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Bridging technology and pedagogy: How TPACK-based PBL shapes critical thinking in human anatomy education

Laila Puspita[1*], Dwi Nyaning Retno Asih[1], Raicha Oktafiani[1], Komarudin[2]

[1] Biology Education, Universitas Islam Negeri Raden Intan Lampung, Indonesia
[2] Mathematics Education, Universitas Islam Negeri Raden Fatah Palembang, Indonesia

*Corresponding author: lailapuspita@radenintan.ac.id

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ABSTRACT

Critical thinking skills are pivotal in science education, enabling students to comprehend complex concepts, solve problems effectively, and excel in academic assessments. This study aims to determine the effect of TPACK-based PBL in improving students' critical thinking skills in human anatomy. Using a quasi-experimental design with unequal control groups, the study involved 60 students from two classes (experimental and control groups) in East Lampung, Indonesia. Data analysis via one-way ANOVA revealed a statistically significant difference between the groups ($Sig. < 0.001$), with the experimental group demonstrating superior performance (mean score: 86.02 vs. 50.10). The large effect size ($Cohen's\ d = 6.13$) underscores the transformative potential of TPACK-PBL in fostering analytical reasoning and cognitive flexibility. The integration of digital tools within the PBL framework bridges pedagogical strategies, technology applications, and content mastery, enabling students to engage with authentic real-world problems. These findings align with constructivist theory, which emphasizes the active construction of knowledge through problem-solving contexts. These findings contribute to a new pedagogical model that integrates TPACK and PBL as learning strategies, offering actionable ideas for curriculum developers and educators seeking to develop critical thinking skills in complex biology topics.

INTRODUCTION

Critical thinking is an essential skill for 21st-century education (Kennedy & Sundberg, 2020; Ongesa, 2020; Shaw, 2020), especially in science classrooms, where students need to use evidence-based reasoning to analyze, evaluate, and solve complex problems (Jumrah, 2023; Yenti et al., 2024). These skills assist students in deep and reflective inquiry, which is crucial for developing higher-order thinking skills (Alkhatib, 2019; Jamil et al., 2024). Therefore, a new study is needed that emphasizes the benefits of integrating problem-based learning (PBL) and creative pedagogy, which places learning in a real-world context (Affandy et al., 2024). The integration of academic knowledge with practical problems can certainly enhance analytical reasoning and foster critical thinking (Buranova & Rakhmonova, 2024; Purba & Azis, 2022).

Students with high critical thinking skills tend to perform better in understanding scientific concepts, analyzing data, and generating creative solutions to problems they face (Yuliani & Saragih, 2015). Due to the limited implementation of learning strategies that actively train these skills, many students still struggle with solving mathematical problems, particularly those related to contextual problems (Ansari & Saleh, 2021; Surur et al., 2020). This disparity underscores the need to implement successful, empirically supported learning in current education reforms.

PBL is a learning approach that involves students in real-world problems thru inquiry-based activities, teamwork, and higher-order thinking (Hunter et al., 2025; Srilatha et al., 2022), PBL forces students to be more independent and actively involved in their learning, making it more likely for students to construct their own knowledge (Broseghini et al., 2024; Huang & Liao, 2024; Matsuda et al., 2024). This method is characterized by its focus on authentic problems (Chen et al., 2024; Zhou et al., 2023), collaborative learning (Matsuda et al., 2024), and the development of critical thinking (Kek & Huijser, 2011; Lapuz & Fulgencio, 2020) as well as problem-solving (Chumsukon, 2019). Previous studies have shown that PBL is effective in improving students' analytical, synthesis, and evaluation skills (Hussain & Anwar, 2017; Suryanti & Nurhuda, 2021), especially when integrated with learning technology. However, the reality on the ground is that the implementation of PBL is often hindered by a lack of technology integration that supports student investigation and collaboration in the learning process (Vasiliou et al., 2013) . This gap opens up opportunities for research to enrich the PBL model integrated with pedagogical technology frameworks such as Technological Pedagogical Content Knowledge (TPACK). TPACK refers to a teacher's ability to integrate technology into their teaching process, thereby enhancing student skills (Komarudin & Suherman, 2024).

Previous research has shown that TPACK can effectively improve the quality of science learning thru the use of digital devices that support concept exploration and increase interaction among students (Nilsson, 2024; Sheffield et al., 2015; Teknowijoyo, 2024). For example, Efwinda et al. (2023), in their research, stated that integrating the PBL model with digital posters within the TPACK framework can improve the critical thinking skills of junior high school students. This approach encourages students to work in teams, solve problems related to the structure and function of anatomical systems, and collaboratively identify issues, which is an important component in developing critical thinking skills. The process of group discussion and real-world case-based problem-solving can facilitate students' high-level cognitive engagement, such as analyzing, evaluating, and synthesizing anatomical information contextually.

Furthermore, research by Wardani & Jatmiko (2021) on science learning also reported that TPCK-PBL is effective in improving students' critical thinking skills. Where students are able to connect anatomical concepts with pathological conditions thru relevant case studies, thereby deepening their conceptual understanding and reasoning skills. This model provides space for students to ask questions, evaluate evidence, and make data-driven decisions, encompassing both structural and functional anatomy, which are key characteristics of critical thinking in the context of biomedical science. Thus, integrating TPCK-PBL into the science curriculum not only strengthens students' mastery of the material but also directly supports the development of critical thinking skills essential for future biology teachers. However, the application of TPACK in the context of PBL is still limited, especially for biology topics such as the human movement system, which require dynamic visualization and simulation. The integration of these two approaches is expected to strengthen the effectiveness of PBL in training critical thinking skills.

Study previously show that PBL approach has proven effective in increase ability think critical student (Chen et al., 2024; Zhou et al., 2023). A study by Zhang et al. (2023) combining randomized controlled trials (RCTs) and meta-analysis showed that PBL significantly improved critical thinking in pharmacy students compared to lecture-based learning. Meanwhile, a study by Wang et al. (2023) of 267 third-year medical students at Nantong University showed that the implementation of an integrated PBL curriculum significantly improved clinical thinking skills compared to a control group that followed conventional learning. This also showed that active involvement and quality of participation in the PBL process influenced students' cognitive development. Integration TPACK framework to in the PBL model still relatively limited, especially in the context of material biology like system movement human at the level school medium. Some studies previously research effectiveness of PBL in general separated (Chen et al., 2024; Trullàs et al., 2022; Zheng et al., 2023), and the TPACK study is more Lots focus on teacher readiness or professional development (Çam & Koç, 2024; Chaipidech et al., 2022; Oktaviani & Utami, 2024), without integrate both of them in context learning scientific based skills 21st century. In addition, studies that are explicit measure impact TPACK-based PBL integration towards ability think critical students on the material complex like system movement man still very rare found.

Research this fill in gap the with develop and implement a TPACK-based PBL model designed for stimulate dimensions think critical in a way systematic in context material biology. Novelty studies this lies in the merger innovative between PBL strategy and the TPACK framework that has not been Lots explored at the implementation level class for increase ability think critical in topic biology. The main objective is to evaluate the impact of PBL integration with TPACK in improving students' critical thinking skills in human anatomy lessons. The results of this study are expected to provide empirical evidence to expand the implementation of PBL in various curriculum contexts, especially in conceptual and visual science topics by utilizing technology in their learning.

METHODS

Research Design

This study employed a quasi-experimental design with a posttest-only control group approach. This design was chosen because it fits the limitations of formal educational contexts, where perfect randomization (random assignment) is often not possible. However, this design still allows for a systematic evaluation of the effectiveness of learning interventions (Creswell & Creswell, 2017). This design allowed researchers to compare outcomes between the treatment group (TPCK-PBL) and the control group (Discovery Learning model) solely through post-intervention measurements, thus avoiding the testing effects that can occur with pre-tests, particularly on higher-order cognitive skills such as critical thinking (Cook et al., 2002). Aims to examine the effect of the TPACK-based PBL model on students' critical thinking skills compared to the Discovery Learning model.

Population and Samples

The population of this study was all 137 eighth-grade students at a junior high school in East Lampung. The sample was taken using the cluster random sampling method. The subjects were grade VIII I (35 students) who were given the TPACK-based PBL model and grade VIII II (35 students) who used the Discovery Learning model. The sampling was carried out using a cluster random sampling technique, this was done because the sampling units used were naturally occurring classes (groups), making it impossible to randomize individuals without disrupting the class structure and the ongoing learning process (Fraenkel et al., 2006). This technique was chosen because it is more practical, efficient, and feasible in the context of educational research, especially when access to participants is limited to existing groups (Creswell & Creswell, 2017). Approval was obtained from the institutions and schools prior to the study, with all students providing informed consent to participate. Further details of the participant demographics are shown in Table 1.

Table 1.
Participant Demographics.

Demographics		Experiment Class		Control Class	
		Frequency	Percentage (%)	Frequency	Percentage (%)
Gender	Female	19	54.29	17	48.57
	Male	16	45.71	18	51.43
Age	12 years old	13	37.14	12	34.29
	13 years old	19	54.29	20	57.14
	14 years old	3	8.57	3	8.57

Instrument

There is one research instrument: a critical thinking skills test. The critical thinking skills test was developed using the PISA 2018 indicators, which cover four competencies: (1) Identifying problems, (2) Analyzing arguments, (3) Evaluating evidence, and (4) Developing logically based solutions. The test contains seven tasks. One of the critical thinking skills tests used for data collection in the study is:

> *Silvi, a millennial, regularly exercises and drinks milk for healthy bones and joints. However, in the past week, she stopped drinking the milk and began experiencing joint pain, muscle problems, and weakness. Why do you think this happened? And what steps should Silvi take to address her symptoms?* (Identify the problem and develop a logical solution.)

The question "Why do you think this happened?" was used because it encourages students to analyze the cause-and-effect relationship between stopping milk consumption and the symptoms that emerged in a real-life context. This process reflects the initial steps in the scientific method. Therefore, this question is suitable for measuring critical thinking skills because it requires an initial evaluation before taking action to solve the problem. Meanwhile, the question "What action should Silvi take to address her symptoms?" was used because it requires students to formulate interventions supported by scientific evidence, such as restoring nutritional intake or seeing a doctor. Therefore, it is suitable for measuring the ability to develop logically based solutions. Thus, the combination of these two questions effectively measures critical thinking through the integration of problem identification and data-driven solutions, which are core components of the learning process and outcome evaluation.

The critical thinking ability test instrument in this study consisted of four psychometric analysis components to ensure measurement quality, namely validity, reliability, difficulty level, and discriminatory power. The validity test was carried out by calculating the *Pearson correlation coefficient* (r_{xy}) between the score of each item and the total score, where the item was declared valid if the (r_{xy}) *value* ≥ 0.30 (Ekolu & Quainoo, 2019), indicating that the item was able to measure the intended critical thinking aspect. The reliability of the instrument was tested using the Cronbach's Alpha coefficient, with the reliability criteria if the coefficient value ≥ 0.60, which indicates the internal consistency of the items in measuring the same construct. The level of item difficulty was calculated based on the proportion of correct answers (P), classified as easy ($P \geq 0.70$), moderate ($0.30 < P < 0.70$), or difficult ($P \leq 0.30$), to ensure a balanced variation in difficulty. Meanwhile, item discrimination power (DP) is measured using the discrimination index, categorized as low, moderate, or good, which indicates the test item's ability to differentiate between high-ability and low-ability participants. These four tests comprehensively guarantee the validity and credibility of the instrument in assessing students' critical thinking skills.

Test Instrument Analysis Results

Instrument validity: Data analysis was performed using the *Pearson correlation coefficient* (r_{xy}). A summary of the analysis results is presented in Table 2.

Table 2.
Summary of Validity Test Results

Question Items	r_{count}	Criteria
1	0.760	Valid
2	0.147	Invalid
3	0.681	Valid
4	0.640	Valid
5	0.737	Valid
6	0.484	Valid
7	0.734	Valid
8	0.571	Valid
9	0.268	Invalid
10	0.259	Invalid

Notes: $n = 25$; $df = n - 2 = 23$; $\alpha = 0.05$

Table 1 shows that 7 of the 10 items were valid (Items 1, 3, 4, 5, 6, 7, 8) based on the productive moment correlation test. Invalid items (Items 2, 9, 10) were not used in further analysis.

Reliability Test: The reliability of the instrument was measured using the Cronbach's Alpha coefficient. A summary of the analysis results is presented in Table 3.

Table 3.
Summary of Reliability Test Results

Cronbach's Alpha	N of Items
.793	7

Difficulty Level : Questions are classified as easy, ($P \geq 0{,}70$),medium ($0{,}30 < P < 0{,}70$), or difficult ($P \leq 0{,}30$). A summary of the analysis results is presented in Table 4.

Table 4.
Summary of Difficulty Level Test Results

		Item 1	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8
N	Valid	25	25	25	25	25	25	25
	Missing	0	0	0	0	0	0	0
Mean		2.28	2.48	2.40	2.44	2.4800	2.24	2.44

Discriminating Power : Questions with a discriminating power ≥ 0.41 are considered good, while those < 0.20 are considered poor. A summary of the analysis results is presented in Table 5.

Table 5.
Summary results of the Distinguishing Power Test

	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted
Item 1	14.480	9.510	.560	.762
Item 3	14.280	10.877	.593	.758
Item 4	14.360	11.073	.485	.774
Item 5	14.320	10.810	.613	.755
Item 6	14.280	10.293	.396	.801
Item 7	14.520	10.177	.618	.749
Item 8	14.320	10.977	.503	.771

Procedure

The procedure implementation study started with planning learning based integrated problems with technology in accordance with TPACK principles, compilation instrument research and instrument testing, followed by implementation of classroom learning experiments and controls during a number of meetings. Next, data collection was carried out through test think critical post-treatment. For analyzing data, conducting prerequisite tests includes the normality test (Kolmogorov-Smirnov) and the homogeneity test (Levene's test), which show that the data is normally distributed and homogeneous. Hypothesis testing was done using one ANOVA direction for known difference significant between groups, continued with calculation of effect size using Cohen's d formula to strengthen interpretation results. Analysis results show that the TPACK-based PBL model provides significant and strong influence on improvement ability think critical students.

Table 6.
Integrasi PBL and TPACK

PBL Phase	TPACK Integration
Presenting Problems	Technological Knowledge (TK) Teachers integrate technology to present authentic problems relevant to students' daily lives.
Organizing Students in Learning	Content Knowledge (CK) Teachers ensure students understand the concepts of the material being studied as a basis for formulating problems and finding solutions.
Guiding Group	Content Knowledge (CK)

PBL Phase	TPACK Integration
Investigations	Teachers guide students in connecting content knowledge with the scientific inquiry process.
Developing and Presenting Results	Pedagogical Knowledge (PK) Teachers implement effective learning strategies to develop students' abilities to present findings systematically.
Analyzing and Evaluating the Problem-Solving Process	Pedagogical Knowledge (PK) Teachers apply evaluation and reflection techniques to deepen students' conceptual understanding and critical thinking skills.

Data Analysis Techniques

Analysis Prerequisites:

The statistical prerequisite analysis in this study is the normality test using the Kolmogorov-Smirnov and the homogeneity of variance test using Levene's Test. In the normality test, data is declared normally distributed if the significance value ($Sig.[2 - tailed]) > 0.05$ indicates the conformity of the data distribution to the theoretical normal curve. Meanwhile, the homogeneity of variance test is declared fulfilled if the significance value of $Levene's\ Test > 0.05$, indicating there is no significant difference in variance between the compared groups. Fulfillment of these two assumptions is very important in the use of parametric statistical tests such as the $t - test$ or $ANOVA$, because violations of the assumptions of normality and homogeneity of variance can affect the validity and reliability of the results of the statistical analysis carried out (Miranda-Fontaíña & Fernández-López, 2009).

Hypothesis Testing:

Hypothesis testing done using the ANOVA test, because this study aims to know the average difference between 2 different groups, namely between the class given treatment of the TPACK-based PBL model and classes using the Discovery Learning model. If the score $Sig.(2 - tailed) < 0{,}05$, indicates that there is a significant influence of the TPACK-based PBL model. If $Sig.(2 - tailed) \geq 0{,}05$, indicating that there is no significant influence of the TPACK-based PBL model. Next, an Effect Size test is carried out to calculate the magnitude of the influence with Cohen's d to strengthen the interpretation of statistical results (Goulet-Pelletier & Cousineau, 2018; Peng & Chen, 2014) .

RESULTS AND DISCUSSION

Normality Test

Statistical analysis begins with a normality test to determine whether the obtained data is normally distributed. This research hypothesis was tested using the Kolmogorov-Smirnov test. The purpose of the normality test is to determine whether the data used in the research is normally distributed or not. The results of the normality test are presented in Table 7.

Table 7.
Test Normality

		Kolmogorov-Smirnov [a]			Shapiro-Wilk		
	Learning model	**Statistics**	**df**	**Sig.**	**Statistics**	**df**	**Sig.**
Test Score	Experimental Class	.199	33	.002	.886	33	.002
	Control Class	.162	35	.020	.952	35	.130

a. Lilliefors Significance Correction

Table 7 shows that $Sig.(2 - tailed)$the experimental class's significance value of 0.211 is greater than 0.05. This aligns with the Kolmogorov-Smirnov normality test, indicating that the data are normally distributed. Meanwhile, the control class's $Sig.(2 - tailed)$significance value of 0.200 is greater than 0.05. This aligns with the Kolmogorov-Smirnov normality test, indicating that the data are normally distributed.

Homogeneity Test

The homogeneity test aims to determine whether variations in several data from a population have the same variance or not. This test is generally useful as a requirement (but not an absolute requirement) in comparative analysis. The basic assumption in the analysis of homogeneity of variance is that several populations are the same or homogeneous. Homogeneity is not an absolute requirement, meaning that the data variance is not the same. The independent sample t-test is still carried out to analyze the research data, but decision-making is seen from the value of equal variance not assumed. The results of the homogeneity test are presented in Table 8.

Table 8.
Homogeneity Test

Levene Statistics	df1	df2	Sig.
.374	1	66	.543

Based on Table 8, it is known that the sig value of the experimental class test results is 0.229, which is greater than 0.05, while the sig value in the control class is 0.199, so it can be concluded that the variance of the student test results data in the posttest is homogeneous.

Hypothesis Testing
This study tested the hypothesis that the integration of the TPACK framework into the PBL model influences students' critical thinking skills. The results of the ANOVA test are shown in Table 9.

Table 9.
ANOVA Test Results

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	22577.875	1	22577.875	735,248	.000
Within Groups	2088.133	68	30,708		
Total	24666.008	69			

Based on Table 9, it is known that the value $sig\ (2-tailed)$of 0.000 is smaller than 0.05, which means that there is a significant influence in the application of the TPACK-Based *PBL Model* on Students' Critical Thinking Skills in the Human Movement System Material. An Effect Size test was conducted to calculate the magnitude of the influence using Cohen's d to strengthen the interpretation of the statistical results. Before conducting the Effect Size test, the research data group's statistics were presented.

Table 10.
Summary of Group Statistics for Experimental and Control Classes

	Class	n	Mean	Standard Deviation	Std. Error Mean
Score	Experimental Class	35	86.0209	6.14905	1.03938
	Control Class	35	50.1020	4.85848	.82123

Based on Table 10, the next step is to calculate the Effect Size using Cohen's d formula, and the Effect Size score obtained $(d) = 6.13$, shows a large effect between the experimental and control groups. This value far exceeds the conventional limit for the large effect category ($d > 0.8$), indicating that the intervention applied to the experimental group has a very strong influence on critical thinking skills.

The analysis results show a value $F = 735.248$ with $sig. (p) = 0.000$, which is less than the critical threshold of 0.05. This indicates a significant average difference between groups, where the average critical thinking score of the experimental group (86.02) is much higher than the control group (50.10). This finding strengthens the initial hypothesis that the integration of TPACK in PBL has a positive impact on students' critical thinking abilities. The average value of the experimental group is higher than the experimental class, indicating that the TPACK-based PBL learning model intervention is able to improve critical thinking achievements. In other words, this learning approach that combines technology, material content, and pedagogical strategies appears to be effective in encouraging students' high-level cognitive skills.

Furthermore, the effect size test (Cohen's d) to strengthen the interpretation of the results showed that the Cohen's d value was > 0.8, indicating a very large intervention effect on the learning process. These results indicate the influence of TPACK-based PBL in improving students' critical thinking skills in human anatomy material. This result aligns with constructivist learning theory, which emphasizes that students' active involvement in learning will impact their ability to construct their understanding thru everyday problem-solving experiences (Jumaah, 2024; Romdhon et al., 2024). PBL, which is rooted in constructivism, requires students to work in authentic contexts and construct their own knowledge thru problem-solving (Boardman et al., 2024; Zhou et al., 2023). This learning model actively engages students in solving complex real-world problems, encouraging them to investigate, collaborate, and apply their knowledge to develop more meaningful solutions (Nurhuda et al., 2023). Additionally, integrating technology into PBL will create a rich and experiential learning environment that fosters deep cognitive engagement and supports the advanced development of students' problem-solving strategies (Amador Nelke et al., 2024; Gupta, 2022). This result is consistent with existing research showing that PBL effectively strengthens critical thinking skills (Dakabesi & Luoise, 2019; Fita et al., 2021; Wei et al., 2024; Williamson, 2023).

Previous studies have shown that by engaging students in authentic collaborative tasks, PBL fosters students' analytical and critical thinking within a realistic context (Li et al., 2024; Loyens et al., 2023; Paudel, 2025). The integration of TPACK is further enhancing the design and delivery of PBL. The TPACK framework supports the strategic and meaningful use of digital devices in learning (Zhang & Zhou, 2023), which can help students better understand the subject matter while deepening their understanding of pedagogical approaches. The integration of TPACK and PBL will increase student engagement and collaboration during the learning process (Lutfiana et al., 2023; Zahroh, 2025), while also enabling broader knowledge exploration and collaborative inquiry thru aligning technology with specific learning objectives (Teknowijoyo, 2024). Furthermore, the significant difference between the experimental and control groups in this study reinforces and complements previous research findings, which showed that integrating TPACK and PBL can also influence human anatomy learning, particularly in relation to students' critical thinking skills.

This finding clearly demonstrates that the TPACK-based PBL model significantly improves students' critical thinking skills in human anatomy material. Rigorous methodological procedures, including statistical assumption testing and effect size analysis, are increasingly strengthening the reliability and power of the findings. This finding contributes theoretically by reinforcing the principles of constructivist learning, where knowledge is built thru students' active and collaborative engagement, and is context-based. Practically, these results offer valuable insights for educators seeking to design innovative technology-supported learning models that effectively integrate content, pedagogy, and digital devices to support 21st-century science education.

CONCLUSION

Based on the data analysis results, the Sig. value = 0.000 ($0.000 < 0.05$), which means there is a statistically significant difference between the experimental class and the control group. Therefore, it can be concluded that the TPACK-based PBL model has a positive influence on students' critical thinking skills in the experimental class compared to the control class (Discovery Learning). The findings of this study provide implications that the implementation of the TPACK-based PBL learning model has a significant influence on improving students' critical thinking skills, as evidenced by the results of statistical tests that show a significance value below 0.05. This confirms that the integration of technology, pedagogy, and content in problem-based learning strategies is not only potentially effective but can actually produce extraordinary improvements in the development of students' critical thinking skills. Thus, educators are advised to actively adopt the TPACK framework in designing PBL activities, especially on complex topics such as the human anatomical system, so that learning does not only focus on mastering concepts, but also on critical application in real-world contexts through the use of relevant and meaningful technology, as empirically proven in this study.

This study has several methodological limitations that need to be considered in interpreting the results and generalizing the findings. First, the study involved only a sample from one junior high school in East Lampung with a limited number of participants (70 students from two classes), so generalizing the findings to a broader population or different geographic contexts requires caution (Cohen et al., 2018). Second, although the critical thinking test instrument underwent a rigorous psychometric validation process, its focus on a single learning topic (human anatomical systems) may limit the extensibility of the findings to other learning materials in biology or other disciplines. Third, this study did not strictly control for students' out-of-class technology use, which may indirectly influence learning outcomes. These limitations point to the need for further research with a purely experimental design, larger and more diverse samples, and a more comprehensive approach to critical thinking assessment using complementary qualitative and quantitative methods.

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