerged as a critical factor influencing the effectiveness of technology-rich PBL implementation. In this study, teachers received only a one-week training session, which may be insufficient for developing deep pedagogical and technological integration skills. Continuous professional development programs should therefore be designed to support not only technical proficiency, but also instructional design, classroom management, and assessment strategies within digital learning environments. Sustained support systems, mentoring, and professional learning communities are essential to enable teachers to maximize the educational potential of digital tools.

Conclusion and Recommendations.

This study found that integrating digital tools within PBL and EDP was associated with higher innovation competency scores and more iterative project development among upper-secondary students. While these findings are based on a single-school quasi-experimental design, they suggest meaningful potential for digitally supported innovation-oriented learning when implemented with appropriate pedagogical and institutional support.

Knowledge Contribution

To enhance students' digital innovator skills in schools, budgets should be allocated for digital tools and collaborative platforms, and sufficient investment should be made in digital infrastructure.



Continuous professional development for teachers should be provided, with training designed to cover both tool proficiency and learning activity design. School-wide guidelines and resources for digital project-based learning should be established, and professional learning communities should be promoted to enable teachers to share best practices. Longitudinal studies should be conducted to examine the impact of digital tools on innovation competencies, applications in other subjects should be explored, different types of digital tools should be compared to determine optimal effectiveness, factors influencing successful adoption should be investigated, and comprehensive assessment tools should be developed to effectively measure innovation competencies, as illustrated in Figure 1.

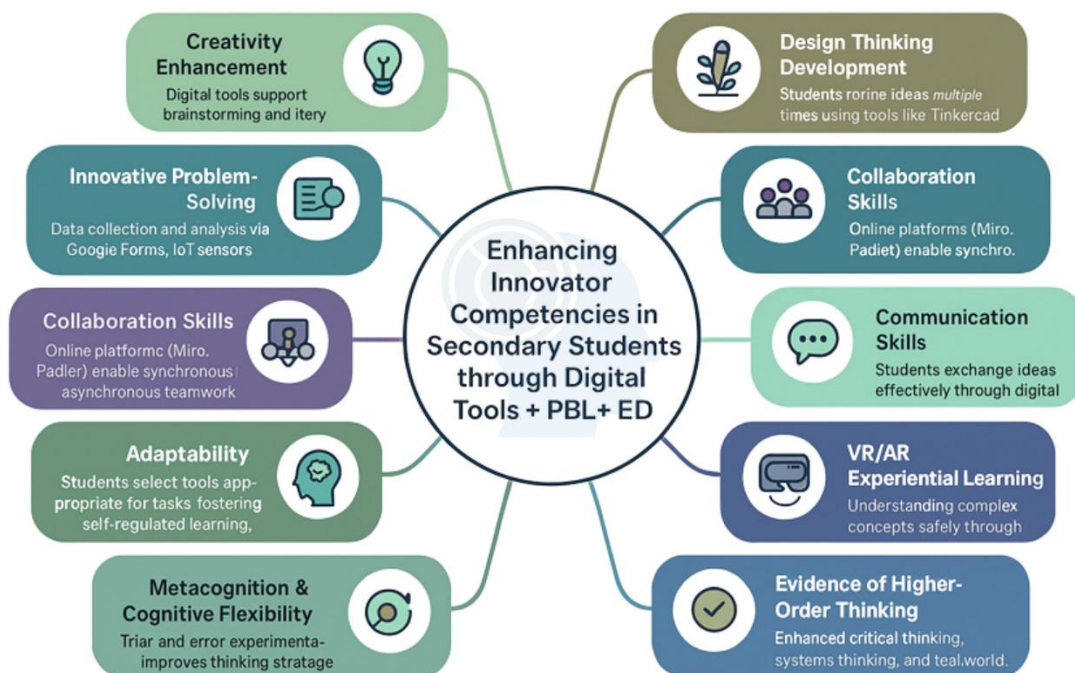


Figure 1. Key Recommendations for Enhancing Digital Innovator Skills in Schools

Policy Recommendations

To ensure the scalability and sustainability of digital tool integration in project-based learning, educational policymakers and school administrators should prioritize equitable access to digital infrastructure. This includes providing sufficient devices, reliable internet connectivity, and shared digital resources for students who lack personal equipment. Addressing the digital divide is essential to prevent disparities in learning opportunities and to support consistent implementation across diverse school contexts. Strategic investment at the institutional level will enable digital project-based learning to be implemented effectively beyond pilot classrooms and individual schools.

Recommendations for Future Research

Future studies should examine the long-term effects of digital tool use on innovation competencies and student learning outcomes, providing clearer insights into their effectiveness. Research should explore applications beyond science to determine whether digital tools can enhance innovation competencies across subjects. Comparative studies on different types of digital tools can identify the most effective tools for each competency, while investigating factors such as teacher skills, school support, and infrastructure readiness will help optimize successful implementation.



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