



## Comparing TPACK-Based E-LKPD and Conventional Instruction in Science: Impacts on Digital Literacy and Higher-Order Thinking Skills

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**Abstract:** This study examines the effectiveness of a TPACK-based Electronic Student Worksheet (E-LKPD) on the digital literacy and higher-order thinking skills (HOTS) of eighth-grade students in science learning. A quasi-experimental non-equivalent control group design was employed, involving an experimental class (n=27) that used the TPACK-based E-LKPD and a control class (n=27) that received conventional instruction using printed LKPD. Data were collected through validated digital literacy questionnaires, HOTS assessments, and student perception questionnaires. Mann-Whitney U tests indicated statistically significant differences in both digital literacy ( $p=0.014$ ) and HOTS ( $p=0.004$ ), favoring the experimental group, with moderate effect sizes (0.4390). Spearman's correlation showed a strong positive relationship between digital literacy and HOTS ( $\rho = 0.686$ ;  $p < 0.001$ ; 95% CI [0.519; 0.801]). Partial Least Squares Structural Equation Modeling (PLS-SEM) indicated that students' positive perceptions of the TPACK E-LKPD predicted their digital literacy ( $\beta = 0.635$ ;  $p = 0.004$ ), which in turn was associated with higher HOTS scores ( $\beta = 0.218$ ;  $p = 0.0216$ ). These findings show that TPACK-based E-LKPD is effective not only in improving two key 21st-century skills simultaneously, but also in revealing a mechanism in which positive student perceptions support digital literacy development and, in turn, higher-order thinking. The study provides empirical evidence for using TPACK as a design framework for digital science worksheets to support digital literacy and higher-order thinking in secondary science education.

**Keywords:** digital literacy; E-LKPD; higher-order thinking skills; PLS-SEM; science education; TPACK

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## INTRODUCTION

Science education in the 21st century increasingly emphasizes integrating digital technology into the instructional process. In addition to mastering basic science concepts, students are expected to have *Higher-Order Thinking Skills* (HOTS) and adequate digital literacy (Dewi et al., 2021; Widiyawati et al., 2021). Digital literacy in this context refers to the ability to find, evaluate, and communicate scientific information through digital media (Reddy et al., 2023). Several studies show that pedagogically designed technology integration can improve student motivation and cognitive skills (Bereczki & Kárpáti, 2021; Kalogiannakis et al., 2021; Timotheou et al., 2023). This highlights the need to develop learning tools that support the development of students' digital literacy and HOTS, including at the junior high school level.

However, empirical data show that Indonesian students' achievement in these skills remains suboptimal. Indonesia's Program for International Student Assessment (PISA) scores in the science domain are consistently below the OECD average, indicating a need to strengthen learning that trains students in complex problem-solving and HOTS (OECD, 2019, 2023). In line with this, local research indicates that the HOTS and digital literacy profiles of junior high school students remain in the low to moderate range (Kurniati et al., 2016; Oktavia et al., 2021; Widiyawati et al., 2021). This is especially evident when learning is dominated by teacher explanation and printed worksheets (Anggraini et al., 2024; Ibrahim et al., 2024; Widiyawati et al., 2021). One factor contributing to this condition is the limited integration of technology into teaching materials (Akram et al., 2022). Science learning that still relies on printed books and conventional Student Worksheets (*Lembar Kerja Peserta Didik*/LKPD) tends to limit students' space for exploration in digital-based activities. These findings show that the problem is not only access to technology, but also the lack of learning designs that turn digital activity into evidence-based thinking practice.

To address this gap, several studies have explored the use of Electronic Student Worksheets (E-LKPD). Previous studies have shown that E-LKPD, especially when combined with problem-based learning (PBL) or the Science, Technology, Engineering, and Mathematics (STEM) approach, can improve students' digital literacy and critical thinking skills compared to conventional learning (Purwati et al., 2023; Rahayu et al., 2022; Sarawati et al., 2025). E-LKPD provides features such as simulations, links to various sources, and direct feedback that are not available in printed worksheets (Herlina et al., 2025; Wati et al., 2025). In line with the increasing research in this field (Anggraini et al., 2025; Ibrahim et al., 2024), the integration of technology in learning needs to be

designed not only as an addition to technical tools but also as a unity between pedagogy, content, and technology (Dewi et al., 2022; Fawns, 2022). Recent studies show that digital worksheets, inquiry-oriented LKPD, and mobile or augmented-reality learning media can improve digital literacy, science literacy, critical thinking, and HOTS when students are required to investigate and discuss evidence rather than memorize facts (Afikah et al., 2022; Haryadi & Pujiastuti, 2023; Rozali et al., 2024; Yuniarti et al., 2024). However, the effectiveness of such tools depends on how well technology, pedagogy, and science content are aligned.

In this context, the Technological Pedagogical Content Knowledge (TPACK) framework provides a conceptual foundation for designing effective technology integration (Mishra & Koehler, 2006; Schmidt et al., 2009). TPACK emphasizes that the use of digital media must be aligned with teaching strategies and content characteristics (Akram et al., 2021; Angraini, 2023; Dewi et al., 2025). Based on the TPACK framework, an E-LKPD for Vibration and Waves material at the junior high school level has been developed and validated in previous research, with an Aiken's V validity ratio of 0.94, indicating very high content validity (Niswah & Dewi, 2024). The worksheet includes virtual laboratory simulations, guided internet searches, and staged scientific inquiry activities designed to connect science content with digital learning practices. However, validation evidence alone does not demonstrate instructional effectiveness. Previous research has generally focused on the development or feasibility of E-LKPD, examined digital literacy and HOTS separately, or limited itself to comparing learning outcomes without explaining how the intervention works (Ibrahim et al., 2024; Widiyawati et al., 2021).

Thus, the present study addresses two gaps. First, many prior studies test digital literacy, science literacy, or HOTS separately, whereas science learning requires these competencies to work together. Second, limited classroom studies explain the pathway through which students' perceptions of a TPACK-based worksheet relate to digital literacy and HOTS. This study therefore compares TPACK-based E-LKPD with conventional worksheet-based instruction and models the role of student perceptions using PLS-SEM. Specifically, this study answers four research questions: 1) Is there a significant difference in digital literacy between the experimental and control classes?; 2) Is there a significant difference in HOTS between the two classes?; 3) What is the relationship between digital literacy and HOTS?; and 4) Do students' perceptions of TPACK E-LKPD influence digital literacy and HOTS?. The study contributes empirical evidence on both outcome differences and the mechanism linking TPACK-oriented design, digital literacy, and higher-order thinking in junior secondary science, extending a literature base that has recently emphasized TPACK-digital literacy links mainly in teacher or pre-service contexts (Aslan et al., 2025; Fazilla et al., 2022; Kim & Paik, 2025; Sari et al., 2024; Sukaria & Nursalim, 2025).

## METHODS

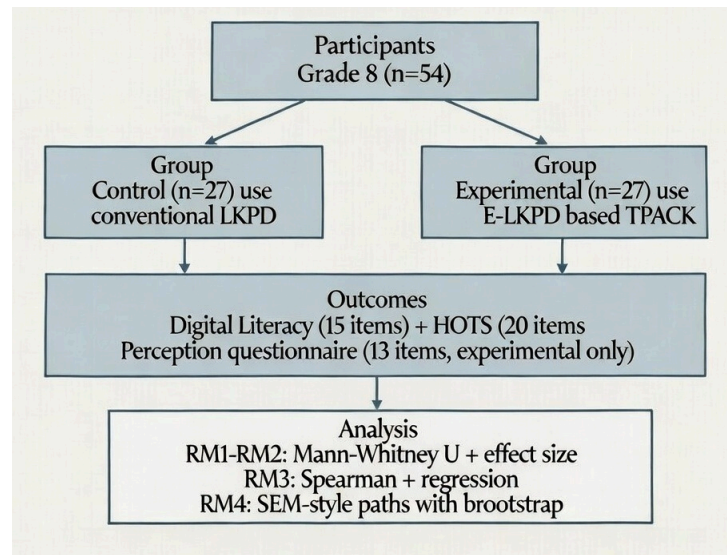
This study adopted a quasi-experimental, non-equivalent control-group design. This model was chosen because restructuring existing administrative classes in schools is impossible, rendering random assignment at the individual level impossible (Cohen et al., 2017; Creswell & Creswell, 2018). The target population in this study was all eighth-grade students at a junior high school in Semarang City in the even semester of the 2025/2026 academic year. Purposive sampling was applied based on recommendations from science partner teachers, taking into account the similarity in curriculum load and initial academic achievement histories across classes. The selected research sample consisted of 54 students, who were then divided into two independent study groups: the Experimental Class, which learned using TPACK-based E-LKPD, consisting of 27 students, and the Control Class, which followed scientific learning assisted by conventional printed LKPD, consisting of 27 students.

The instruments used in this study included treatment and measurement instruments. The treatment instrument in the experimental class was TPACK-based E-LKPD for the subject of Vibration and Waves. This E-LKPD was developed using the ADDIE model and has been validated in previous research (Niswah & Dewi, 2024), with an expert validity score (Aiken's V) of 0.94 (category "Very Valid"). Three measurement instruments were used to measure the dependent variables: 1) Digital Literacy Questionnaire, consisting of 15 statements adapted from the Ministry of Education and Culture's (2017) digital literacy competency indicators, measuring the ability to find, understand, evaluate, create, and communicate digital information; 2) HOTS Test, consisting of 20 problem-based questions compiled based on Bloom's revised taxonomy at levels C4 (Analyzing), C5 (Evaluating), and C6 (Creating); and 3) TPACK Perception Questionnaire, in the form of a 5-point Likert scale with 13 items filled out by the experimental class to measure perceptions of the usefulness, appearance, and cognitive support of E-LKPD. All instruments have been tested for item validity using Product-Moment correlation and for reliability using Cronbach's Alpha ( $\alpha > 0.7$ ) (Niswah & Dewi, 2024).

The research procedure was carried out in three stages. In the pre-treatment stage, a homogeneity test was conducted using students' daily test scores in the previous chapter to ensure the initial abilities of both classes were equal. The treatment stage lasted four meetings, during which the control class used textbooks and printed worksheets, while the experimental class used TPACK-based E-worksheets with interactive links and

virtual laboratory simulations, guided by teachers using TPACK-based pedagogical strategies (Niswah & Dewi, 2024). In the post-treatment stage, both classes completed a Digital Literacy questionnaire and HOTS test. In addition, the experimental class completed a Perception Questionnaire to determine students' responses to the use of TPACK-based E-LKPD.

Data analysis was conducted quantitatively at the 0.05 significance level ( $\alpha = 0.05$ ). Prerequisite tests included the Shapiro-Wilk normality test and Levene's Test of homogeneity of variance. The results of the prerequisite tests showed that the data distribution was not normal ( $p < 0.05$ ), so non-parametric statistical tests were used. 1) Comparative analysis (research questions 1 & 2): differences in digital literacy and HOTS scores between the two groups were tested using the Mann-Whitney U test. The effect size (rank-biserial correlation) was also calculated to determine the practical magnitude of the difference (Coe, 2002); 2) Correlational analysis (research question 3): the relationship between digital literacy and HOTS was analyzed using Spearman's rank correlation ( $\rho$ ) by combining the data of all 54 students; 3) Structural path analysis (research question 4): to model the relationships between variables in the experimental class, variance-based Partial Least Squares Structural Equation Modeling (PLS-SEM) was used with SmartPLS version 4. The analysis was conducted in two stages: evaluation of the outer model (testing composite reliability and convergent-discriminant validity through HTMT) and evaluation of the inner model (testing the significance of path coefficients through bootstrapping 5,000 subsamples, coefficients of determination  $R^2$ , and predictive relevance  $Q^2$ ) (Hair et al., 2022). The research flow from the pre-intervention stage to the structural model analysis is presented in Figure 1.



**Figure 1.** Research design overview

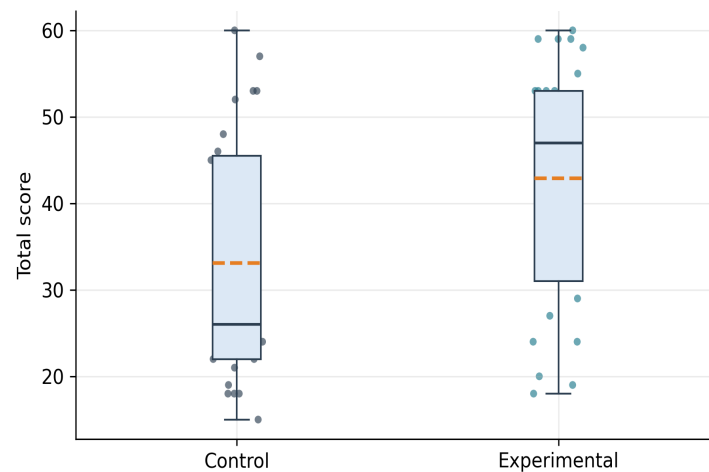
## RESULT AND DISCUSSION

The first analysis examined the differences in digital literacy between the two groups. The Shapiro-Wilk normality test indicated that the distribution of digital literacy data was not normal in either the experimental ( $p=0.012$ ) or the control ( $p=0.006$ ) class. In contrast, Levene's test for homogeneity of variances showed that the variances of the two groups were homogeneous ( $p=0.650 > 0.05$ ). Based on these results, the Mann-Whitney U non-parametric test was used as the comparison procedure. The test results are presented in Table 1.

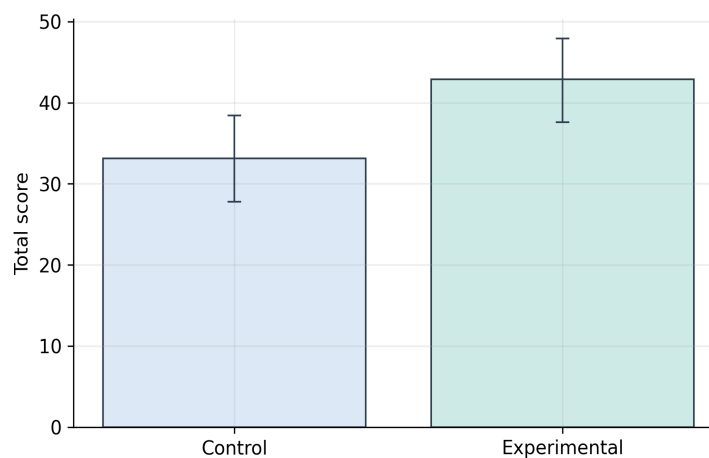
**Table 1.** Results of the digital literacy difference test (Mann-Whitney U)

| Group      | N  | Mean (SD)     | U-statistic | p-value | Effect size (rank-biserial) |
|------------|----|---------------|-------------|---------|-----------------------------|
| Control    | 27 | 33.11 (14.24) | 506.0       | 0.0146  | 0.3882 [0.0933, 0.6585]     |
| Experiment | 27 | 42.89 (13.92) | 506         | 0.0146  | 0.3882 [0.0933, 0.6585]     |

*\*Significant at the  $p < 0.05$  level*



**Figure 2.** Distribution of digital literacy scores for the control vs. experimental groups (boxplot with individual data points)



**Figure 2b.** Comparison of the average and 95% confidence interval of digital literacy scores

Based on Table 1, there was a significant difference in digital literacy scores between the two groups ( $U=506.0$ ,  $p=0.0146 < 0.05$ ). The experimental class showed a higher average score ( $M=42.89$ ,  $SD=13.92$ ) than the control class ( $M=33.11$ ,  $SD=14.24$ ), with a difference of 9.78 points or a relative increase of 29.5%. The rank-biserial effect size of 0.3882 [95% CI: 0.093, 0.659] indicates a moderate effect according to Cohen's classification (Cohen, 1988). The distribution of scores in Figure 2 shows that the median and upper quartile of the experimental class are higher than those of the control class. Figure 2b shows that the 95% confidence intervals for the two groups' means do not overlap, supporting the above statistical findings.

This result is theoretically consistent with the TPACK framework, which posits that technology becomes instructionally effective when it is integrated with pedagogy and content rather than used as an isolated add-on (Koh et al., 2015; Mishra & Koehler, 2006). In the present study, the TPACK-based E-LKPD did not simply replace the printed worksheet with a digital format; it embedded guided internet searches, links to external sources, videos, and inquiry prompts that required students to locate, interpret, evaluate, and communicate information. These activities align directly with the theoretical dimensions of digital literacy (Reddy et al., 2023). Because the worksheet structured students' interaction with digital resources, it likely provided more opportunities for authentic literacy practice than the conventional printed LKPD.

The finding is also in line with previous studies reporting that interactive E-LKPD can strengthen students' digital literacy activities and engagement (Purwati et al., 2023; Rahayu et al., 2022). Features such as links to external information sources, independent search instructions, and demonstration videos encourage students to practice digital information access and evaluation skills (Purwati et al., 2023; Rahayu et al., 2022). Compared to the relatively static printed LKPD, E-LKPD tends to offer more opportunities for interaction with digital sources and for tasks that require information processing. These findings align with Anggraini et al. (2025), who show that an interactive E-LKPD based on Wizer.me can increase digital literacy activities among elementary school students, suggesting consistency across educational levels. Studies on the development of E-LKPD assisted by Liveworksheets and PjBL-based E-LKPD show that digital tools are considered practical and

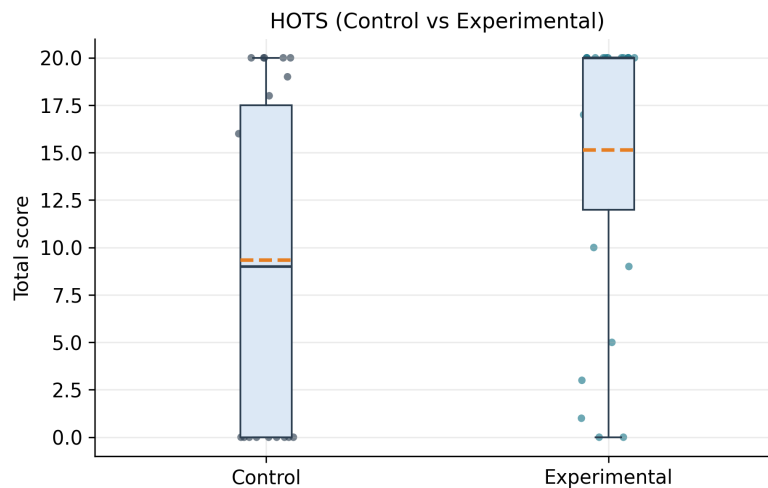
support student engagement (Ghaisani & Setyasto, 2023; Simamora & Hajar, 2025), which is often a prerequisite for increasing digital literacy. These findings also align with the summary of evidence from a systematic review of digital literacy, which emphasizes that literacy improves when learning activities provide space for information evaluation and for digital production/communication, not just content consumption (Tinmaz et al., 2022).

The present study extends that literature in two ways. First, it provides comparative evidence at the junior high school level using a validated TPACK-based worksheet on Vibrations and Waves. Second, it shows a moderate effect size, suggesting that the advantage is not only statistically significant but also educationally meaningful. In practice, this implies that science teachers should design digital worksheets as inquiry-oriented learning environments rather than static digitized handouts. Further testing was conducted on the HOTS variable. Similar to RM1, the Shapiro-Wilk normality test was first applied and indicated highly non-normal distributions in both groups (experimental class,  $p < 0.001$ ; control class,  $p < 0.001$ ), while Levene's homogeneity test showed acceptable variance equality ( $p = 0.100 > 0.05$ ). Thus, the Mann-Whitney U test was again used as a valid comparison procedure. As with digital literacy, the TPACK-based E-LKPD treatment group showed superior performance.

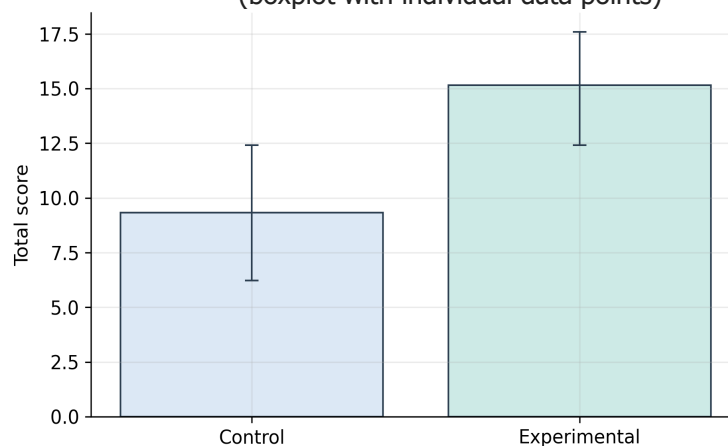
**Table 2.** Results of the HOTS difference test (Mann-Whitney U)

| Group      | N  | Mean (SD)    | U-statistic | p-value | Effect size (rank-biserial) |
|------------|----|--------------|-------------|---------|-----------------------------|
| Control    | 27 | 9.33 (8.34)  | 524.5       | 0.0046  | 0.4390 [0.1632, 0.6955]     |
| Experiment | 27 | 15.15 (7.18) | 524.5       | 0.0046  | 0.4390 [0.1632, 0.6955]     |

*\*\*Significant at the  $p < 0.01$  level*



**Figure 3.** Distribution of HOTS scores for the control vs. experimental classes (boxplot with individual data points)



**Figure 3b.** Comparison of the mean and 95% confidence interval of HOTS scores

The Mann-Whitney U test results for HOTS (Table 2) show a significant difference between the two groups ( $U = 524.5$ ,  $p = 0.0046 < 0.01$ ). The experimental class obtained a higher average score ( $M = 15.15$ ,

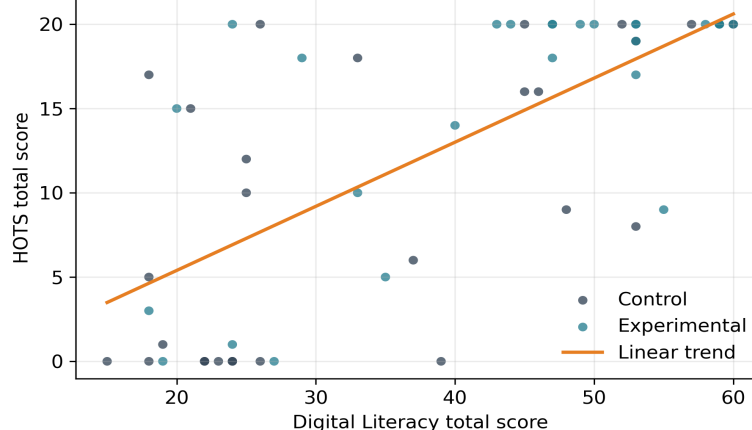
SD=7.18) than the control class (M=9.33, SD=8.34), with a difference of 5.82 points or a relative increase of 62.4%. The rank-biserial effect size of 0.4390 [95% CI: 0.163, 0.696] falls into the moderate-to-high category [23]. The significance level in RM2 ( $p=0.005$ ) was lower than in RM1 ( $p=0.015$ ), and the effect size was also greater (0.439 vs 0.388). This shows that E-LKPD TPACK has a greater influence on HOTS than on digital literacy. The distribution of scores in Figure 3 and the comparison of confidence intervals in Figure 3b support this finding.

The increase in HOTS in the experimental class can be attributed to the E-LKPD feature, which provides scientific inquiry-based activities and virtual laboratory simulations (Niswah & Dewi, 2024). E-LKPD changes the type of cognitive activity from remembering to analyzing/evaluating/creating. The TPACK-based E-LKPD incorporates problem-based questions, data interpretation, and evidence-based decisions, encouraging students to engage in reasoning rather than merely following procedures. For abstract material such as Vibrations and Waves, digital simulations allow students to manipulate variables such as frequency and amplitude, then answer problem-based questions that require the ability to analyze (C4), evaluate (C5), and create (C6) (Bereczki & Kárpáti, 2021). Such activities are difficult to replicate in conventional textbook-based learning (Ibrahim et al., 2024; Sarawati et al., 2025). These findings are consistent with Sarawati et al. (2025), who showed that PBL-based electronic worksheets improved the critical thinking skills of eighth-grade students, and with Herlina et al. (2025), who showed that e-worksheets can develop computational thinking skills. The consistency of these cross-study findings supports the effectiveness of pedagogically designed electronic worksheets in improving HOTS. The findings in RQ1 and RQ2 show that the experimental class outperformed the control class on both variables. This leads to the next question regarding the relationship between digital literacy and HOTS. A correlation analysis was conducted on all 54 students to test the relationship between digital literacy and HOTS. The Spearman correlation results showed  $\rho = 0.686$ ,  $p < 0.001$ , and a 95% CI of [0.519; 0.801], which falls into the strong correlation category according to Dancey and Reidy's criteria.

**Table 3.** Summary of regression and correlation tests (digital literacy versus HOTS)

| Spearman's $\rho$ | $p$ -value  | 95% CI for $\rho$ | $R^2$ (Regression) | Adjusted $R^2$ |
|-------------------|-------------|-------------------|--------------------|----------------|
| 0.6858            | 1.05e-08*** | [0.5185, 0.8013]  | 0.4838             | 0.4636         |

\*\*\*Significant at the  $p < 0.001$  level



**Figure 4.** Scatter plot of the relationship between digital literacy and HOTS with a linear regression line

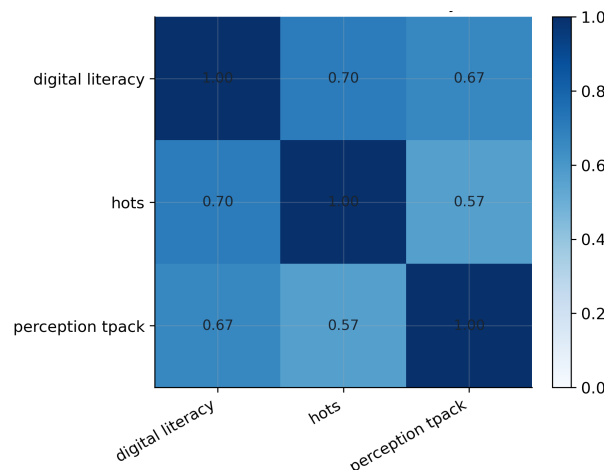
The Spearman correlation in Table 3 shows a strong and significant positive relationship between digital literacy and HOTS ( $\rho = 0.6858$ ,  $p < 0.001$ ), with a 95% confidence interval of [0.519, 0.801]. The value of  $R^2$  is 0.4838 (adjusted  $R^2 = 0.4636$ ), indicating that digital literacy explains approximately 48.4% of the variance in HOTS scores. Figure 4 shows a positive relationship: students with higher digital literacy scores tend to achieve higher HOTS scores. Multivariate regression analysis provides additional information. The standardized regression coefficient for digital literacy on HOTS is  $\beta = 0.634$  ( $p < 0.001$ ), while the group variable (experimental vs. control) is not significant as a predictor after digital literacy is included in the model ( $p = 0.182$ ). These findings indicate that what is directly related to HOTS is students' digital literacy skills, not merely the type of treatment received. In this case, E-LKPD TPACK serves as a means of supporting the development of digital literacy, which, in turn, is related to the improvement of HOTS. Digital literacy acts as a catalyst for HOTS. To think at a high level, students need materials that can be processed—such as text, data, images, or simulations—and then analyzed and evaluated. Students with good digital literacy are usually quicker to find the right sources, more observant in checking whether the information is reliable, and able to compare various pieces of evidence before concluding. Therefore, they have a greater chance of conducting more accurate analysis and evaluation.

In line with this, research by [Furbani et al. \(2025\)](#) on high school students also shows a positive relationship between digital literacy and critical thinking skills. [Ibrahim et al. \(2024\)](#) also found simultaneous increases in digital literacy and HOTS in electronic-based biology learning, consistent with the conceptual framework of [Anggraini et al. \(2025\)](#), which links TPACK with digital literacy and scientific literacy. The positive relationship between these two variables shows the importance of integrating digital instruments into the learning process to support HOTS development. Both share overlapping cognitive components, particularly information evaluation, bias checking, and evidence-based decision-making. The literature emphasizes that exposure to digital information without critical thinking tools actually reduces the quality of information assessment; that is, when digital literacy is directed critically, it contributes directly to HOTS ([Tinmaz et al., 2022](#)). These findings encourage further analysis of how students' perceptions of E-LKPD shape these two skills.

To analyze the relationships among variables in the experimental class ( $n=27$ ), a PLS-SEM analysis was conducted to test the influence of students' perceptions of E-LKPD, digital literacy, and HOTS. PLS-SEM was chosen for its suitability for moderate-sized samples and for predictive modeling ([Hair et al., 2022](#)). The analysis was conducted in two stages: outer model evaluation and inner model evaluation. The results of the outer model evaluation are presented in Table 5. All constructs showed good reliability with Cronbach's Alpha > 0.95 and Composite Reliability > 0.96, both exceeding the minimum threshold of 0.70 for convergent validity ([Hair et al., 2022](#)). Convergent validity was established with Average Variance Extracted (AVE) values exceeding 0.50, indicating that each construct explained more than 64% of its indicators' variance. Discriminant validity was met with inter-construct HTMT values: TPACK Perception–Digital Literacy = 0.667, TPACK Perception–HOTS = 0.566, and Digital Literacy–HOTS = 0.704, all of which were below the threshold of 0.85 (see Figure 6).

**Table 5.** Summary of the measurement model (outer model)

| Construct        | $\alpha$ (Cronbach) | CR     | AVE    |
|------------------|---------------------|--------|--------|
| Perception TPACK | 0.9565              | 0.9620 | 0.6621 |
| Digital Literacy | 0.9589              | 0.9637 | 0.6401 |
| HOTS             | 0.9760              | 0.9786 | 0.7002 |

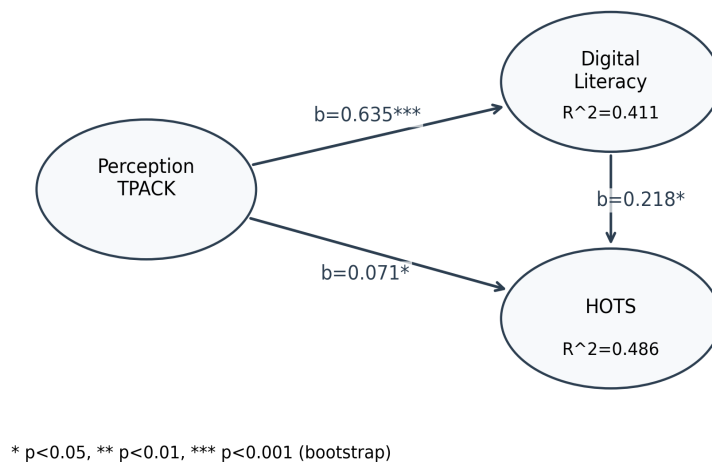


**Figure 5.** HTMT Heatmap (discriminant validity)

After the outer model was fulfilled, the inner model was evaluated. This model (see Figure 5) explains 41.1% of the variance in Digital Literacy and 48.6% of the variance in HOTS ( $R^2$ ), which, according to Cohen's classification, falls into the substantial category. Blindfolding analysis shows adequate predictive relevance with  $Q^2$  for HOTS (0.358) and Digital Literacy (0.313), both above 0.  $f^2$ 's values for each path are: TPACK Perception→ Digital Literacy ( $f^2 = 0.698$ , large effect), Digital Literacy→ HOTS ( $f^2 = 0.364$ , large effect), and TPACK Perception→ HOTS ( $f^2 = 0.039$ , small effect). This pattern indicates that the influence of perception on HOTS is greater through indirect paths (mediated by digital literacy) than through direct paths.

**Table 6.** Results of structural path analysis (bootstrapping)

| Path                              | Path Coefficient ( $\beta$ ) | Confidence Interval (95%) | $p$ -value | $f^2$ | Decision |
|-----------------------------------|------------------------------|---------------------------|------------|-------|----------|
| Perception TPACK→Digital Literacy | 0.635                        | [0.320, 0.901]            | 0.0004     | 0.698 | Accepted |
| Digital Literacy→ HOTS            | 0.218                        | [0.040, 0.341]            | 0.0216     | 0.364 | Accepted |
| Perception TPACK→ HOTS            | 0.071                        | [0.003, 0.180]            | 0.0428     | 0.039 | Accepted |



**Figure 6.** Structural Model of the Experimental Class (PLS-SEM)

The path analysis results (Table 5 and Figure 6) extend previous studies on E-LKPD by demonstrating not only that TPACK-based worksheets improve learning outcomes, but also the mechanism through which these effects occur. Recent studies on development have generally reported post-test improvements in digital literacy, science literacy, or critical thinking following the use of digital worksheets or HOTS-oriented learning media (Anggraini et al., 2024; Haryadi & Pujiastuti, 2023; Yuniarti et al., 2024). However, such studies have rarely integrated comparative testing and structural modeling within a single research design. In the present study, students' perceptions of TPACK-based E-LKPD exerted a strong positive effect on digital literacy ( $\beta = 0.635$ ,  $f^2 = 0.698$ ,  $p < 0.001$ ). The  $f^2$  value substantially exceeds the threshold of 0.35 for a large effect (Hair et al., 2022), indicating that favorable perceptions of E-LKPD are strongly associated with enhanced students' digital literacy. Notably, this relationship represented the largest structural coefficient in the model, suggesting that students' perceived pedagogical quality of the worksheet is not merely affective in nature, but constitutes an important mechanism for sustaining digital engagement, information evaluation, and evidence-based learning practices. In this regard, perceived aspects such as ease of use, display quality, and cognitive support may encourage more intensive participation in digitally mediated learning activities (Akram et al., 2021; Dewi et al., 2025). Positive perceptions may also strengthen students' willingness to engage; when learners perceive E-LKPD as accessible, useful, and interesting, they are more likely to spend longer interacting with the material, explore its features more frequently, and complete the inquiry steps more thoroughly. This helps explain the pathway from perception to digital literacy, as literacy practices are reinforced when students regard the activity as both manageable and meaningful. Such a pattern is consistent with SEM/SmartPLS studies that position attitudinal or perceptual variables as antecedents of engagement and competence, including studies linking digital literacy and thinking skills through structural modeling (Haliq et al., 2025).

Furthermore, digital literacy had a positive effect on HOTS ( $\beta = 0.218$ ,  $f^2 = 0.364$ ). Although the path coefficient is moderate, the  $f^2$  value indicates a substantial contribution within the structural model. This finding suggests that strengthened digital literacy equips students with broader access to information, more refined evaluative skills, and greater capacity to use evidence in analysis, thereby supporting the development of higher-order thinking. This interpretation is supported by a literature review on digital literacy and adolescent critical thinking, which emphasizes that critical thinking develops more effectively when digital literacy is embedded in meaningful learning activities rather than delivered through lecture-based approaches (Azizatus et al., 2025). In addition, students' perceptions of TPACK-based E-LKPD also showed a direct effect on HOTS ( $\beta = 0.071$ ,  $f^2 = 0.039$ ), although the effect size was small. The presence of this direct path indicates that certain features of TPACK-based E-LKPD, including inquiry-oriented tasks and problem-based evaluation components (Niswah & Dewi, 2024; Wati et al., 2025), may independently contribute to higher-order thinking. This result is consistent with Dewi et al. (2021), who found that TPACK integration in digital worksheets enhanced students' creativity in chemistry learning, suggesting that the pedagogical benefits of TPACK-based design are not confined to a single scientific discipline.

Overall, the PLS-SEM results show that students' positive perceptions of TPACK-based E-LKPD influence digital literacy, which, in turn, is associated with increased HOTS. Perceptions increase engagement in digital activities, thereby improving literacy practices, providing students with more materials and tools for analysis/evaluation, and ultimately increasing HOTS. A literature review on digital literacy and critical thinking in adolescents also emphasizes that the development of critical thinking is effective when digital literacy is integrated through meaningful activities (rather than lectures) (Azizatus et al., 2025). Previous research has examined the relationship between TPACK and digital literacy primarily in teacher and pre-service teacher contexts (Aslan et al., 2025; Fazilla et al., 2022; Sari et al., 2024; Sukaria & Nursalim, 2025), whereas empirical

classroom-based evidence at the student level remains limited. Positive perceptions usually increase "willingness to engage": if students find E-LKPD easy, useful, and interesting, they tend to stay longer, try features more often, and be more willing to complete the exploration steps. This explains the path from perception to digital literacy: students practice literacy more because they feel that the activities are doable and valuable. The contribution of this study, therefore, lies not only in demonstrating that the TPACK-based E-LKPD works but also in explaining how it may work through students' perceived usability and literacy practice. From an educational perspective, the findings suggest that schools should support teachers in designing TPACK-oriented digital worksheets and provide sufficient infrastructure to implement digital inquiry activities consistently in science classes.

The study also has practical implications and limitations that should be acknowledged. The results suggest that well-designed TPACK-based E-LKPD can be used as an instructional strategy to strengthen digital literacy and HOTS in junior high school science, especially for abstract topics that benefit from simulation and guided digital inquiry. However, the findings should be interpreted cautiously because the sample was limited to one school, the groups were not randomly assigned, and the intervention effects were measured only after treatment. These limitations open opportunities for follow-up studies with larger samples, stronger designs, and longer observation periods.

## CONCLUSION

This study shows that TPACK-based E-LKPD is more effective than conventional learning in improving students' digital literacy and HOTS in science learning. Four main findings were obtained: 1) there was a significant difference in digital literacy between the experimental and control classes ( $p=0.015$ , rank-biserial= $0.388$ ), with a 29.5% increase in the experimental class; 2) a significant difference was also found in HOTS ( $p=0.005$ , rank-biserial= $0.439$ ), with an increase of 62.4%; 3) Digital Literacy and Digital were strongly and positively correlated with HOTS ( $r=0.686$ ,  $p<0.001$ ), explaining 48.4% of the variance in HOTS; and 4) PLS-SEM showed that students' positive perceptions of E-LKPD influenced Digital Literacy ( $\beta=0.635$ ,  $f^2=0.698$ ), which was further related to HOTS. These findings indicate that TPACK-based digital worksheets can simultaneously support two important 21st-century competencies while offering a plausible mechanism linking perception, literacy practice, and higher-order thinking. The study has several implications for educational practice and policy. For teachers, the results highlight the importance of designing E-LKPD as inquiry-based and digitally interactive learning tools rather than merely converting printed worksheets into electronic form. For schools and policymakers, the findings support the provision of digital infrastructure, teacher training in TPACK-based design, and the integration of digital literacy objectives into science instruction. Several limitations of the study should be noted. First, the small sample size ( $n=27$  per group) limits the generalizability of the findings. Second, the quasi-experimental design without full randomization may leave uncontrolled confounding variables, even though a pre-treatment homogeneity test was conducted. Third, measurements were only taken at one point post-intervention, so the sustainability of the effects cannot yet be determined. Further research is recommended to: 1) replicate the study with a larger sample and multiple schools; 2) use a longitudinal design to measure skill retention; 3) develop E-LKPD TPACK on other science topics to test cross-content generalization; and 4) integrate formative assessment based on learning analytics to obtain more detailed learning behavior data.

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