

# Improving Students' Mathematical Understanding and Problem-Solving Performance through the Integration of Quantum Learning and Interactive Digital Assessment

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## ABSTRACT

**Background:** Difficulties in developing mathematical conceptual understanding and problem-solving ability persist in secondary education, indicating the need for learning approaches that actively engage students and make use of digital assessment support.

**Aims:** This study sought to investigate how the integration of Quantum Learning with interactive digital assessment influences students' mathematical conceptual understanding and problem-solving performance, both as separate outcomes and in combination.

**Methods:** The study adopted a quantitative quasi-experimental design involving 190 tenth-grade students selected through cluster random sampling. Two experimental groups and one control group were formed. Quantum Learning was applied in the experimental classes, with one group receiving additional support through interactive digital assessment, while the control class followed conventional instruction. Data were obtained through validated essay tests and analyzed using MANOVA after the assumptions of normality and homogeneity were fulfilled.

**Result:** The analysis revealed meaningful differences in both conceptual understanding and problem-solving performance between students in the experimental and control groups. Learners exposed to Quantum Learning supported by interactive digital assessment demonstrated higher achievement levels than those taught using conventional methods. Multivariate testing confirmed a statistically significant simultaneous effect of the instructional model on both learning outcomes.

**Conclusion:** Integrating Quantum Learning with interactive digital assessment contributes to stronger mathematical understanding and more effective problem-solving performance. This approach supports active participation and meaningful learning processes, suggesting its potential value for contemporary mathematics instruction.

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## Introduction

Mathematics education is widely acknowledged as a foundation for developing analytical thinking and structured reasoning (Kollosche, 2021; Wang et al., 2025). Through mathematics, students learn to interpret information, identify relationships, and draw logical conclusions. Conceptual understanding plays a central role in enabling students to grasp mathematical meaning beyond procedural execution (Stovner & Klette, 2022). When students understand concepts deeply, they are better prepared to apply knowledge flexibly across different contexts. However, conceptual understanding is often overshadowed by an emphasis on procedural accuracy. Classroom instruction frequently prioritizes speed and correctness over reasoning and explanation. This imbalance limits students' opportunities to construct meaning independently. As a result, mathematical knowledge is often retained only at a surface level.

Alongside conceptual understanding, problem-solving ability represents a crucial outcome of mathematics learning (Chen, 2025; Sinaga et al., 2023). Problem solving requires students to integrate concepts, select appropriate strategies, and evaluate solutions critically. These skills are essential for navigating both academic tasks and real-life situations. Despite its importance, many students struggle when confronted with unfamiliar or complex mathematical problems (Hodgson & Wilkie, 2022). Such struggles often arise because students lack a solid conceptual foundation. Without conceptual clarity,

problem-solving becomes a trial-and-error process rather than a reasoned activity. Students may memorize formulas without understanding their underlying principles. This condition reduces confidence and limits long-term learning development.

One persistent challenge in mathematics education is the dominance of teacher centered instructional practices (Emanet & Kezer, 2021; Zhang & Star, 2025). In such environments, knowledge is transmitted rather than constructed. Students are expected to follow procedures demonstrated by the teacher with minimal exploration. This approach restricts opportunities for discussion, questioning, and reflection. When students are not actively involved, their engagement tends to decrease (Doolittle et al., 2023; O'Connor, 2022). Low engagement further weakens motivation and interest in mathematics. Over time, passive learning habits become normalized. These conditions contribute to ongoing difficulties in both conceptual understanding and problem-solving performance.

The increasing integration of digital technology in education has introduced new possibilities for improving learning experiences (Alenezi, 2021; Valverde-Berrocoso et al., 2021). Digital tools can present mathematical ideas through interactive visuals, instant feedback, and adaptive tasks. These features offer potential support for diverse learning needs. However, technology does not automatically lead to better learning outcomes (Liu & Yu, 2023; Major et al., 2021). When digital tools are used without pedagogical alignment, their impact remains limited. In many cases, technology simply replicates traditional instruction in digital form. This substitution does little to enhance understanding or engagement. Therefore, technology must be meaningfully integrated within instructional design.

Active learning approaches have emerged as promising alternatives to traditional mathematics instruction (Doolittle et al., 2023; Lugosi & Uribe, 2022). These approaches emphasize student participation, collaboration, and experiential learning. By involving students actively, learning becomes more meaningful and durable. Quantum Learning is one model that focuses on creating a positive and supportive learning environment (Khozaei et al., 2022). It integrates cognitive processes with emotional and social engagement. Students are encouraged to explore ideas, express understanding, and reflect on learning experiences. Such conditions support deeper conceptual development. Consequently, Quantum Learning is considered relevant for addressing persistent learning challenges in mathematics.

Assessment practices also influence how students learn mathematics (Boström & Palm, 2023; Granberg et al., 2021). Conventional assessments often emphasize final answers rather than learning processes. This focus provides limited insight into students' conceptual development. Interactive digital assessment offers an alternative by embedding evaluation within learning activities (All et al., 2021; Barana, 2021). Through immediate feedback, students can recognize errors and refine understanding. Digital assessment can also motivate students through interactive formats. When assessment supports learning, it becomes a tool for growth rather than judgment. Integrating assessment with instruction is therefore increasingly important. This shift reflects a broader movement toward formative and learner-centered evaluation.

Despite growing interest in active learning and digital assessment, research examining their integration remains limited (Abildaeva et al., 2022; R. Li et al., 2023). Many studies investigate instructional models independently of assessment strategies. Others focus on digital tools without considering pedagogical foundations. This separation restricts understanding of how instructional elements interact. Moreover, existing research often concentrates on single learning outcomes (X. Li et al., 2022). Conceptual understanding and problem-solving ability are rarely examined together. This narrow focus overlooks the interconnected nature of mathematical competencies. Consequently, comprehensive evidence supporting integrated instructional approaches is still insufficient.

In the context of contemporary education, addressing these gaps has become increasingly urgent (Chand, 2024; Rycroft-Smith, 2022). Students are expected to develop flexible thinking, problem-solving skills, and conceptual clarity. Teachers require instructional strategies that align with both pedagogical principles and technological developments. Investigating integrated approaches offers practical insights for improving classroom practice. Such research can guide educators in designing meaningful

mathematics instruction (Koskinen & Pitkäniemi, 2022; Polman et al., 2021). It also contributes to theoretical discussions on effective learning environments. Given persistent learning challenges, further empirical evidence is needed. Therefore, this study is necessary to support the advancement of mathematics education in a digital era.

Mathematical conceptual understanding is widely recognized as a critical foundation for effective learning because it allows students to interpret ideas and apply knowledge flexibly. Recent studies indicate that digital tools can strengthen conceptual learning when they promote active engagement rather than passive reception. Fathi et al. (2025) showed that digital tools enhance geometric concept understanding by supporting multiple forms of representation. Similarly, Kritikos et al. (2025) emphasized that learner created digital representations encourage deeper meaning construction in educational contexts. Problem solving ability has been identified as closely interconnected with conceptual understanding and reflective reasoning. Thuy et al. (2025) demonstrated that AI-supported formative assessment fosters reflective problem-solving strategies in mathematics education. The role of assessment integration was further highlighted by Castañeda et al. (2025), who found that technology-enhanced assessment improves instructional effectiveness when aligned with pedagogy. Broader investigations into digital systems and evaluation frameworks also contribute relevant insights. examined digital evaluation in higher education, while Erol et al. (2025) and (Bakioglu, 2025) discussed structured digital transitions in complex systems. Studies by Korchenko et al. (2025), Zhang et al. (2025), and Dong et al. (2025) further illustrate the value of integrated analytical approaches. Despite these advances, research that simultaneously integrates active pedagogy, digital assessment, and multiple cognitive outcomes such as conceptual understanding and problem-solving remains limited, underscoring the need for further investigation.

Persistent difficulties in developing students' mathematical conceptual understanding and problem-solving ability indicate that instructional improvement remains necessary. Many learning environments still treat pedagogy and assessment as separate components, which limits their combined instructional impact. Active learning models are known to encourage engagement and deeper understanding, yet their effectiveness may be reduced when assessment does not actively support learning processes. At the same time, digital assessment tools are often implemented only as measurement instruments rather than as integral parts of instruction. This separation prevents assessment from functioning as a mechanism for guiding and reinforcing learning. An instructional approach that integrates pedagogy and assessment is therefore required to support meaningful mathematics learning. Quantum Learning offers a pedagogical framework that emphasizes engagement, interaction, and reflection. When supported by interactive digital assessment, this approach has the potential to strengthen both conceptual understanding and problem-solving performance.

Although various instructional innovations and digital tools have been introduced in mathematics education, their application often remains fragmented. Instructional approaches frequently emphasize active learning without systematic assessment support that guides students' conceptual development and problem-solving processes. Conversely, digital assessment is commonly used independently of instructional models, focusing primarily on evaluation rather than learning enhancement. In addition, conceptual understanding and problem-solving ability are often examined as separate learning outcomes, despite their close interrelationship. Instructional designs that intentionally address both competencies within a single learning framework are still limited. Empirical investigations that analyze the simultaneous effects of integrated pedagogy and assessment on multiple cognitive outcomes are also relatively scarce. This condition creates a pedagogical and methodological gap in understanding how integrated instructional approaches influence students' overall mathematical competence.

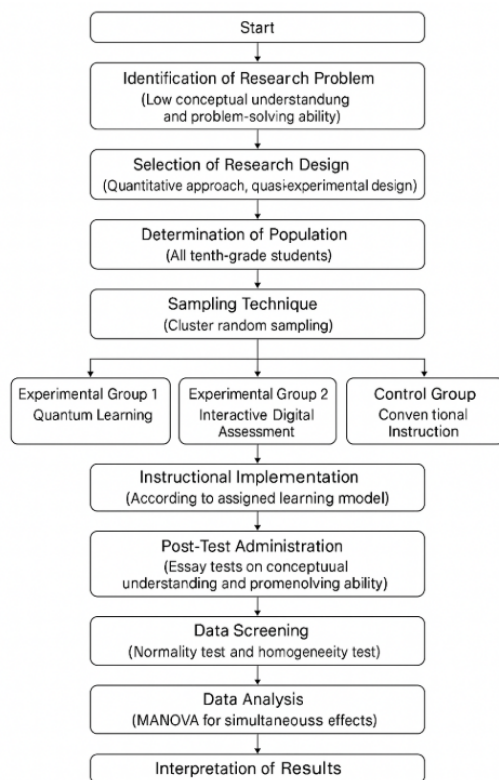
The purpose of this study is to examine the effectiveness of integrating Quantum Learning with interactive digital assessment in mathematics instruction. Specifically, the study aims to investigate the influence of the integrated approach on students' mathematical conceptual understanding and problem-solving performance, both individually and simultaneously. Through a quasi-experimental design, the

study seeks to determine whether the integrated instructional model produces learning outcomes superior to conventional instruction. Based on this purpose, the study is guided by the hypothesis that students who experience mathematics learning through Quantum Learning supported by interactive digital assessment demonstrate higher levels of conceptual understanding and problem-solving performance than students who receive conventional instruction.

## Method

### Research Design

This study adopted a quantitative approach using a quasi-experimental design to examine the effectiveness of an instructional intervention in a natural classroom setting. The design involved three intact groups consisting of two experimental groups and one control group, as individual randomization was not feasible. The experimental groups implemented Quantum Learning, with one group supported by interactive digital assessment, while the control group received conventional instruction. A post-test-only control group design was applied to focus on outcome differences attributable to the instructional treatments. To clarify the overall sequence of the research process, a procedural flowchart is provided in Figure 1.



**Figure 1.** Flowchart of the Research Procedure

### Participant

The participants consisted of 190 tenth-grade students selected through cluster random sampling. Intact classes were randomly assigned to two experimental groups and one control group to preserve instructional authenticity. One experimental group implemented Quantum Learning, the second experimental group applied Quantum Learning supported by interactive digital assessment, and the control group received conventional instruction.

### Instrument

Data were collected using essay-based mathematics tests designed to assess conceptual understanding and problem-solving performance. The instruments measured students' ability to explain concepts, apply strategies, and evaluate solutions. Prior to implementation, the instruments were reviewed by experts to ensure content validity and clarity.

## Data Analysis

Data analysis was conducted using statistical software to ensure analytical accuracy. Prior to hypothesis testing, assumption checks were performed, including tests of normality and homogeneity of variance. After the assumptions were satisfied, multivariate analysis of variance was employed to examine the simultaneous effects of the instructional model on students' conceptual understanding and problem-solving performance. The level of statistical significance was set at 0.05 to determine the presence of meaningful differences among groups.

## Results and Discussion

### Results

This section reports the outcomes of the study derived from descriptive statistical analysis and multivariate testing. The findings are organized based on the two measured learning outcomes, mathematical conceptual understanding and mathematical problem solving performance, and are compared across the three instructional conditions.

#### Mathematical Conceptual Understanding

Students' conceptual understanding was evaluated through a post intervention test administered after the completion of the instructional treatments. A summary of the descriptive statistics is presented in Table 1.

**Table 1.** Descriptive Statistics of Post-Test Scores for Mathematical Conceptual Understanding

<b>Instructional Group</b>	<b>Minimum</b>	<b>Maximum</b>	<b>Mean</b>	<b>Standard Deviation</b>
Quantum Learning	62	94	80.00	9.06
Quantum Learning + Quizizz	69	98	81.25	7.21
Conventional Instruction	31	75	52.70	10.33

As shown in Table 1, notable differences in conceptual understanding were observed among the instructional groups. Learners who experienced Quantum Learning supported by Quizizz attained the highest average performance, followed closely by those who participated in Quantum Learning without digital support. In contrast, students exposed to conventional instruction demonstrated markedly lower conceptual understanding. The relatively smaller standard deviation in the experimental groups indicates more consistent achievement compared to the control group.

#### Mathematical Problem-Solving Performance

Students' problem-solving ability was measured using a post-test focusing on analytical reasoning and solution execution. The descriptive statistics for this outcome are summarized in Table 2.

**Table 2.** Descriptive Statistics of Post-Test Scores for Mathematical Problem-Solving Performance

<b>Instructional Group</b>	<b>Minimum</b>	<b>Maximum</b>	<b>Mean</b>	<b>Standard Deviation</b>
Quantum Learning	65	98	84.83	9.04
Quantum Learning + Quizizz	70	98	81.33	6.72
Conventional Instruction	35	80	53.16	10.39

Table 2 indicates that students in both experimental conditions achieved higher problem-solving scores than those in the control group. The strongest performance was observed among students who learned through Quantum Learning, while those taught using Quantum Learning supported by Quizizz also demonstrated strong outcomes. Conversely, students receiving conventional instruction exhibited

the lowest level of problem-solving performance. These findings suggest that instructional approaches emphasizing active engagement contribute meaningfully to students' problem-solving development.

### **Assumption Testing**

Prior to conducting inferential analysis, the data were examined to ensure that the assumptions required for multivariate analysis were satisfied. Tests of normality confirmed that the score distributions for both outcome variables were within acceptable limits. In addition, homogeneity testing indicated that variance across groups was sufficiently equivalent. These results confirm that the dataset was appropriate for subsequent multivariate procedures.

### **Multivariate Analysis**

To investigate the combined effect of instructional approach on conceptual understanding and problem-solving performance, a multivariate analysis of variance was conducted. The analysis revealed a statistically significant multivariate effect, indicating that differences among instructional groups were present when both learning outcomes were considered simultaneously. Follow-up univariate analyses further demonstrated that the instructional model exerted a significant influence on each outcome independently. These results reinforce the descriptive patterns observed in Tables 1 and 2 and confirm the effectiveness of the applied instructional approaches.

### **Discussion**

The results of this study indicate that learning environments combining active pedagogy and digital support foster stronger mathematical conceptual understanding. Students exposed to such environments demonstrated clearer conceptual representations and more stable comprehension patterns. This finding resonates with the study by Kritikos, Moutsios Rentzos, and Panytsidou (2021), who emphasized the role of learner-generated representations in strengthening conceptual interpretation. In both studies, learning was framed as an active meaning-making process. The present findings suggest that conceptual understanding improves when students engage cognitively and reflectively with learning materials. Digital support served as a medium that reinforced conceptual coherence. Rather than replacing instruction, technology enhanced conceptual engagement. These findings underline the importance of designing learning experiences that prioritize conceptual construction.

The contribution of digital tools to conceptual learning is further reinforced by Fathi, Moundy, Nfissi, Aimara, and Benabid (2022). Their work demonstrated that technology-enhanced environments support abstraction and visualization in mathematical learning. Similar patterns were observed in the current study, where digital assessment complemented instructional strategies. Students demonstrated greater consistency in conceptual reasoning across tasks. This suggests that digital tools can function as cognitive supports when aligned with pedagogy. The effectiveness of these tools depended on how they were embedded within instruction. When used strategically, technology supported deeper conceptual engagement. This reinforces the necessity of pedagogically driven technology integration.

Problem solving performance also benefited from active and digitally supported instruction. Students in the experimental groups demonstrated stronger strategic reasoning compared to those receiving conventional instruction. These findings align with Thuy, et al (2023), who highlighted the role of formative digital assessment in promoting reflective problem solving. Although artificial intelligence was not explicitly implemented in this study, the feedback mechanisms played a similar formative role. Students were able to revise strategies based on immediate feedback. This process encouraged analytical reasoning rather than mechanical solution attempts. Problem-solving tasks became learning opportunities. Such conditions support the development of higher-order mathematical reasoning.

Differences between conceptual understanding and problem-solving outcomes suggest that these competencies, while related, are influenced by distinct instructional elements. Digital assessment showed a stronger contribution to conceptual clarity than to problem-solving performance. This observation is consistent with Castañeda, et al (2021), who emphasized that technology-enhanced learning must be balanced with instructional interaction. In the present study, classroom discussion and guided

exploration played a crucial role in problem-solving development. Technology alone was insufficient to sustain strategic reasoning. Effective instruction required pedagogical mediation. This highlights the importance of maintaining balance between technological tools and instructional practices. Instructional synergy remains essential for complex skill development.

The weaker performance of students receiving conventional instruction underscores limitations of traditional teaching approaches. Students in this group demonstrated lower conceptual coherence and less effective problem-solving strategies. This pattern parallels findings reported, who identified challenges in learners' competencies under limited digital exposure. Conventional instruction often restricted opportunities for feedback and engagement. As a result, students struggled to develop robust understanding. The absence of interactive elements constrained learning depth. These findings suggest that traditional instructional models may not meet current learning demands. Educational practices must adapt to contemporary contexts. Digital integration emerges as a necessary instructional shift.

The simultaneous effect observed across learning outcomes highlights the integrated nature of instructional influences. This finding aligns with perspectives presented by Erol, et al (2023), who emphasized the effectiveness of integrated systems in addressing complex challenges. Although their work focused on technological systems beyond education, the underlying principle remains applicable. In the present study, pedagogy and assessment functioned as interconnected components. Improvements in instructional design influenced multiple learning outcomes concurrently. This interconnectedness explains the observed multivariate effects. Instructional integration enhances overall learning effectiveness. Such findings support holistic instructional design approaches.

From a broader standpoint, the study contributes to discussions on sustainable digital transition in education. Bakioglu (2023) highlighted that digital transition supports sustainability when implemented systematically. Similarly, the present findings suggest that digital assessment promotes sustainable learning by encouraging continuous engagement and reflection. Students benefited from ongoing feedback rather than isolated evaluation. Such practices support long-term learning development. Digital tools facilitated adaptive learning processes. This aligns with principles of sustainable education. Instructional sustainability depends on continuous improvement mechanisms. Digital assessment plays a key role in this process.

The importance of reliable digital systems is further reflected in research on digital infrastructure. Korchenko, et al (2022) emphasized that dependable systems are essential for effective digital operations. In educational settings, similar reliability is required to support learning processes. Stable digital assessment tools ensure consistency and trust. When systems function reliably, students can focus on cognitive engagement. Technical disruptions can undermine learning experiences. Thus, digital reliability is foundational for effective instruction. The present study indirectly reinforces this requirement. Infrastructure quality remains a critical consideration in digital education.

The findings also echo research emphasizing precision through data-driven approaches. Zhang, et al (2021) demonstrated how integrated data systems enhance accuracy in complex analyses. Analogously, digital assessment allows educators to monitor learning progress with greater precision. Teachers gain clearer insights into student understanding. This supports targeted instructional adjustments. Learning becomes more responsive to individual needs. The present study illustrates how assessment data inform instructional effectiveness. Precision in assessment contributes to improved decision-making. Such practices strengthen instructional quality.

Finally, the study aligns with methodological discussions on evaluating complex systems. Dong, et al (2022) emphasized the need for rigorous evaluation frameworks. Similarly, this study employed robust statistical methods to examine instructional effects. The use of multivariate analysis allowed for comprehensive outcome evaluation. This methodological approach strengthened the validity of the findings. Integrating multiple outcomes provided a holistic perspective on instructional effectiveness. The discussion synthesizes empirical results with contemporary digital research. Together, these insights

advance understanding of integrated learning environments. The study offers meaningful contributions to mathematics education research.

### **Implications**

The outcomes of this study provide meaningful implications for mathematics teaching in digitally evolving learning environments. The evidence suggests that learning designs combining active instructional approaches with digital assessment can foster deeper conceptual understanding and stronger problem-solving abilities. Mathematics teachers may benefit from shifting instructional emphasis toward learner engagement, reflection, and interaction rather than procedural repetition. The integration of digital assessment enables continuous feedback that supports students' learning regulation and conceptual refinement. These findings also imply that assessment should be viewed as an integral component of instruction rather than a separate evaluative stage. For curriculum planners, the results highlight the importance of coherence between instructional strategies, learning objectives, and assessment practices. Educational institutions may consider supporting instructional innovation through targeted professional development. Overall, the study underscores the role of pedagogically grounded digital integration in enhancing the quality of mathematics education.

### **Limitations**

Several limitations should be considered when interpreting the findings of this study. The research was conducted within a single instructional context, which may limit the extent to which the results can be generalized to broader educational settings. Although the sample size met analytical requirements, it may not fully represent variations in student backgrounds and learning characteristics. The study examined learning outcomes within a limited instructional period, which restricts conclusions regarding long-term learning retention or transfer. Additionally, the quasi-experimental design did not allow for full randomization of participants. External factors such as students' prior experiences with digital tools may also have influenced the results. The digital assessment component was limited to one platform, which constrains comparative interpretation across technologies. These factors indicate that the findings should be interpreted within the scope of the study design.

### **Suggestions**

In light of the findings and identified limitations, several directions for future research and practice are suggested. Future investigations may involve broader participant groups across different educational contexts to enhance external validity. Longitudinal studies could be conducted to explore the sustainability of learning gains over time. Researchers are also encouraged to examine alternative or emerging digital assessment tools to compare their instructional impact. From a practical standpoint, teachers may experiment with varied forms of digital feedback while maintaining strong pedagogical guidance. Institutional support in the form of infrastructure and training may further enhance effective implementation. Future studies might also explore additional learning dimensions, such as students' motivation or self-regulated learning. These recommendations aim to support the continued development of effective and responsive mathematics instruction.

### **Conclusion**

The results of this study confirm that mathematics instruction grounded in active learning and supported by digital assessment can substantially improve students' learning outcomes. Learners who participated in Quantum Learning-based instruction demonstrated stronger conceptual understanding and more effective problem-solving performance than those taught through conventional methods. These findings indicate that meaningful engagement and continuous feedback are key drivers of successful mathematical learning. The study also reveals that conceptual understanding and problem-solving skills, while closely related, respond differently to instructional design. Digital assessment was shown to be particularly effective in strengthening conceptual clarity, whereas instructional interaction played a more prominent role in problem-solving development. The multivariate findings further suggest that instructional approaches influence multiple learning outcomes in an integrated manner. Overall, the

study highlights the necessity of aligning pedagogy, assessment, and digital tools within mathematics instruction. By providing empirical evidence from an integrated instructional framework, this research contributes to the advancement of effective and sustainable practices in contemporary mathematics education.

### Author Contributions Statement

Anelia Kusuma Ningrum contributed to the conception and design of the study, data collection, data analysis, and the initial drafting of the manuscript.

Netriwati provided academic supervision, contributed to the research framework, validated the research instruments, and critically reviewed the manuscript for intellectual content.

Siska Andriani assisted in data interpretation, statistical analysis, and manuscript revision, particularly in refining the results and discussion sections. All authors participated in revising the manuscript, approved the final version for publication, and agreed to be accountable for all aspects of the work.

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