Salud, Ciencia y Tecnología. 2025; 5:1931
doi: 10.56294/saludcyt20251931

ORIGINAL

The Influence of SaLDI Biology Learning Model Integrated with TPACK on 4C Skills and Student Learning Independence

La influencia del modelo de enseñanza de Biología SaLDI integrado con TPACK en las habilidades 4C y la autonomía del aprendizaje de los estudiantes

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Cite as: Aldi S, Adnan, Azis AA, Syamsul Bahri HS. The Influence of SaLDI Biology Learning Model Integrated with TPACK on 4C Skills and Student Learning Independence. Salud, Ciencia y Tecnología. 2025; 5:1931. https://doi.org/10.56294/saludcyt20251931

Submitted: 20-02-2025 **Revised:** 17-05-2025 **Accepted:** 25-08-2025 **Published:** 26-08-2025

Editor: Prof. Dr. William Castillo-González

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ABSTRACT

Introduction: 21st century skills such as critical thinking, creativity, communication, collaboration (4Cs), and learning independence are essential competencies that learners must have to face the challenges of the global era that are important to integrate with technology. However, in many schools, these skills are still low, largely due to the dominance of teacher-centred learning methods and the lack of optimal use of technology.
Objective: to analyse the effect of SaLDI Biology learning model integrated with TPACK on students' critical thinking skills, creativity, communication, collaboration, and learning independence.
Method: this research is a quasi-experiment with post-test control group design. The population was class XI students of SMAN 14 Makassar. A random sample of 64 students was divided into experimental and control groups. Instruments included a description test and observation sheet. Data analysis used MANOVA test to measure differences in 4C skills and learning independence between groups.
Results: the research results of this study are the SaLDI Biology learning model integrated with TPACK can improve critical and creative thinking skills, communication, collaboration and learning independence. The sig evidences this value <0,05.
Conclusions: the implementation of the TPACK-integrated SaLDI Biology learning model can improve critical thinking skills, creativity, communication, collaboration, and learning independence. These findings indicate that the model is an innovative strategy to develop 21st century skills (4C).

Keywords: High School Students; Learning Independence; SaLDI Biology Learning Model; TPACK; 21st Century Skills (4C).

RESUMEN

Introducción: las competencias del siglo XXI, como el pensamiento crítico, la creatividad, la comunicación, la colaboración (4C) y la autonomía en el aprendizaje, son esenciales para que los estudiantes enfrenten los desafíos de la era global, y su integración con la tecnología es fundamental. Sin embargo, en muchas escuelas, estas habilidades siguen siendo bajas, en gran parte debido al predominio de métodos de enseñanza centrados en el docente y a la falta de un uso óptimo de la tecnología.
Objetivo: analizar el efecto del modelo de aprendizaje de Biología SaLDI integrado con TPACK sobre las habilidades de pensamiento crítico, creatividad, comunicación, colaboración y autonomía en el aprendizaje de los estudiantes.
Método: esta investigación es un experimento con diseño de grupo control con post-test. La población

estuvo compuesta por estudiantes de undécimo grado de SMAN 14 Makassar. Se seleccionó aleatoriamente una muestra de 64 estudiantes, divididos en grupos experimental y de control. Los instrumentos incluyeron una prueba descriptiva y una hoja de observación. El análisis de datos se realizó mediante la prueba MANOVA para medir las diferencias en las habilidades 4C y la autonomía en el aprendizaje entre los grupos.
Resultados: los resultados muestran que el modelo de aprendizaje de Biología SaLDI integrado con TPACK puede mejorar las habilidades de pensamiento crítico y creativo, la comunicación, la colaboración y la autonomía en el aprendizaje. El valor de significancia fue <0,05, lo que evidencia diferencias estadísticamente significativas.
Conclusiones: la implementación del modelo de aprendizaje de Biología SaLDI integrado con TPACK puede mejorar las habilidades de pensamiento crítico, creatividad, comunicación, colaboración y autonomía en el aprendizaje. Estos hallazgos indican que este modelo constituye una estrategia innovadora para desarrollar las competencias del siglo XXI (4C).

Palabras clave: Estudiantes de Educación Secundaria; Autonomía en el Aprendizaje; Modelo de Aprendizaje de Biología Saldi; TPACK; Competencias del Siglo XXI (4C).

INTRODUCTION

The era characterised by the integration of technology in almost all aspects of life, including education, the skills of critical thinking, creativity, communication and collaboration (4Cs) have become very important. However, many students have not mastered these skills optimally to face the rapidly evolving global challenges.[1,2,3,4] Critical thinking skills help students in analysing an event to make the right decision, creative skills can encourage students in making innovative solutions to the obstacles faced.[5,6] Communication skills can be a means of expressing ideas, data information, opinions and messages effectively,[7]while collaboration can train students' ability to build a social spirit in the 21st century.[8,9]

Students are emphasized to be independent and responsible for their learning.[10,11] Various skills need to be done to support students to learn independently. Students can adapt to changes that occur very quickly. Therefore, teachers need to facilitate learning and provide guidance that can optimize the skills that can be needed. This can provide encouragement for students to learn independence.[12,13] Learning independence can be optimised through the use of innovative learning models.[14,15,16] In addition, learning independence can be improved through teaching materials.[17,18] The integration of 4C skills and learning independence can enable students to prepare themselves in holistic ways to face the challenges of the times, which can be developed through learning at school.

There are problems experienced by students in learning Biology in the classroom regarding low 4C skills. Based on the results of previous research, it is revealed that students' 4C skills are still categorised low and need to be optimized.[19,20] Teachers still have a low ability to provide 4C skills learning experiences for students.[21] The problem may stem from teacher-centered learning methods students.[22,23] Educational trends emphasise learning independence, where teachers guide and students manage their learning abilities. However, the dominance of lectures makes students passive and lacks exploration. Optimising the 4Cs and learning independence requires innovative technology-based models that demand active student engagement without neglecting basic skills.[24]

The SaLDI Biology learning model integrated with TPACK is an innovation that optimises critical, creative, collaborative, communicative thinking skills (4C) and learning independence. The first stage, stimulation, triggers curiosity through interactive activities and contextual phenomena, increasing motivation and critical and creative thinking skills.[25,26] Second, learning community, emphasises collaboration, idea sharing and mutual support to practice cooperation and communication.[27,28,29] Third, discovery, encourages concept exploration, data collection, experimentation, and independent learning.[30] Fourth, inferring, trains logical inference, synthesis of knowledge, and application of findings to new situations, while strengthening creativity and critical thinking.[4]

The TPACK framework in the SaLDI Biology learning model was born out of the need for harmonised integration of technology, pedagogy and content to strengthen student learning. Its development encourages teachers to incorporate technology in teaching practice appropriately, so that the quality of materials and pedagogical strategies support each other.[31,32,33] Effective use of technology, such as visualisations, interactive simulations and collaboration tools, is proven to help students understand complex biological concepts.[34,35,36] This integration makes the SaLDI Biology model potentially enhancing the learning experience through the utilisation of relevant and contextual technologies.[37,38]

The superiority of the SaLDI Biology learning model integrated with TPACK is seen in its ability to encourage student collaboration through the saldi.id technology platform. Features such as discussion forums, wikis,

online chats and shared documents are tools that strengthen the learning environment, while developing effective communication and collaboration skills.[39,40] The Saldi.id platform can contain learning activities that include assignments containing case studies and making practicum reports. It can hone student's critical and creative abilities in schools.[41,42] The Saldi.id platform also contains class management, teachers and students. Therefore, it can help teachers organize classes including, determining topics, assignments, and exercises, creating groups, absences, learning resources, and real-time assessments.[43,44] The TPACK-integrated SaLDI Biology learning model uses blended learning supported by platforms such as saldi.id. Student learning independence can be effectively optimized through online and offline learning.[45,46] Integration of technology in the SaLDI Biology learning model significantly helps students have an optimal impact on the 4C skills and encourages learning independence.

The novelty of this research lies in the first application of the SaLDI Biology learning model integrated with the TPACK framework. This integration proved effective in encouraging critical thinking, creativity, collaboration and communication skills, while facilitating concept discovery through the TPACK approach. This research also enhanced the utilisation of technology in Biology learning, differing from most previous studies that only examined TPACK or other learning models separately. This combined approach offers a holistic perspective, enabling material mastery, learning implementation and technology mastery to align with 21st century skills. In addition, this study examines the 4C skills simultaneously in one learning model, providing a comprehensive picture of how students collaborate, communicate, and think critically and creatively with technology support. Another novelty is the exploration of aspects of learning independence facilitated by the saldi.id platform, which allows students to set the pace of learning and develop independent learning skills. This study aims to analyse the effect of the SaLDI Biology learning model integrated with TPACK on critical thinking, creative, communication, collaboration, and learning independence skills of high school students. The findings are relevant as a consideration for education policy makers to improve the quality of learning.

METHOD

Research type

This study used a quasi-experimental design with post-test control group type. The experimental class was given the SaLDI Biology learning model integrated with TPACK, while the control class used the STAD learning model. After the learning process was completed, a final exam (post-test) was given to both groups to identify differences in students' critical thinking, creative thinking, communication, collaboration, and learning independence skills.

Population and sample

The population of this study included all students of class XI of SMAN 14 Makassar in Indonesia. The research sample consisted of two randomly selected XI classes. The total sample size was 64 students, divided into 32 students in the experimental group and 32 in the control group. (Y5).

Variable

The variables in this study consisted of independent variables and dependent variables. The independent variables include the TPACK-integrated SaLDI Biology learning model (X1) and the Student Teams Achievement Divisions (STAD) type cooperative learning model (X2). The TPACK-integrated SaLDI Biology learning model is defined as a biology learning model that combines scientific, learning community, discovery, digital, constructivistic approaches, with the TPACK framework to optimise technology-based learning processes, pedagogy, and content in an integrated manner. Meanwhile, the STAD model is a form of cooperative learning that emphasises cooperation in heterogeneous small groups, where students collaborate to understand the material, help each other complete tasks, and get group awards based on increased individual achievement.

The dependent variables of this study include five 21st century competencies, namely critical thinking (Y1) as the ability to analyse, evaluate and conclude information, creative thinking (Y2) as the ability to generate ideas, solutions and innovations, communication (Y3) as the skill to convey ideas orally and in writing, collaboration (Y4) as the ability to work together and share responsibilities, and learning independence (Y5) as the capacity to manage the learning process. Both learning models are positioned to influence these five aspects.

Instruments

The research instruments were designed to measure five 21st century competencies, namely critical thinking, creative thinking, communication, collaboration, and learning independence. All instruments were developed by referring to relevant theories, then validated by experts before being used in data collection. Critical thinking skills were measured through an essay test consisting of six items based on the FRISCO model (focus, reason, inference, situation, clarity, overview).[47] The test was intended to assess students' skills in analysing information, constructing logical arguments, and drawing conclusions. Validation was conducted through expert

judgement by two experts, who provided input for improvement before the instrument was declared feasible. The application of the instrument was conducted in the form of a written exam, and students' answers were scored using a rubric with a score range of 1-10 for each indicator.

The creative thinking instrument is an essay test with four questions that reflect indicators of fluency, flexibility, originality and elaboration.[48] The instrument was designed to assess students' ability to generate new ideas, alternative solutions, and innovations related to biology learning. Content, construct, and readability validity were checked by two experts, and the answers were scored using a creativity rubric. Students' communication skills were measured using an observation sheet containing four statements regarding oral communication, receptive communication, clarity of delivery, and understanding the purpose of communication.[49] The instrument was validated by two experts and used by an independent observer on a scale of 1-10.

Furthermore, collaboration skills were measured by an observation sheet containing eight indicators, including active participation, openness, support for group members, constructive evaluation of contributions, sharing resources, and respect for differences.[50] The instrument was validated by two experts and implemented through observation on a scale of 1-10. Finally, learning independence was measured by a questionnaire containing 49 statements covering aspects of planning, implementation, and evaluation.[41] The instrument was validated by two experts and implemented in the form of a questionnaire on a Likert scale of 1-5, with interpretation based on the average score reflecting the level of student learning independence.

Data collection and processing

Data collection was carried out after the treatment using a post-test to measure student learning outcomes in five aspects, namely critical thinking, creative thinking, communication, collaboration, and learning independence. The test and non-test instruments used have gone through validity and reliability tests to ensure the accuracy of the measurement results. The data obtained were then processed through several stages of statistical analysis.

The first stage is the analysis prerequisite test, which includes a normality test to determine whether the data distribution is close to normal, as well as a homogeneity test to ensure the similarity of variances between groups. Normality test was conducted using Kolmogorov-Smirnov or Shapiro-Wilk test, while homogeneity test was conducted using Levene's Test. Data that met the assumptions of normality and homogeneity were then analysed further.

The second stage is hypothesis testing, analysing differences in critical thinking skills, creativity, communication, collaboration, and learning independence between groups of students who follow the TPACK-based SaLDI Biology learning model and groups who follow the STAD model using independent sample t-test with the help of SPSS 24 for Windows software. H0: There is no significant difference in critical thinking skills, creativity, communication, collaboration, and learning independence between the group following the TPACK-based SaLDI Biology model and the group following the STAD model. H1: There is a significant difference in critical thinking skills, creative thinking, communication, collaboration, and learning independence between groups that follow the TPACK-based SaLDI Biology model and groups that follow the STAD model. The basis for decision making is if the significance value (2-tailed) < 0,05, then H0 is rejected and H1 is accepted; otherwise if the significance value (2-tailed) > 0,05 then H0 is accepted and H1 is rejected.[51]

Selain uji-t, penelitian ini juga menggunakan analisis multivariat untuk mengetahui kontribusi masing-masing aspek hasil belajar. Analisis dilakukan dengan memperhatikan nilai Pillai's Trace, Wilks' Lambda, Hotelling's Trace, dan Roy's Largest Root. Nilai Pillai's Trace yang tinggi menunjukkan kontribusi yang lebih besar dari variabel bebas terhadap model. Wilks' Lambda bernilai antara 0 hingga 1; semakin kecil nilainya, semakin besar pengaruh variabel bebas. Hotelling's Trace yang semakin meningkat menunjukkan adanya kontribusi signifikan, sedangkan Roy's Largest Root menunjukkan hubungan paling kuat antara variabel bebas dengan variabel terikat. Analisis ini memperkuat hasil uji-t dengan memberikan gambaran menyeluruh tentang signifikansi model pembelajaran terhadap kelima aspek hasil belajar mahasiswa.

Ethical standards

This study was conducted in accordance with the ethical standards of educational research. All participants were explained the purpose of the study, their rights and obligations, and data confidentiality was guaranteed. Informed consent was obtained from the participants, while the interactions during the study were conducted by upholding the principles of professionalism and fairness.

RESULTS

Critical, creative, communication, collaboration, and student learning independence

The following are the study's results, based on descriptive analysis of on critical thinking, creativity, communication, collaboration, learning independence frequency distribution, normality test, homogeneity test and hypothesis testing.

Table 1 shows that the experimental class obtained higher average scores on all aspects of 4C skills and learning independence than the control class. The biggest difference was seen in creative thinking (17,75 points) and critical thinking (16,72 points), followed by learning independence (15,69 points). These results confirm that the TPACK-integrated SaLDI Biology learning model is more effective in improving students' higher order thinking skills and learning independence than the STAD-type cooperative learning model.

Table 1. Descriptive statistics of students' critical thinking, creative thinking, communication, collaboration, and learning independence in experimental and control classes

Statistics	Critical thinking		Creative thinking		Communication		Collaboration		Independence	
	1	2	1	2	1	2	1	2	1	2
Total Sample	32	32	32	32	32	32	32	32	32	32
Average	84,44	67,72	83,81	66,06	83,00	68,59	81,09	69,34	85,03	69,34
Maximum	92	86	91	78,00	91,00	80,00	88,00	81,00	90,00	80,00
Minimum	80	55	78	56,00	75,00	58,00	76,00	58,00	78,00	58,00
Std. Deviation	3,28	8,56	3,63	5,58	3,92	5,60	3,12	5,69	3,69	6,09

Description:
1: Experiment Class (SaLDI Biology Learning Model integrated with TPACK)
2: Control Class (STAD-type Cooperative Learning Model)

The post-test results showed a clear difference between the experimental and control classes. Students in the experimental class were generally in the Good category for all 4C skills and learning independence, indicating the effectiveness of the learning model applied. In contrast, students in the control class were mostly only in the Fair category, so their skill achievement was relatively lower. The complete frequency and percentage distribution is presented in table 2 below.

Table 2. The following is a table of frequency distribution and percentage of critical thinking, creative thinking, communication, collaboration, and student learning independence in experimental and control classes

Statistics	Critical thinking				Creative thinking				Communication				Collaboration				Independence			
	1		2		1		2		1		2		1		2		1		2	
	F	%	F	%	F	%	F	%	F	%	F	%	F	%	F	%	F	%	F	%
Very Good 91 ≤ X ≤ 100	1	3	0	0	1	3	0	0	2	6	0	0	0	0	0	0	0	0	0	0
Good 76 ≤ X < 90	31	97	7	22	31	97	2	6	29	91	5	16	32	100	4	13	32	100	7	22
Simply 61 ≤ X < 75	0	0	18	56	0	0	23	72	1	3	24	75	0	0	26	81	0	0	21	66
Less 41 ≤ X < 60	0	0	7	22	0	0	7	22	0	0	3	9	0	0	2	6	0	0	4	13
Very Less X < 40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Description:
1: Experiment Class (SaLDI Biology Learning Model integrated with TPACK)
2: Control Class (STAD-type Cooperative Learning Model)

Normality Test

The Kolmogorov-Smirnov normality test showed that all data had significance values greater than 0,05, so the distribution of scores was normal. In addition, Levene's test and Box's covariance matrix equality test also showed significance values above 0,05. Thus, the research data fulfils the assumption of homogeneity. The results of the normality test are shown in table 3.

Hypothesis Test

The MANOVA test conducted showed a significant difference in 4C skills and learning independence simultaneously between students who took part in learning with the TPACK-integrated SaLDI Biology Model and students taught using the STAD type cooperative model. The test results through Pillai's Trace, Wilks' Lambda, Hotelling's Trace, and Roy's Largest Root all show significance values below 0,05. Meanwhile, the Partial Eta

Squared value of 0,890 indicates that the treatment contributes 89 % to the variance of 4C skills and learning independence. Details of the test results are presented in table 4.

Table 3. Normality Result Table

		Kolmogorov-Smirnov[a]		
Indicator	**Learning model**	**Statistic**	**df**	**Sig. > 0,05**
Critical thinking	1	0,103	32	0,200
	2	0,091	32s	0,200
Critical thinking	1	0,153	32	0,055
	2	0,115	32	0,200
Communication	1	0,122	32	0,200
	2	0,115	32	0,200
Collaboration	1	0,121	32	0,200
	2	0,136	32	0,142
Learning Independence	1	0,153	32	0,055
	2	0,113	32	0,200

Description:

1: Experiment Class (SaLDI Biology Learning Model integrated with TPACK)
2: Control Class (STAD-type Cooperative Learning Model)

Table 4. Manova Test Analysis Results

Effect	**Value**	**F**	**Hypothesis df**	**Error df**	**Value**	**Sig.**	**Partial Eta Squared**
Intercept	Pillai's Trace	0,999	8593,749b	5,000	58,000	0,000	0,999
	Wilks' Lambda	0,001	8593,749b	5,000	58,000	0,000	0,999
	Hotelling's Trace	740,840	8593,749b	5,000	58,000	0,000	0,999
	Roy's Largest Root	740,840	8593,749b	5,000	58,000	0,000	0,999
Model_Learning	Pillai's Trace	0,890	94,178b	5,000	58,000	0,000	0,890
	Wilks' Lambda	0,110	94,178b	5,000	58,000	0,000	0,890
	Hotelling's Trace	8,119	94,178b	5,000	58,000	0,000	0,890
	Roy's Largest Root	8,119	94,178b	5,000	58,000	0,000	0,890

The Tests of Between-Subject Effects test results show that the SaLDI Biology learning model integrated with TPACK has a significant effect on 4C skills and student learning independence. All significance values are below 0,05, which indicates a real influence on each variable. The Partial Eta Squared value also shows a strong contribution, with variation in explanation ranging from 62 % to 79 %. This finding confirms that the TPACK-integrated SaLDI model is able to partially improve critical thinking skills, creativity, communication, collaboration, and learning independence. Details of the test results are shown in table 5.

Table 5. Test of Between-Subjects Effects Analysis Results

Source	**Dependent Variable**	**Type III Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	**Partial Eta Squared**
Corrected Model	Critical thinking	4472,266a	1	4472,266	106,387	0,000	0,632
	Creative thinking	5041,000b	1	5041,000	227,345	0,000	0,786
	Communication	3320,641c	1	3320,641	142,014	0,000	0,696
	Collaboration	2209,000d	1	2209,000	104,076	0,000	0,627
	Independence	3937,563e	1	3937,563	155,280	0,000	0,715
Intercept	Critical thinking	370424,391	1	370424,391	8811,697	0,000	0,993
	Creative thinking	359400,250	1	359400,250	16208,631	0,000	0,996
	Communication	367690,641	1	367690,641	15724,995	0,000	0,996
	Collaboration	362103,063	1	362103,063	17060,377	0,000	0,996
	Independence	381306,250	1	381306,250	15037,003	0,000	0,996

Model Learning	Critical thinking	4472,266	1	4472,266	106,387	0,000	0,632
	Creative thinking	5041,000	1	5041,000	227,345	0,000	0,786
	Communication	3320,641	1	3320,641	142,014	0,000	0,696
	Collaboration	2209,000	1	2209,000	104,076	0,000	0,627
	Independence	3937,563	1	3937,563	155,280	0,000	0,715
Error	Critical thinking	2606,344	62	42,038			
	Creative thinking	1374,750	62	22,173			
	Communication	1449,719	62	23,383			
	Collaboration	1315,938	62	21,225			
	Independence	1572,188	62	25,358			
Total	Critical thinking	377503,000	64				
	Creative thinking	365816,000	64				
	Communication	372461,000	64				
	Collaboration	365628,000	64				
	Independence	386816,000	64				
Corrected Total	Critical thinking	7078,609	63				
	Creative thinking	6415,750	63				
	Communication	4770,359	63				
	Collaboration	3524,938	63				
	Independence	5509,750	63				

The results of the analysis showed that the application of the TPACK-integrated SaLDI Biology Learning Model was significantly more effective than the STAD-type cooperative model in improving 4C skills and learning independence. Significance value smaller than 0,05 for all skills, with a considerable contribution of variation as shown by the Partial Eta Squared value. This confirms that the SaLDI model is able to have a real influence on improving students' critical thinking skills, creativity, communication, collaboration, and learning independence. Details of the analysis results are presented in table 6.

Table 6. Parameter Estimates

Dependent Variable	Parameters	B	Std. Error	t	Sig.	95 % Confidence Interval		Partial Eta Squared
						Lower Bound	Upper Bound	
Critical Thinking	Intercept	67,719	1,146	59,083	0,000	65,428	70,010	0,983
	1	16,719	1,621	10,314	0,000	13,479	19,959	0,632
	2	0[a]						
Creative Thinking	Intercept	66,063	0,832	79,362	0,000	64,399	67,726	0,990
	1	17,750	1,177	15,078	0,000	15,397	20,103	0,786
	2	0[a]						
Communication	Intercept	68,594	0,855	80,244	0,000	66,885	70,302	0,990
	1	14,406	1,209	11,917	0,000	11,990	16,823	0,696
	2	0a						
Collaboration	Intercept	69,344	0,814	85,145	0,000	67,716	70,972	0,992
	1	11,750	1,152	10,202	0,000	9,448	14,052	0,627
	2	0a						
Learning Independence	Intercept	69,344	0,890	77,898	0,000	67,564	71,123	0,990
	1	15,688	1,259	12,461	0,000	13,171	18,204	0,715
	2	0a						

Description:

1: Experiment Class (SaLDI Biology Learning Model integrated with TPACK)
2: Control Class (STAD-type Cooperative Learning Model)

DISCUSSION

The application of the SaLDI Biology learning model combined with TPACK principles has been proven to improve 4C skills and student learning independence.[37,45] This finding is in line with previous research that confirms that discovery-based learning and collaboration encourage students' critical thinking skills, creativity, and cooperation.[27,30] The integration of TPACK in this model also supports the creation of an interactive and meaningful learning atmosphere, as reported by other studies highlighting the role of technology in strengthening students' active participation.[31,32] Therefore, the results of this study corroborate the theoretical assumption in the introduction that the combination of pedagogical strategies with technology is relevant to equip students to face the challenges of the 21st century.[29,30] The characteristics of SaLDI involving simulation, learning community, discovery, and inferring provide contextual learning experiences so that students not only understand biological concepts in depth, but are also accustomed to solving problems and managing independent learning.[25,26,30]

Critical thinking skills help students analyse, evaluate and solve problems with precision.[6,47,52] The results showed that students in the experimental class experienced a higher increase in critical thinking indicators, especially analysis and evaluation, compared to the control class. This improvement was influenced by the discovery stage in the TPACK-integrated SaLDI Biology learning model, which encourages students to explore real problems and develop concepts through investigation. These activities provide hands-on experience to analyse information and construct evidence-based arguments.[53] This finding is consistent with previous research confirming that discovery learning strengthens critical thinking through problem analysis and evidence-based reasoning.[30] The integration of technology in TPACK also accelerates the analysis process by presenting a wider range of learning resources. In addition, the teacher's guiding questions play a role in helping students find information, recognise patterns and draw logical conclusions, making it superior to conventional learning.

The results showed that students' creative thinking skills in the experimental class with the SaLDI Biology model integrated with TPACK increased significantly compared to the control class. Students are better able to express ideas, develop alternative solutions, and actively participate in discussions. This is in accordance with the opinion that creative skills encourage students to produce innovative solutions to learning obstacles.[6,48,52] Improvements were seen through the learning community in the model syntax, where students could share ideas, as well as the use of worksheets that train the exploration of ideas.[54,55] These findings are in line with other studies that emphasise group work, but this study is superior because TPACK integration enriches the process with discussion forums, chat, and the saldi.id wiki. Thus, the increase in creativity is not only supported by the learning community, but also reinforced by the TPACK integration that connects content, pedagogy, and technology.[31,33]

The results of this study confirm that the application of the SaLDI Biology Learning Model combined with TPACK is able to optimise the development of 21st century skills, especially communication, collaboration, and learning independence. Improved communication skills were seen at the stimulation stage, when students were more willing to ask questions, discuss, and express arguments based on the stimulus, in accordance with the view that communication plays an important role in conveying ideas, data, and messages.[7,27,39,40] Collaboration develops at the learning community stage, where students work in small groups, share information and build positive interactions, in line with previous research findings [8,9,28,29] which emphasise the importance of cooperation in the 21st century. Meanwhile, learning independence was evident at the inferring stage, where students analysed information, drew conclusions, and evaluated understanding, supporting the literature that emphasises the urgency of independent learning.[10,11] Thus, the results, analyses, and literature consistently show that the integration of SaLDI and TPACK is effective in fostering students' cognitive and social competencies.

Based on the data in table 1, the SaLDI Biology learning model integrated with TPACK is more effective than STAD in improving critical thinking skills, creativity, communication, collaboration, and learning independence. This advantage arises because the initial stages of the SaLDI model emphasise stimulation of contextual problems that are able to arouse intrinsic motivation while activating students' prior knowledge, as confirmed by previous research that stimulation effectively supports the development of higher order thinking skills.[25,26] The learning community stage provides opportunities for students to work in heterogeneous groups, which has been shown to develop communication, cooperation, and understanding of concepts.[27] Furthermore, the discovery stage requires students to find patterns, facts, and solutions through discovery activities. This finding is in line with constructivism theory that emphasises inquiry as a means of developing creativity and learning independence.[28,29] Other studies have also confirmed that discovery-based strategies contribute significantly to student independence.[30] Thus, this study not only confirms the effectiveness of SaLDI-TPACK, but also extends previous findings by showing that the integration of technological, pedagogical and content knowledge supports contextualised, interactive and meaningful Biology learning.[31,32]

Table 2 shows that the frequency distribution and percentage of critical thinking skills, creativity, communication, collaboration, and learning independence in the experimental class are more dominant in the good and very good categories than the control class. This advantage is confirmed by the results of

the MANOVA test in table 4 which shows a significance of <0,05 and a Partial Eta Squared value of 0,890, indicating a very large contribution of the SaLDI-TPACK model to the variation of 4C skills and student learning independence. Furthermore, the Test of Between-Subjects Effects results in table 5 show that all variables obtained a significance value <0,05 with a partial contribution of 62-79 %, which means that this model has a real impact on each aspect of 21st century skills. This improvement can be explained by the stages of the SaLDI model, where the initial stimulation triggers students' motivation and prior knowledge [25,26] the learning community stage trains cooperation and communication in heterogeneous groups [27,28,29] while the discovery stage requires students to find patterns and solutions through inquiry, in line with constructivism theory (30). The Parameter Estimation results in table 6 also show significant mean differences, such as 16,72 points on critical thinking and 17,75 points on creativity, 14,40 points on communication, 11,75 on collaboration, 15,68 on learning independence which confirms the effectiveness of this model compared to STAD. Overall, these findings not only corroborate previous research on the importance of inquiry and collaboration,[19,20,56,57] but also extend it with evidence that TPACK integration makes Biology learning more contextual, interactive,[58,59,60] and meaningful according to 21st century competency needs.[31,32,39,40].

CONCLUSIONS

This research confirms that the application of the SaLDI Biology learning model integrated with TPACK is effective in supporting the achievement of 21st century skills, especially strengthening 4C skills and increasing students' learning independence. The integration of the learning model with the utilisation of technology and specific content not only provides a strategic alternative in Biology learning practices, but also enriches the literature on learning models that are relevant to contemporary educational needs. In addition to making theoretical contributions to the development of technology-based pedagogy studies, this research also opens up space for practical use for teachers, lecturers, and educational practitioners in designing learning that is more adaptive to global developments. The broader implication is the need for educational policy support that encourages innovation in sustainable learning models so as to improve the quality of education and prepare the younger generation to face the complexity of 21st century challenges.

REFERENCES

1. Nganga L. Preservice teachers perceptions of teaching for global mindedness and social justice: Using the 4Cs (Collaboration, Critical thinking, Creativity and Communication) in teacher education. J Soc Stud Educ Res. 2019;10(4):26-57. Disponible en: https://jsser.org/index.php/jsser/article/view/1262/407

2. Shinta EM, Triastuti A. Communicative language teaching and its application in developing slow learners' 21st century skills. En: Teacher Education and Professional Development in Industry 4.0. Milton Park, Oxfordshire: Taylor & Francis; 2020. p. 261-6. Disponible en: https://www.taylorfrancis.com/chapters/edit/10.1201/9781003035978-40/communicative-language-teaching-application-developing-slow-learners-21st-century-skills-shinta-triastuti

3. Thornhill-Miller B, Camarda A, Mercier M, Burkhardt JM, Morisseau T, Bourgeois-Bougrine S, et al. Creativity, critical thinking, communication, and collaboration: assessment, certification, and promotion of 21st century skills for the future of work and education. J Intell. 2023;11(3):54. doi:10.3390/jintelligence11030054

4. Ye P, Xu X. A case study of interdisciplinary thematic learning curriculum to cultivate "4C skills". Front Psychol. 2023;14:1080811. doi:10.3389/fpsyg.2023.1080811

5. Wecshler SM, Saiz C, Rivas SF, Vendramini CMM, Almeida LS, Mundim MC, et al. Creative and critical thinking: Independent or overlapping components? Think Skills Creat. 2018;27:114-22. doi:10.1016/J.TSC.2017.12.003

6. Ahmady S, Shahbazi S. Impact of social problem-solving training on critical thinking and decision making of nursing students. BMC Nurs. 2020;19(1):94. doi:10.1186/s12912-020-00487-x

7. Hasan N, Pandey MK, Ansari SN, Purohit VR. An Analysis of English Communication Skills. World J Engl Lang. 2022;12(3):194-202. doi:10.5430/wjel.v12n3p194

8. Liebech-Lien B, Sjølie E. Teachers' conceptions and uses of student collaboration in the classroom. Educ Res. 2021;63(2):212-28. doi:10.1080/00131881.2020.1839354

9. Lin TJ, Kraatz E, Ha SY, Hsieh MY, Glassman M, Nagpal M, et al. Shaping classroom social experiences through collaborative small-group discussions. Br J Educ Psychol. 2022;92(10):131-54. doi:10.1111/bjep.12442

10. Polivanova K, Bochaver A. Is Students' Autonomy Possible at Contemporary School? Psychol Educ. 2022;27(3):6-15. doi:10.17759/pse.2022270301

11. Garashkina N, Druzhinina A. Technology of organising students' project activities towards the development of educational independence of a future pedagogue. Perspect Sci Educ. 2023;65(5):145-62. doi:10.32744/pse.2023.5.9

12. Hockings C, Thomas L, Ottaway J, Jones R. Independent learning - what we do when you're not there. Teach High Educ. 2018;23(2):145-61. doi:10.1080/13562517.2017.1332031

13. Leeuwen A, Janssen J. A systematic review of teacher guidance during collaborative learning in primary and secondary education. Educ Res Rev. 2019;21:71-89. doi:10.1016/J.EDUREV.2019.02.001

14. Adnan A, Abimanyu S, Patta R, Arsyad N. The Improving of junior high school student in learning motivation through implementation constructivistic biology learning model based on information and communication technology. J Educ Pract. 2014;5(2):63-71. Disponible en: https://www.iiste.org/Journals/index.php/JEP/article/view/10639

15. Adnan A, Saenab S, Rahmatullah, Almunawarah R, Sahira S, Aldi S. Model Pembelajaran Citizen Science Project. NTB: Penerbit P4I; 2024. Disponible en: https://books.google.co.id/books/about/Model_Pembelajaran_Citizen_Science_Proje.html?id=Jc4gEQAAQBAJ&redir_esc=y

16. Aldi S, Adnan A, Azis AA. The Influence of SaLDI Learning Model (Stimulation, Learning Community, Discovery, Inferring) on Activity, Motivation, and Learning Outcomes of Biology of High School Students. J Penelit Pendidik IPA. 2024;10(11):9064-77. doi:10.29303/jppipa.v10i11.9379

17. Aldi S, Ismail I. Keterampilan Proses Sains: Panduan Praktis untuk Melatih Kemampuan Berpikir Tingkat Tinggi. Purbalingga: Eureka Media Aksara; 2023. Disponible en: https://repository.penerbiteureka.com/publications/560571/keterampilan-proses-sains-panduan-praktis-untuk-melatih-kemampuan-berpikir-tingk

18. Adnan A, Aldi S, Dzulkarnain AF, Marliyah S. Pengaruh e-LKPD Berbasis Keterampilan Proses Sains terhadap Hasil Belajar, Motivasi Belajar, dan Kemampuan Metakognitif Peserta Didik Kelas XI SMA. Bioeduscience. 2022;6(3):304-13. doi:10.22236/jbes/6310259

19. Supena I, Darmuki A, Hariyadi A. The Influence of 4C (Constructive, Critical, Creativity, Collaborative) Learning Model on Students' Learning Outcomes. Int J Instr. 2021;14(3):873-92. doi:10.3390/jintelligence11030054

20. Medina-Barahona CJ, Mora GA, Calvache-Pabón C, Salazar-Castro JA, Mora-Paz HA, Mayorca-Torres D. Propuesta de arquitectura IoT orientada a la creación de prototipos para su aplicación en plataformas educativas y de investigación. Rev Colomb Tecnol Av. 2022;1(39):118–25. doi:10.24054/rcta.v1i39.1405

21. Dahlan T, Judijanto L, Hali F. Improving the quality of mathematics teacher education: An integrated approach to the 4C skills. JRAMathEdu. 2024;9(1):16-33. doi:10.23917/jramathedu.v9i1.2687

22. Khalaf BK, Mohammed Zin ZB. Traditional and inquiry-based learning pedagogy: A systematic critical review. Int J Instr. 2018;11(4):545-64. doi:10.12973/IJI.2018.11434A

23. Maddens L, Depaepe F, Raes A, Elen J. Fostering students' motivation towards learning research skills: the role of autonomy, competence and relatedness support. Instr Sci. 2023;51(1):165-99. doi:10.1007/s11251-022-09606-4

24. Børte K, Nesje K, Lillejord S. Barriers to student active learning in higher education. Teach High Educ. 2023;28(3):597-615. doi:10.1080/13562517.2020.1839746

25. Asrizal A, Yurnetti Y, Usman E. ICT Thematic Science Teaching Material with 5E Learning Cycle Model to Develop Students' 21st-Century Skills. Indones J Sci Educ. 2022;11(1):61-72. doi:10.15294/jpii.v11i1.33764

26. Sun J, Chen Q, Zhang Q, Li Y, Li H, Wei D, et al. Training your brain to be more creative: brain functional and structural changes induced by divergent thinking training. Hum Brain Mapp. 2016;37(10):3375-87.

doi:10.1002/hbm.23246

27. Lorencová H, Jarošová E, Avgitidou S, Dimitriadou C. Critical thinking practices in teacher education programmes: a systematic review. Stud High Educ. 2019;44(7):844-59. doi:10.1080/03075079.2019.1586331

28. Rehm M, Mulder RH, Gijselaers W, Segers M. The impact of hierarchical positions on the type of communication within online communities of learning. Int J Comput Support Collab Learn. 2016;10(2):158-70. doi:10.1016/j.chb.2015.12.065

29. Jäppinen AK, Leclerc M, Tubin D. Collaborativeness as the core of professional learning communities beyond culture and context: Evidence from Canada, Finland, and Israel. Sch Eff Sch Improv. 2016;27(3):315-32. doi:10.1080/09243453.2015.1067235

30. Oyarzun B, Martin F. A Systematic Review of Research on Online Learner Collaboration from 2012-21: Collaboration Technologies, Design, Facilitation, and Outcomes. Online Learn. 2023;27(1):71-106. doi:10.24059/olj.v27i1.3407

31. Simamora RE, Saragih S. Improving Students' Mathematical Problem Solving Ability and Self-Efficacy through Guided Discovery Learning in Local Culture Context. Int Electron J Math Educ. 2019;14(1):61-72. doi:10.12973/iejme/3966

32. Stoilescu D. A Critical Examination of the Technological Pedagogical Content Knowledge Framework. J Educ Comput Res. 2015;52(4):514-47.

33. Glover I, Hepplestone S, Parkin H, Rodger H, Irwin B. Pedagogy first: Realising technology enhanced learning by focusing on teaching practice. Br J Educ Technol. 2016;47(5):993-1002. doi:10.1111/bjet.12425

34. Adnan A, Muharram M, Jihadi A. Pengembangan e-book biologi berbasis konstruktivistik untuk meningkatkan motivasi belajar siswa SMA Kelas XI. Indones J Educ Stud. 2019;22(2):112-9. doi:10.26858/ijes.v22i2.11773

35. Helikar T, Cutucache C, Dahlquist L, Herek T, Larson J, Rogers J. Integrating Interactive Computational Modelling in Biology Curricula. PLoS Comput Biol. 2015;11(3):e1004131. doi:10.1371/journal.pcbi.1004131

36. Jenkinson J. Molecular Biology Meets the Learning Sciences: Visualisations in Education and Outreach. J Mol Biol. 2018;430(21):4013-27. doi:10.1016/j.jmb.2018.08.020

37. Oliver JS, Hodges GW, Moore JN, Cohen A, Jang Y, Brown SA, et al. Supporting high school student accomplishment of biology content using interactive computer-based curricular case studies. Res Sci Educ. 2019;49(2):1783-808. doi:10.1007/s11165-017-9675-6

38. Sandoval Carrero NS, Acevedo Quintana NM, Santos Jaimes LM. Lineamientos desde la industria 4.0 a la educación 4.0: caso tecnología IoT. Rev Colomb Tecnol Av. 2022;1(39):81–92. doi:10.24054/rcta.v1i39.1379

39. Alqurashi E, Gokbel E, Carbonara D. Teachers' knowledge in content, pedagogy and technology integration: A comparative analysis between teachers in Saudi Arabia and United States. Br J Educ Technol. 2017;48(6):1414-26. doi:10.1111/bjet.12514

40. Christodoulou A, Angeli C. Adaptive Learning Techniques for a Personalised Educational Software in Developing Teachers' Technological Pedagogical Content Knowledge. Front Educ. 2022;7:789397. doi:10.3389/feduc.2022.789397

41. Jeong H, Hmelo-Silver C. Seven Affordances of Computer-Supported Collaborative Learning: How to Support Collaborative Learning? How Can Technologies Help? Educ Psychol. 2016;51(2):247-65. doi:10.1080/00461520.2016.1158654

42. Sun Z, Liu R, Luo L, Wu M, Shi C. Exploring collaborative learning effect in blended learning environments. J Comput Assist Learn. 2017;33(6):575-87. doi:10.1111/jcal.12201

43. Al-Zahrani A. From passive to active: The impact of the flipped classroom through social learning platforms on higher education students' creative thinking. Br J Educ Technol. 2015;46(6):1133-48. doi:10.1111/bjet.12353

44. Hwang G, Lai C, Liang J, Chu H, Tsai C. A long-term experiment to investigate the relationships between high school students' perceptions of mobile learning and peer interaction and higher-order thinking tendencies. Educ Technol Res Dev. 2018;66(6):75-93. doi:10.1007/S11423-017-9540-3

45. Liu Z, Lomovtseva N, Korobeynikova E. Online Learning Platforms: Reconstructing Modern Higher Education. Int J Emerg Technol Learn. 2020;15(13):4-21. doi:10.3991/ijet.v15i13.14645

46. Rojas Puentes MDP, Parada CJ, Leal Pabón JL. Estructuras desglosadas de trabajo (EDT) en la gestión de alcance de proyectos de desarrollo de software. Rev Colomb Tecnol Av. 2022;1(39):51–58. doi:10.24054/rcta.v1i39.1375

47. Mihai D, Mihailescu M, Cărăbaş M, Tapus N. Integrated High-Workload Services for E-Learning. IEEE Access. 2023;11(13):8441-54. doi:10.1109/ACCESS.2023.3238967

48. Castro R. Blended learning in higher education: Trends and capabilities. Educ Inf Technol. 2019;24(4):2523-46. doi:10.1007/s10639-019-09886-3

49. Hoic-Bozic N, Dlab MH, Mornar V. Recommender system and web 2.0 tools to enhance a blended learning model. IEEE Trans Educ. 2015;59(1):39-44. doi:10.1109/TE.2015.2427116

50. Ennis RH. Nationwide Testing of Critical Thinking for Higher Education. Teach Philos. 2011;31(1). doi:10.5840/teachphil20083111

51. Guilford JP. Intelligence, Creativity, and Their Educational Implications. San Diego: Robert R. Knapp; 1968.

52. Greenstein L. Assessing 21st Century Skills: A Guide to Evaluating Mastery and Authentic Learning. California: Corwin; 2012.

53. Borich GD. Effective teaching methods. Pearson Education India; 2017.

54. Herzog C, Handke C, Hitters E. Analyzing talk and text II: Thematic analysis (pp. 385-401). Switzerland: Springer International Publishing; 2019.

55. Wechsler SM, Saiz C, Rivas SF, Vendramini CMM, Almeida LS, Mundim MC, et al. Creative and critical thinking: Independent or overlapping components? Think Skills Creat. 2018;27:114-22. doi:10.1016/J.TSC.2017.12.003

56. Shi Y. Talk About Evidence During Argumentation. Discourse Process. 2020;57(9):770-92. doi:10.1080/0163853x.2020.1777498

57. Ma Q, Lee H, Gao X, Chai C. Learning by design: Enhancing online collaboration in developing pre-service TESOL teachers' TPACK for teaching with corpus technology. Br J Educ Technol. 2024;55(6):2639-67. doi:10.1111/bjet.13458

58. Lixia W, Jun L, Choi. TPACK and EdTech Integration in Teaching and Learning Process: A Systematic Literature Review (2014-2024). Commun Appl Nonlinear Anal. 2024;31(7s):487-505. doi:10.52783/cana.v31.1381

59. Kwangmuang P, Jarutkamolpong S, Sangboonraung W, Daungtod S. The development of learning innovation to enhance higher order thinking skills for students in Thailand junior high schools. Heliyon. 2021;7(6):e07309. doi:10.1016/j.heliyon.2021.e07309

60. Nisa H, Isnaini M, Utami LS, Islahudin I. Collaborative learning effect on improving students' creativity and critical thinking in the independent curriculum. AL-ISHLAH J Pendidik. 2023;15(3):4038-48. doi:10.35445/alishlah.v15i3.3538

FINANCING

Our gratitude goes to the supervisors, validators, teachers and students for their contributions to completing this research. The authors would like to thank the DRTPM of the Ministry of Education and Culture for supporting this research (Decree number 0459/E.5/PG.02.00/2024 and Agreement/Contract number 2768/UN36.11/LP2M/2024).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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