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The Effect of TPACK-Based Instructional Design on Science Learning Activity and Achievement: A Quasi-Experimental Study in Primary Education

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Abstract: This study addresses the low level of active learning and inconsistent science achievement among primary school students. It aims to examine the effect of Technological Pedagogical and Content Knowledge (TPACK)-based instructional design on students' learning activity and science performance. A quasi-experimental method with a nonequivalent posttest-only control group design was employed involving two classes: one taught using a TPACK-based approach and another using conventional instruction. Learning activity was measured through observation checklists and structured questionnaires, while science achievement was assessed through a multiple-choice test. Data were analyzed using descriptive statistics and an independent samples t-test. The results show that students in the TPACK group demonstrated notably higher levels of learning activity across visual, mental, and emotional dimensions compared to the control group. Their activity level was categorized as good, whereas the control group remained fairly good. Science test outcomes also revealed higher mean scores and lower score variance in the TPACK group. Statistical analysis confirmed significant differences between groups in both learning activity and science achievement. The study concludes that TPACK-based instructional design effectively integrates technology, pedagogy, and content to promote active engagement and enhance science learning outcomes in primary education.

Keywords: Instructional design; Learning activity; Primary education; Science achievement; TPACK

Introduction

Elementary education is important for molding students' character and scientific thinking since early age. In a 21st-century environment, education should be seen as preparing learners for the construction of essential skills such as critical thinking, collaboration, communication, and creativity (Chalkiadaki, 2018; Hermansah et al., 2024). But to accomplish such goals requires a far-reaching shift away from old-school convention toward instructional formats that are more integrative, engaging, and technology supported. Technology, including AI and digital resources, plays a crucial role in supporting flexible, personalized, and engaging learning experiences, but must be used thoughtfully to avoid over-reliance and address issues like technology anxiety (Benvenuti et al., 2023; Susanti, 2025).

Elementary science education serves as a crucial foundation for developing scientific literacy and inquiry skills, which are essential for preparing students to think critically and function as responsible citizens in a

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science- and technology-driven world (Cahyaningtyas & Desstya, 2024; Parisu et al., 2025). Effective approaches to fostering these skills include the integration of interactive multimedia and digital tools, all of which have been shown to significantly improve students' understanding of scientific concepts, critical thinking, and motivation to learn (Mochamad et al., 2024; Winarni et al., 2024).

Unfortunately, many instructional methods remain mostly teacher-centered and didactic in nature. Field observations conducted from April 18th to 29th, 2025, in Grade V classes of SDN Gugus I in IV Koto District evidenced that science learning activities are predominantly lecture-based, with an extremely limited repertoire of teaching strategies and even lesser use of interactive technologies. Science learning in many classrooms remains predominantly teacher-centered and lecture-based, often limiting student engagement and the use of interactive technologies (Kranzfelder et al., 2020; Rimahdani et al., 2023). Teacher-centered methods, while sometimes effective for delivering content, are generally less successful at fostering deep understanding, critical thinking, and active participation compared to student-centered or inquiry-based approaches (Alarcon et al., 2023; Ismail et al., 2024; Mukagihana et al., 2021).

This kind of instructional model constrains and limits students to passive roles as listeners and note takers, whereas the teacher is the sole source of knowledge. Unidirectional classroom talk permits little opportunity for student inquiry, experimentation, or critical dialogue (Leong, 2025; Yu et al., 2022). And therefore, when the classroom environment doesn't support an interactive setup, such students become disengaged and unwilling to offer any active contribution to the learning process (Ahshan, 2021; Steen-Utheim & Foldnes, 2018).

In this atmosphere, students often display poor interpretation of scientific content. During classroom activities, many were seen to have difficulty explaining or applying concepts, many of whom simply copied from fellow students without appreciating the reasoning, while some simply withhold questions for fear of looking silly or because of lack of confidence (Hidayatulloh et al., 2020).

The greater extent to which this problem manifests itself is in trying to assess the level of learning. From the outcome of the Mid-Semester Assessment (Penilaian Tengah Semester - PTS) for Science in the 2024/2025 academic year, the majority of Grade V students in the Gugus I cluster failed to attain the Minimum Mastery Criteria (MMC) of 70. The summary of average scores and achievements of students from eight schools is shown in Table 1.

Table 1. Grade V Science Mid-Semester Assessment Results – Gugus I SD Cluster (2024/2025)

School Name	Average Score	Students Achieving MMC
SDN 01 Sungai Jariang	60.57	7 out of 21
SDN 05 Kampung Pisang	67.67	4 out of 9
SDN 08 Koto Gadang	62.55	9 out of 22
SDN 09 Jambak	66.38	7 out of 16
SDN 10 Sianok	67.56	7 out of 16
SDN 12 Pahambek	66.67	1 out of 3
SDN 14 Lambah	67.83	3 out of 6
SDN 15 Sutijo	67.50	3 out of 8

Source: Principal of SDN Gugus I Sungai Jariang (2025)

Of the 101 students, only 41 met the standard minimum criteria of the MMC, amounting to about 40.6%. On the other hand, the other 60 students, or 59.4% of the total sample, did not meet the criteria. The average scores in most schools are in the ranges of 60 to 67, and below the expected threshold. These findings, therefore, show low teaching methods, which could provide understanding and mastery of science contents.

According Irawan (2022), outdated instructional approaches and the lack of technology and student-centered strategies lead to poor student performance most times. Students who are not appropriately accommodated by the instructional designs in their learning needs and learning preferences are not actively involved in and probably might not retain any conceptual understanding (Mat & Jamaludin, 2024; Wang, 2023). Technology integration further enhances learning by increasing accessibility, visualization, and engagement, particularly when combined with learner-centered pedagogies and collaborative activities (Aljehani, 2024; Schweiker & Levonis, 2023).

A strong theoretical foundation for improving classroom practices can be drawn from instructional systems theory, which emphasizes that effective learning requires deliberate structuring of activities, guidance, and support. Gagné (1985) explains that meaningful understanding emerges when instructional experiences stimulate attention, engagement, and purposeful cognitive processing. When instruction remains highly didactic and does not activate these conditions, students are likely to memorize without comprehension and show limited participation. In line with this view, constructivist perspectives also underline the importance of allowing learners to explore ideas, interact with peers, and build understanding collaboratively. Vygotsky (1978) highlights that learning develops through social interaction and scaffolding within the learner’s zone of proximal development, while Jonassen (1999) argues that authentic, technology-supported tasks help students construct deeper knowledge. These perspectives affirm that learning becomes more meaningful when instructional design intentionally integrates cognitive, social, and experiential elements.

The lack of innovation in instructional design, however, is closely related to the limitations of professional knowledge of the teachers on applying more dynamic models in teaching. In a word, Hastutie et al. (2024) maintain that no learning design models may assist teachers or educators comprehensively in creating classroom environments for meaningful student participating engagement.

This issue is aptly met with Technological Pedagogical Content Knowledge, or TPACK. TPACK combines all the technological tools, pedagogical strategies, and subject-matter knowledge into a coherent conception, which supports teachers in instructional planning and delivery (Ulya et al., 2023). This design can enable teachers to better construct lessons that are both conceptually solid and engaging.

Many studies have shown that TPACK is an effective approach in science learning, as reported by Gunawan et al. (2024). Classrooms that use TPACK as a strategy may achieve better learning gains than those classrooms applying the traditional lecture. Similarly, the work of Rachmawati et al. (2024) found that differentiated instruction based on TPACK improved student motivation and achievement.

In addition, the combination of TPACK with constructivist, for example, Problem-Based Learning (PBL), and collaborative approach such as the Talking Stick method, can create a positive effect on critical thinking and student participation (Normaya et al., 2023). These combinations not only enrich teaching and learning dynamics in the classroom but also bridge the theory-practical divide.

The area under TPACK has, however, been scantily researched on dual TPACK-based instructional design impacts on learning activity and achievement in science at the elementary level. The few that exist mostly isolate cognitive or behavioral outcomes and so are mostly conducted in secondary or high education contexts (Andriyani et al, 2024).

In this respect, the study sought to analyze the impact of TPACK-based instructional design on science learning activity and achievement of Grade V primary school learners. With this quasi-experimental design, the study hopes to plug the existing gap by providing empirical evidence of the TPACK benefits holistically.

Method

This investigation used a quantitative method by using quasi-experimental designs to find the impact of the TPACK instructional design model on students' learning activities and learning outcomes in science. The study employed a nonequivalent posttest only control group design in which one group received instruction through TPACK-based model instruction while the other group adhered to conventional teaching procedures. This design was opted since comparative analysis could be done between such natural settings in which random assignment becomes impractical but can still preserve internal validity (Lestari & Yudhanegara, 2019).

Time and Location of the Research

The research was conducted during April–May 2025 in the Cluster I public elementary schools located in Sungai Jariang, IV Koto District. All teaching interventions, observations, and posttests were carried out in the respective Grade V classrooms where the sample groups were situated.

Population and Sample

The population was fifth graders from the public elementary schools in Cluster I, Sungai Jariang during the 2024/2025 academic years, amounting to 101 students from 8 schools. There were two classes purposively selected as samples using three criteria: similarity in academic ability frequency determined by the science midterm test scores; equality of classroom facilities; and comparable teacher qualifications and teaching experiences. Class V of SDN 08 Koto Gadang was assigned as the experimental group and Class V of SDN 09 Jambak was used as the control group.

Type of Research and Research Method

This study applied a quasi-experimental method with a nonequivalent posttest-only control group design. The experimental group received instruction through a structured TPACK-based instructional design integrating technological tools, pedagogical strategies, and content-based learning tasks. Meanwhile, the control group followed conventional lecture-based teaching aligned with the school's regular instructional practices.

Research Stages

This research work was done in three phases: preparation of instruments, development and validation of the instruments, instructional material preparation, and sample selection. The implementation period consisted of the experimental group taught with the TPACK-based model while the control group received instruction in the conventional way. Observations were carried out with both groups post lesson completion. All data were collected and made ready in the final phase.

Data Collection Techniques and Instruments

For data collection, it used two instruments. The first was a combined observation checklist and structured questionnaire that was designed to measure students' learning activities. The questionnaire included 16 items grouped into eight dimensions of student behavior: visual, oral, listening, writing, drawing, motor, mental, and emotional (Purwanto, 2011). Each dimension was represented by two specific behavioral statements. The items were validated by science education experts and the reliability was tested using the Cronbach alpha formula (Hermawan et al., 2019).

Table 2. Student Learning Activity Questionnaire Items Based on Activity Dimensions

Activity Dimension	Item Numbers	Sample Statements
Visual (reading, observing)	1–2	Reading about Earth's structure; observing water cycle demonstrations
Oral (asking, discussing)	3–4	Asking questions about plate tectonics; giving opinions in discussions
Listening (teacher or peer)	5–6	Listening to teacher explanations; listening to peers during group work
Writing (summarizing, reporting)	7–8	Writing a lesson summary; writing an observation report
Drawing (diagramming, mapping)	9–10	Drawing the water cycle; creating a concept map of Earth's layers
Motor (experimenting, modeling)	11–12	Conducting a plate movement experiment; making an Earth layer model
Mental (analyzing, problem-solving)	13–14	Analyzing the impact of tectonic shifts; solving problems related to the water cycle
Emotional (interest, confidence)	15–16	Showing high interest during lessons; demonstrating confidence when presenting

The second instrument was a science achievement test, consisting of thirty multiple-choice questions. The items were constructed on core curriculum content and competency standards in relation to Earth's layers, the water cycle, and tectonic plate movement. The questions were distributed across three content areas in accordance with a test specification table to guarantee content balance and alignment with instructional objectives. The tests were then validated by experts, and the items analyzed for difficulty, discrimination, validity, and reliability (Suherman, 2003).

Table 3. Test Specification Table for the Science Achievement Test

Test Indicator	Item Numbers	Item Type
Identifying the structure of Earth's layers (lithosphere, hydrosphere, atmosphere) and related geographic features	1–10	Multiple choice
Explaining the water cycle and changes on Earth's surface	11–20	Multiple choice
Describing tectonic plate movement caused by mantle convection	21–30	Multiple choice

Data Analysis

Statistical analysis was done through the software Minitab. The Anderson-Darling test was applied for normalcy testing while F-test was used to test for the homogeneity of the variance. Hypothesis tests finally were selected depending on the outcome of those assumption tests. According to the assumption tests, independent samples t-test was applied for data that fulfilled both assumptions. Welch's t' test was used for normally distributed but nonhomogeneous data, while Mann-Whitney U tests were used to analyze data that did not meet normality assumptions. The learning activity instrument and the science test scores were converted to percentage values and categorized according to existing interpretation categories (Sarwono & Handayani, 2021). These evaluations would find whether the TPACK Instructional Design Model has a statistically significant effect on students' participation in class and their performance in science.

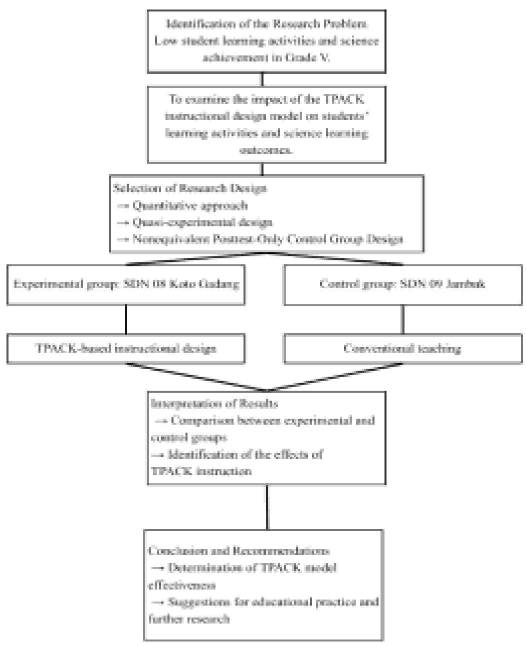

Figure 1. Flowchart of the research method

Result and Discussion

Student Learning Activity Results

Findings of this study reveal that the implementation of the TPACK Instructional Design Model had a huge effect on student learning activities and learning outcomes of fifth-grade elementary school students. Eight major indicators were discussed to represent the eight dimensions of student activities such as visual, oral, listening, writing, drawing, motor, mental, and emotional activities.

Comparison of Activity Indicators between Groups

It was recorded that, in the observational study, students were far more active in learning in the experimental class than in the control class, who learned in the way of business-as-usual. The average score for the activity of the learning process in the experimental group was 72.64 percent, which is rated as "good." The control group got an average score in the learning activity of 59.38 percent, which can be considered quite good. With 80 percent activity on this indicator, visual activity is the strongest indicator of performance in the experimental class (very good). However, in the control class, visual activity scored poorly at only 65 percent. In addition, mental activities and emotional activities gained a high percentage in the experimental group: 76.11 percent and 72.22 percent, respectively. This indicates that the TPACK-based instructional approach engages students cognitively while shaping their motivation toward and attitude concerning learning in a favorable way.

The following table shows the comparison of recorded indicators of learning activities between experimental and control classes.

Table 4. Final Average Scores of Learning Activities in Both Sample Classes

Activity	Experimental Class	Category	Control Class	Category
Visual Activities	80	Very Good	65	Good
Oral Activities	71.11	Good	55.56	Fairly Good
Listening Activities	72.22	Good	60.56	Good
Writing Activities	67.78	Good	58.33	Fairly Good
Drawing Activities	70.56	Good	58.89	Fairly Good
Motor Activities	71.11	Good	60	Good
Mental Activities	76.11	Good	60	Good
Emotional Activities	72.22	Good	56.67	Fairly Good
Average	72.64	Good	59.38	Fairly Good

Student Learning Outcome Results

Regarding student learning outcomes, posttest data showed that the experimental class obtained higher and more consistent scores than the control group. The experimental class's average was 26.25, which has the highest score of 30 and lowest score of 22; on the contrary, the control class had an average score of 23.89, with the same maximum score of 30 but having a lower minimum of 20. The median and mode for the experimental group were 27, which means that there is a more centralized and consistent distribution of scores. For the control group, median equals 23.5 while mode equals 21. Meanwhile, the standard deviation and variance in the experimental group were 2.69 and 7.25, respectively. Both figures are lower than those in the control group, recorded at 2.96 and 8.81. This confirms that the learning outcomes in the experimental group were higher but also more evenly distributed. A summary of test results is shown in a chart below.

Table 5. Descriptive Data of Student Achievement Test Scores

Class	N	Mean	Max	Min	Median	Mode	SD	Variance
Experimental	20	26.25	30	22	27	27	2.69	7.25
Control	18	23.89	30	20	23.5	21	2.96	8.81

Inferential Statistical Findings

The normality test, which was performed using the Anderson-Darling method, indicated that both groups of data were sampled from a normally distributed population, evidenced by the p-values being greater than 0.05. The homogeneity of variance was confirmed by an F-test where variances among groups were statistically equal. In turn, after fulfilling both assumptions, an independent sample t-test was performed, resulting in a 0.002 p-value showing that this value was lower than .05. Thus, it can be concluded that a statistically significant difference exists in learning activity between students taught using the TPACK model and those taught via conventional methods. For learning outcomes, the p-value also comes to be 0.006, lower than the threshold of 0.05, indicating a significant difference in achievement between students studying under two methods. The quantitative analysis, therefore, indicates the TPACK Instructional Design Model-tremendous-increases in student engagement and achievement. Pedagogy, content, and technology are brought together in a seamless whole that makes learning more interactive, equitable, and meaningful.

This study proves that TPACK-based instructional design can substantially advance students' academic endeavors in learning activities and science learning achievement. Unlike traditional teachings, which separate content, method, and media into three distinct entities, TPACK courses are all put together in one plan. Practually, this means that teachers go beyond their responsibilities for teaching content to formulating delivery strategies while ascertaining support by technological means through which science learning becomes active and engaging for students (Muzaini, 2023).

A central tenet of TPACK's greatness lies in the set-out nature of its instructional design process. Teachers start with choosing the scientific content of their teaching and matching that with curriculum requirements and the level of their students to ensure accuracy and relevance. Then, they might decide on a number of pedagogical strategies that best support student processing of the selected content. These might involve inquiry-based ways of teaching, experiments, or collaborative projects, wherein students naturally ask questions, observe, and draw conclusions. Finally, the teachers will choose appropriate technological tools that can help visualize, simulate, or provide enhanced versions of these strategies in ways that in real terms could not be achieved through mere chalk-and-talk (Irawan, 2022).

By following this sequence, teachers provide students with less and less structure as lessons unfold. Thus, for example, a natural cycles lesson might begin with teacher-defining content and teacher-driven presentation of visual media; this could develop into interactive simulation, with students changing and adjusting variables to see what happens, concluding with observations from group discussion where students communicate what was found (Anwar et al., 2024; Usman et al., 2024). Each phase demands active student participation and critical thinking about what they have witnessed. TPACK thrives in such a staggered design because this is what translates into meaningful learning (Rofiqoh et al., 2024).

The evidence presented in the research by Hayati (2022) shows convincingly the differential impact of the careful application of TPACK steps on science achievements. Her study demonstrated that students exposed to tutoring based on TPACK design had a greater increase in their test scores than those taught by conventional lectures. When students become active with the activities, they retain what they learn because they make connections between new knowledge and real-life experiences and test out their ideas through digital tasking.

The other interesting thing about TPACK is that it changes technology's role from an add-on into one of an integrated learning support. Rather than just putting on video for a reason, teachers incorporate media in every stage of learning. The teacher, for instance, starts the lesson with the animation to introduce a concept, midway, a digital quiz to test understanding, and, at the end, an online reflection activity. This kind of integration keeps the students active and offers them several options on how to make sense of the science concepts (Mustika et al., 2023).

The blessing of TPACK lies in promoting such scientific skills as analysis and experimentation, according to Ilmi et al. (2020) and Sonsupap et al. (2024). In virtual labs and simulations, students can test predictions without being limited by the unavailability of physical resources. They can run experiments repeatedly to observe patterns and share their findings, which will augment their understanding and build confidence in explaining their ideas (Hong et al., 2025; Li et al., 2024).

TPACK steps comprise assessment planning during every phase of the lesson, not only at the conclusion. Teachers observe the responses of the students to digital tasks, group discussions, and individual reflections. Such continuous feedback strengthens teachers' potential to modify their instructions spontaneously, ensuring that students remain engaged and difficulties are addressed early (Widaningsih et al., 2023).

Another reason that contributes to TPACK's success is the adaptability to the individual needs of the students, one of the most students not always learning at the same speed. With digital tools, teachers are able to extend the practice to those students who need extra practice and to expand tasks for students who are ready to dive deeper (McLay & Reyes, 2024; Witarsa & Siregar, 2023). Every student still remains active using homework personalization which saves students from getting bored, frustrated, or withdrawn in class.

Well-designed TPACK must create ties between what takes place in the global classroom with local actualities. For example, students studying weather can compare online weather data with the local observations. Such activities make science relevant and meaningful to the students, thus, ensuring motivation for maximum involvement in the tasks (Mustika et al., 2023).

TPACK will only work depending on the teachers' comprehension of each step of design, as well as their confidence in the chosen tools. In the absence of alignment, technology would end up being used superficially and is less likely to support learning goals. As indicated by Muzaini (2023) practical training for the teachers in planning lessons that could combine content, method, and media is important.

Another problem within the teaching profession is the lackadaisical attitude of digital infrastructure. A teacher may have a good plan, but if there is no device, internet, or technical support, implementation will shortchange students or learners. Therefore, schools need to invest in good resources, as well as give teachers time and space to learn how to use technology meaningfully.

Despite all this, this study maintains that when teacher plans lesson using the full TPACK cycle, students learn. They detect, investigate, inquire, and conclude scientific ideas rather than passively listening. Such active processes equip learners with content knowledge as well as scientific skills such as critical thinking and problem solving (Batool et al., 2025; Chai et al., 2020).

The empirical findings of TPACK on learning results reveal that design is equally important as content. Just obtaining digital facilities is not enough; teachers should decide what instruments match the lesson's goal and how they involve students for efficient interaction with science concepts.

TPACK practically answers the question of science education shifting towards the improvement of 21st-century skills. Given that it contains a balance of content mastery with pedagogical strategy and technology that supports both, the lessons are often those that can easily be infused with the possibility of creating deeper questions, testing of different ideas, and connecting knowledge with lives.

In the conclusion, the successful improvement of TPACK in learning activity and science achievement is step by step according to the design process. Schools need to keep running such teacher-oriented trainings and adequate resources to convert more science lessons from passive information delivery into active exploration and meaningful understanding.

Conclusion

This study concludes that the integration of content, pedagogy, and technology through the TPACK framework effectively addresses low learning activity and weak science achievement among primary school students, as evidenced by increased engagement and improved performance during the intervention. The findings indicate that structured TPACK-based instructional design enables teachers to create more active, inquiry-oriented lessons that connect scientific concepts with students' real-life experiences, offering practical implications for classroom practice. However, this study is limited by its small sample size, short implementation period, single-school cluster, and the absence of long-term learning measures, which restrict the generalizability of the results. Future research should examine the model in broader school contexts, incorporate longitudinal assessments, and explore modified or hybrid TPACK approaches to strengthen its applicability across diverse learning environments.

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Author Contributions

All authors were actively involved in the preparation of this article. Each contributed meaningfully to tasks such as data gathering, analysis, and writing specific sections of the manuscript. Throughout the process, every author shared original ideas, constructive feedback, and additional refinements that strengthened the overall content. Their combined efforts ensured the production of a thorough and well-developed article.

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Conflicts of Interest

The authors declare no conflict of interest.

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