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RESEARCH ARTICLE

The effectiveness of differentiated learning-based digital worksheets in enhancing vocational high school students' mathematical literacy

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ABSTRACT

Background: Mathematical literacy is essential for real-world problem-solving, yet vocational students often demonstrate low competence due to teacher-centered instruction and uniform worksheets that fail to accommodate diverse readiness.
Purpose: This study examined the effectiveness of differentiated learning-based digital worksheets in enhancing vocational students' mathematical literacy. The novelty lies in integrating differentiated pedagogy with adaptive digital worksheets tailored to automotive vocational contexts, providing personalized learning pathways across formulate, employ, and interpret competencies.
Method: This quantitative field study employed a one-group pretest–posttest design. Random sampling was used to select 32 Grade XI students from the Automotive Engineering program at SMKN 1 Kendal Ngawi, Indonesia. Data were collected using a three-item contextual mathematical literacy test representing the formulate, employ, and interpret competencies of the OECD framework. The instrument was validated by experts for content, construct, and language validity before administration. Data were analyzed using descriptive statistics, the Shapiro–Wilk test, Wilcoxon Signed-Rank Test, effect size, and a one-sample proportion test.
Findings: Students' mean mathematical literacy score increased from 50.1 to 80.0, while classical mastery reached 88%. The Wilcoxon test indicated a significant difference ($p < 0.001$), with a large effect size ($r = 0.87$). Formulate showed the highest achievement (88.64%), followed by employ (82.10%), while interpret was the lowest (65.23%).
Implication: These findings suggest the potential of differentiated digital worksheets to support vocational students' mathematical literacy through adaptive and contextual learning experiences. Because the study lacked a control group, the findings should be interpreted cautiously.

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INTRODUCTION

Mathematical literacy is a multidimensional competency that involves using mathematical knowledge and reasoning to address problems arising in real-world contexts. In the OECD framework, mathematical literacy refers to an individual's capacity to reason mathematically and to formulate, employ, and interpret mathematics to solve problems in a variety of contexts (OECD, 2022). Formulate involves identifying and structuring the mathematical aspects of a contextual situation; employ involves applying mathematical concepts, procedures, facts, and tools to obtain a mathematical solution; and interpret involves evaluating mathematical results and relating them back to the original context. Thus, mathematical literacy extends beyond performing routine calculations because it requires students to connect mathematical representations with contextual situations, reason about quantitative information, and judge the meaning and reasonableness of solutions. These competencies are particularly important in vocational education, where students are expected to apply mathematics to workplace situations involving measurement, data interpretation, estimation, and problem-solving. Consequently, mathematics instruction in vocational high schools should emphasize contextual understanding and authentic applications that reflect industrial practices rather than procedural knowledge alone (OECD, 2022; Rejeki et al., 2023; Sumandya & Widana, 2022).

Recent educational research has increasingly highlighted the integration of digital technology into mathematics instruction to improve higher-order thinking skills and mathematical literacy. Digital learning environments provide interactive representations, multimedia resources, immediate feedback, and flexible learning pathways that enhance students' conceptual understanding and engagement (Juliana et al., 2024; Reinhold et al., 2020). Simultaneously, differentiated learning has gained considerable attention as an instructional approach that accommodates learners' diverse readiness levels, interests, and learning profiles by adapting instructional content, learning processes, and expected products (Bi et al., 2023; Pozas et al., 2021). The convergence of educational technology and differentiated instruction offers promising opportunities for creating more personalized mathematics learning environments capable of supporting students with heterogeneous characteristics.

Differentiated learning and digital worksheets can be understood as complementary components of adaptive mathematics instruction. Differentiated learning provides the pedagogical framework for responding to differences in students' readiness, interests, and learning profiles by adjusting content, learning processes, and expected products (Bi et al., 2023; Pozas et al., 2021; Tomlinson, 2001). Digital worksheets provide a technology-mediated environment through which such differentiation can be implemented using adaptive learning pathways, multimedia representations, scaffolded tasks, and immediate feedback (Juliana et al., 2024; Reinhold et al., 2020). These features can help students engage with mathematical modelling, reasoning, and contextual problem-solving at an appropriate level of challenge, thereby supporting the development of the formulate, employ, and interpret competencies described in the OECD framework (OECD, 2022). From a social cognitive perspective, timely feedback and scaffolded success experiences may also strengthen students' confidence in solving mathematical problems because mastery experiences are an important source of self-efficacy (Bandura, 1997).

Despite these developments, a considerable gap remains between the expected outcomes of mathematics education and classroom realities, particularly in Indonesian vocational schools. Although vocational curricula emphasize contextual problem-solving and mathematical literacy, classroom instruction frequently remains teacher-centered and relies on uniform printed worksheets that provide identical learning activities for all students regardless of their differences in academic readiness or learning preferences. Such practices limit students' opportunities to develop mathematical reasoning through authentic and differentiated learning experiences.

This gap was confirmed through preliminary research conducted at SMKN 1 Kendal Ngawi. Classroom observations and interviews with mathematics teachers revealed that mathematics instruction remained predominantly teacher-centered and relied on one-size-fits-all worksheets that did not accommodate students' diverse learning readiness. Observation data showed that approximately 86% of Grade XI Automotive Engineering students experienced difficulties in formulating, employing, and interpreting mathematical solutions in authentic vocational contexts, while teachers emphasized the need for adaptive digital instructional materials capable of accommodating students' diverse learning readiness. These findings demonstrate a practical need for instructional media capable of facilitating differentiated mathematics learning in vocational classrooms and provide a clear rationale for the present study.

Considering these conditions, integrating differentiated learning into digital worksheets appears to be a promising instructional solution. Differentiated learning enables teachers to adjust instructional content, learning processes, and assessment products according to students' readiness, interests, and learning profiles (Tomlinson, 2001). When implemented through digital worksheets, these principles can be operationalized more efficiently by providing adaptive learning pathways, multimedia explanations, scaffolded activities, contextual problems, and immediate feedback. Such features allow students to learn at an appropriate level of challenge while maintaining active engagement throughout the learning process. From the perspective of social cognitive theory, immediate feedback and scaffolded success experiences also contribute to students' confidence in solving mathematical problems because mastery experiences represent the strongest source of academic self-efficacy (Bandura, 1997).

Recent studies consistently demonstrate that both digital worksheets and differentiated instruction contribute positively to mathematics learning, although they have generally been investigated independently. Digital worksheets have been shown to improve students' conceptual understanding, engagement, and mathematical literacy by integrating multimedia resources and contextual learning activities (Amaliya et al., 2024; Dewi et al., 2022). Likewise, differentiated instruction has consistently been associated with improvements in mathematical problem-solving, computational thinking, and classroom participation because it accommodates learners' diverse readiness levels and learning profiles (Bi et al., 2023; Pozas et al., 2021; Putranto et al., 2024). However, these studies differ substantially in terms of instructional design, participant characteristics, and outcome measures. While studies on digital worksheets primarily focused on improving conceptual understanding and engagement through technology-enhanced learning, studies on differentiated instruction emphasized accommodating learner diversity to improve problem-solving and computational thinking. Consequently, existing evidence remains fragmented because the pedagogical benefits of differentiated learning and the technological affordances of digital worksheets have rarely been investigated simultaneously within a single instructional intervention. Most investigations evaluated either digital worksheets or differentiated instruction separately, whereas only limited studies have explored their integrated implementation in vocational mathematics classrooms. In addition, most previous studies were conducted in general secondary education, whereas empirical evidence from vocational mathematics classrooms remains relatively scarce despite their distinct instructional characteristics and diverse student readiness levels. Furthermore, previous studies primarily examined conceptual understanding or academic achievement, with relatively little attention devoted to mathematical literacy based on the OECD framework. These methodological and contextual limitations indicate the need for further empirical evidence regarding the effectiveness of differentiated learning-based digital worksheets in improving vocational high school students' mathematical literacy (Juliana et al., 2024; Qalfin et al., 2024).

Taken together, the literature indicates three unresolved issues. First, evidence on digital worksheets and differentiated instruction remains fragmented because the two approaches have generally been examined separately. Second, empirical evidence on their integrated implementation in vocational mathematics classrooms is still limited, particularly in settings characterized by heterogeneous student readiness. Third, relatively few studies have examined mathematical literacy explicitly through the OECD formulate, employ, and interpret framework within an adaptive digital learning environment. These gaps point to the need for empirical research that examines whether an integrated differentiated digital worksheet can effectively strengthen mathematical literacy in vocational mathematics education (Juliana et al., 2024; Qalfin et al., 2024).

The novelty of this study lies in the design and empirical evaluation of a differentiated learning-based digital worksheet specifically developed for matrix learning in vocational mathematics. The worksheet integrates adaptive learning pathways based on students' readiness levels with differentiated content, process, and product activities, contextual automotive-related mathematical problems, multimedia learning resources, scaffolded exercises, and real-time feedback within a single digital learning environment. This integrated design operationalizes differentiated instruction through a digital medium while directly targeting mathematical literacy in an authentic vocational context. The study therefore contributes empirical evidence on how an adaptive digital worksheet can simultaneously accommodate heterogeneous learner readiness and support the development of students' formulate, employ, and interpret competencies. By examining this integrated instructional design in a vocational mathematics classroom, the study also provides practical guidance for teachers seeking to implement differentiated learning through digital resources.

Based on these considerations, the objective of this study is to examine the effectiveness of differentiated learning-based digital worksheets in enhancing vocational high school students' mathematical literacy. The findings are expected to provide empirical evidence supporting the implementation of differentiated digital learning environments in vocational mathematics classrooms and contribute to the development of adaptive instructional media capable of accommodating diverse student characteristics while improving mathematics learning quality. The study also provides practical implications for mathematics teachers by demonstrating how differentiated learning principles can be operationalized through adaptive digital worksheets to support students with heterogeneous learning needs.

Accordingly, the research hypothesis formulated in this study is Students who learn using differentiated learning-based digital worksheets demonstrate significantly higher mathematical literacy after the implementation than before the intervention.

METHODS

This study employed a field research design using a quantitative approach to evaluate the effectiveness of a differentiated learning-based digital worksheet in improving vocational high school students' mathematical literacy. The research was empirical in nature because it investigated the effect of implementing the developed learning media on students' mathematical literacy through direct classroom intervention. A one-group pretest-posttest design was adopted to compare students' mathematical literacy before and after the implementation of the digital worksheet. This design was selected because the study aimed to conduct an initial evaluation of the instructional effectiveness of the developed digital worksheet under authentic classroom conditions, where random assignment to experimental and control groups was not feasible. Although the one-group pretest-posttest design enables the measurement of learning gains following the intervention, it does not completely control for potential threats to internal validity, such as maturation and testing effects. Therefore, the findings should be interpreted as preliminary evidence of effectiveness, and future studies employing quasi-experimental or randomized controlled designs are recommended to strengthen causal inference.

The study was conducted from April to May 2026 at SMKN 1 Kendal Ngawi, East Java, Indonesia, involving Grade XI students in the Automotive Engineering (Teknik Kendaraan Ringan/TKR) program. The participants consisted of 32 students from class XI TKR-2 who were selected through random sampling from the available Grade XI Automotive Engineering classes. Random selection was performed after confirming that all classes had comparable curriculum implementation, learning facilities, and student characteristics. The selected class represented heterogeneous levels of learning readiness, making it suitable for implementing differentiated learning.

The learning intervention utilized a differentiated learning-based digital worksheet developed for the matrix topic. Prior to instruction, students completed an initial readiness assessment that categorized them into three readiness levels: basic (score < 40), intermediate (score 40–79), and advanced (score ≥ 80). Based on these categories, the digital worksheet automatically directed students to differentiated learning pathways through variations in learning content, learning processes, and task complexity while maintaining identical learning objectives. Content differentiation was implemented by providing learning materials with tiered levels of conceptual complexity. Process differentiation was achieved through adaptive learning pathways, scaffolded guidance, multimedia explanations, and varying levels of instructional support according to students' readiness. Product differentiation required students to complete mathematical tasks with different degrees of complexity while maintaining identical learning objectives and mathematical literacy indicators across all readiness groups. The worksheet also integrated multimedia resources, contextual vocational problems related to automotive engineering, scaffolded exercises, and real-time feedback to support students throughout the learning process. The intervention was implemented across three consecutive 90-minute mathematics lessons following the lesson plans designed according to differentiated learning principles. During each lesson, students engaged in learning activities specifically tailored to their level, while the teacher monitored progress and provided adaptive scaffolding before students proceeded to subsequent tasks.

The primary research data consisted of students' mathematical literacy scores obtained from the pretest and posttest. The mathematical literacy instrument was constructed based on the OECD (2019, 2022) mathematical literacy theoretical framework, which defines mathematical literacy as an individual's capacity to formulate, employ, and interpret mathematics in solving real-world contextual problems. In this study, mathematical literacy was operationalized through three core competencies: (1) Formulate, which assesses students' ability to identify relevant information and transform real-world automotive workshop situations into mathematical matrix models; (2) Employ, which measures the application of mathematical concepts, matrix algebraic procedures (such as matrix transposition, addition, subtraction, and multiplication), and tools to solve contextual problems; and (3) Interpret, which evaluates students' ability to reflect upon, evaluate the reasonableness of mathematical results, and explain their practical implications within automotive operational contexts.

The instrument comprised three contextual essay questions, with each question consisting of three structured sub-items (a, b, and c) corresponding sequentially to the formulate, employ, and interpret indicators (yielding a total of 9 item-level assessment tasks across 3 multifaceted problems). All contextual scenarios were authentically contextualized around automotive engineering tasks, such as recording vehicle service intake, calculating operational workload, and determining workshop revenue. Before classroom implementation, the mathematical literacy test underwent content, construct, and language validation by two mathematics education experts and one educational assessment expert. The validation process evaluated the relevance, clarity, contextual appropriateness, and alignment of each item with the OECD mathematical literacy framework using a 5-point Likert scale.

The expert validation yielded an average score of 4.69 out of 5.00 for content/construct validity and 4.79 out of 5.00 for media/linguistic appropriateness, categorizing the instrument as "Very Valid" (Sangat Baik) and confirming that all items were methodologically sound for classroom implementation without substantive modification. The analytical scoring rubric (with maximum scores ranging from 2 to 4 points per sub-item and a total cumulative score of 30 converted to a scale of 0–100) was developed to ensure consistent and objective scoring across all student responses based on predefined mathematical literacy indicators. The analytical scoring rubric was developed to ensure consistent scoring across all student responses based on predefined mathematical literacy indicators.

Data were collected through classroom testing administered before and after the intervention. The pretest was conducted before students used the differentiated learning-based digital worksheet, whereas the posttest was administered after all learning activities had been completed. Student responses were scored using the validated analytical scoring rubric aligned with the OECD mathematical literacy indicators assessed in each test item.

The collected data were analyzed quantitatively using descriptive and inferential statistics. Descriptive analysis was conducted to determine the mean, standard deviation, minimum score, and maximum score of students' mathematical literacy before and after the intervention. Prior to hypothesis testing, the normality of the score distribution was examined using the Shapiro-Wilk test ($n = 32$). Because the pretest dataset violated the assumption of normality ($p = .000 < .05$), the Wilcoxon Signed-Rank Test was employed as the non-parametric alternative to the paired-samples t-test for evaluating pretest-to-posttest learning gains. A significance level of 0.05 was applied to determine whether the improvement in students' mathematical literacy after the intervention was statistically significant. To complement the hypothesis testing, the practical significance of the intervention was evaluated by calculating the effect size using the formula $r=|Z|/\sqrt{N}$. The effect size was interpreted according to Cohens (2013) criteria, where values of approximately 0.10, 0.30, and 0.50 indicate small, medium, and large effects, respectively. Furthermore, instructional effectiveness was examined using a one-sample proportion test to determine whether the proportion of students achieving the school's minimum mastery criterion significantly exceeded the predetermined benchmark of 70%. The statistical hypotheses were formulated as H0: $p \leq 0.70$ and H1: $p > 0.70$, where p represents the proportion of students achieving mastery. The null hypothesis was rejected when the significance value was less than 0.05.

In the Indonesian vocational education assessment framework and educational evaluation theory, an instructional intervention is deemed effective when the proportion of students reaching the minimum mastery criterion (*Kriteria Ketercapaian Tujuan Pembelajaran / KKTP ≥ 70*) significantly exceeds the standard institutional threshold of 70% (Akbar, 2013). The statistical hypotheses were formulated as H0: $p \leq 0.70$ and H1: $p > 0.70$, where p represents the proportion of students achieving mastery. The test statistic was calculated using the Z-proportion formula:

$$Z=\frac{x-np_0}{\sqrt{np_0(1-p_0)}}$$

Where x represents the number of students achieving mastery, n is the total sample ($n = 32$), and p_0 is the hypothesized benchmark proportion (0.70).

RESULT AND DISCUSSION

Improvement in Students' Mathematical Literacy

The effectiveness of the differentiated learning-based digital worksheet was evaluated by comparing students' mathematical literacy before and after the learning intervention. Table 1 summarizes the descriptive statistics of students' pretest and posttest performance.

Table 1 shows a clear improvement in students' mathematical literacy following the implementation of the differentiated learning-based digital worksheet. Overall, students achieved higher levels of mathematical literacy with reduced score variability, and the proportion of students attaining classical learning mastery exceeded the minimum criterion established by the school. Overall, the posttest scores and classical mastery results were higher than those obtained in the pretest.

Table 1.

Students' Mathematical Literacy Achievement Before and After the Intervention

Variable	Pretest	Posttest
Highest score	87	100
Lowest score	30	60
Mean score	50.1	80.0
Standar Deviation	17.51	10.18
Students achieving mastery	8	28
Classical mastery	25%	88%

Prior to hypothesis testing, the distribution of the pretest and posttest scores was examined using the Shapiro–Wilk normality test because the sample size was relatively small ($n = 32$). The normality test indicated that the score distribution did not satisfy the assumption of normality ($p < 0.05$). Therefore, a non-parametric statistical procedure was required for hypothesis testing.

Table 2.

Results of the Shapiro–Wilk Normality Test

Variable	Sig.	Decision
Pretest	0.000	Not normally distributed
Posttest	0.784	Normally distributed

The pretest scores were not normally distributed ($p = 0.000$), whereas the posttest scores followed a normal distribution ($p = 0.784$). Because one dataset violated the assumption of normality, a non-parametric Wilcoxon Signed-Rank Test was employed to test the research hypothesis.

The Wilcoxon Signed-Rank Test (table 3) yielded $Z = -4.939$ with $p = 0.000$, indicating a statistically significant difference between the pretest and posttest scores. Since the significance value was lower than 0.05, the null hypothesis was rejected. Therefore, the differentiated learning-based digital worksheet significantly improved students' mathematical literacy. Furthermore, the Wilcoxon ranking results showed 32 positive ranks, with no negative ranks or ties, indicating that every student demonstrated improvement after the intervention.

Table 3.

Wilcoxon Signed-Rank Test

Statistic	Value
Z	-4.939
Asymp. Sig. (2-tailed)	< .001
Effect Size (r)	0.87
Interpretation	Large

The one-sample proportion test indicated that the proportion of students achieving the minimum mastery criterion was significantly higher than the predetermined benchmark of 70% ($p = 0.0104$). Therefore, the differentiated learning-based digital worksheet satisfied the predefined criterion for instructional effectiveness**.**

To examine students' cognitive progress in greater depth, mathematical literacy achievement was analyzed across the three core process competencies defined in the OECD (2019, 2022) mathematical literacy theoretical framework: Formulate (translating contextual problems into mathematical matrix equations), Employ (applying matrix operations and computational procedures), and Interpret (evaluating and explaining the contextual implications of mathematical solutions). Table 4 presents the percentage of achievement for each mathematical literacy indicator along with its operational definition.

Table 4.

Achievement of Mathematical Literacy Indicators

Indicator	Operational Definition / Cognitive Process	Percentage
Formulate	Identifying relevant technical data and transforming real-world workshop scenarios into matrix structures (OECD, 2019, 2022)	88.64%
Employ	Executing matrix operations (transposition, addition, subtraction, multiplication) and algebraic procedures	82.10%
Interpret	Evaluating the reasonableness of mathematical solutions and explaining practical technical meanings in vocational contexts	65.23%

Among the three competencies, Formulate demonstrated the highest achievement (88.64%), followed by Employ (82.10%), whereas Interpret showed the lowest achievement (65.23%). This hierarchy of performance indicates that while students excelled at contextual modeling and algebraic execution, articulating and reflecting upon the technical meaning of the mathematical results remained the most challenging cognitive phase.

DISCUSSION

The improvement in students' mathematical literacy indicates that differentiated learning supported by digital worksheets has the potential to facilitate the development of mathematical literacy competencies. This finding may be explained by the adaptive learning pathways, scaffolded activities, and contextual vocational problems embedded in the digital worksheet, which allowed students to engage with mathematical concepts according to their readiness levels. This result is consistent with previous studies reporting that differentiated instruction combined with digital learning environments enhances students' mathematical reasoning and contextual problem-solving abilities (Bi et al., 2023; Juliana et al., 2024; Pozas et al., 2021; Setambah et al., 2025).

The findings indicate that students' mathematical literacy improved following the implementation of the differentiated learning-based digital worksheet, as reflected by the increase in posttest scores and the achievement of classical mastery learning. In addition to statistical significance, the intervention produced a large practical effect ($r = 0.87$), indicating that the observed improvement was not only statistically significant but also educationally meaningful. The large effect size suggests that the differentiated learning-based digital worksheet benefited students across varying levels of learning readiness, supporting its practical value for heterogeneous vocational classrooms. These findings indicate that learning activities tailored to students' readiness levels can facilitate meaningful mathematical learning by allowing learners to engage with instructional tasks that match their cognitive needs. According to Tomlinson (2001), differentiated learning enables teachers to adjust content, learning processes, and learning products to accommodate student diversity, thereby promoting equitable learning opportunities. Recent studies have similarly reported that differentiated instruction significantly improves students' mathematical achievement, engagement, and higher-order thinking because it provides learning experiences that are responsive to learners' readiness and learning profiles (Bi et al., 2023; Putranto et al., 2024; Qalfin et al., 2024; Supratman et al., 2025). However, because this study employed a one-group pretest-posttest design without a comparison group, the findings should be interpreted as evidence of improvement associated with the intervention rather than definitive causal evidence. Future studies employing quasi-experimental or randomized controlled designs are needed to strengthen causal inference.

The improvement in mathematical literacy can also be interpreted through the OECD mathematical literacy framework, which conceptualizes mathematical literacy as the capacity to formulate, employ, and interpret mathematics in a variety of authentic contexts (OECD, 2022). The differentiated learning-based digital worksheet incorporated contextual vocational problems, adaptive learning pathways, and scaffolded activities that required students to connect mathematical concepts with real-life situations. Specifically, contextual vocational problems primarily supported students' ability to formulate mathematical situations into mathematical models, scaffolded exercises facilitated the employ competency by guiding students through increasingly complex mathematical procedures, whereas real-time feedback encouraged students to evaluate and interpret mathematical solutions within authentic vocational contexts. Therefore, each digital worksheet feature was intentionally aligned with one or more competencies of the OECD mathematical literacy framework. This alignment indicates that differentiated digital worksheets can serve not only as learning media but also as instructional tools that systematically support the sequential development of the formulate, employ, and interpret competencies proposed in the OECD mathematical literacy framework. Such learning experiences are consistent with constructivist perspectives, which emphasize that conceptual understanding develops more effectively when learners actively construct knowledge through contextual problem-solving rather than memorizing procedures. Previous studies have likewise shown that digital worksheets integrating contextual tasks and inquiry-based activities significantly enhance mathematical literacy by encouraging students to reason, explore multiple solution strategies, and reflect on their mathematical thinking (Dewi et al., 2022; Esen et al., 2023; Kappassova, et al., 2025; Saat et al., 2024; Widodo, et al., 2023).

Among the three mathematical literacy competencies, the Formulate indicator achieved the highest percentage (88.64%), followed by Employ (82.10%), whereas Interpret obtained the lowest achievement (65.23%). The high performance in the formulate competency indicates that students became more proficient in identifying relevant information and translating contextual situations into mathematical models. This finding is consistent with the OECD framework, which considers mathematical modelling as the initial stage of mathematical literacy (Alsina & Salgado, 2022; OECD, 2022). The adaptive structure of the digital worksheet likely supported this competency by providing guided questions, contextual illustrations, and step-by-step scaffolding that assisted students in recognizing mathematical relationships embedded within vocational situations. While Amaliya et al. (2024) demonstrated that contextual digital worksheets improved students' ability to formulate mathematical models, the present study extends these findings by integrating differentiated learning principles within a vocational mathematics context. Rather than providing identical learning experiences for all students, the digital worksheet adapted learning pathways according to students' readiness levels, thereby enabling contextual mathematical modelling to be developed through personalized learning experiences.

The relatively high achievement in the Employ indicator suggests that students successfully applied mathematical concepts and procedures to solve contextual problems. This result may be attributed to the differentiated tasks embedded within the digital worksheet, which provided learning activities of varying complexity according to students' readiness levels. Adaptive task difficulty allows learners to develop procedural fluency progressively without experiencing excessive cognitive load. This interpretation aligns with Cognitive Load Theory, which argues that instructional materials should minimize unnecessary cognitive burden while maximizing meaningful learning (Sweller, et al., 2019). From the perspective of Cognitive Load Theory, adaptive task difficulty reduces extraneous cognitive load by matching instructional complexity with students' readiness levels. Consequently, students can allocate more working-memory resources to understanding mathematical procedures and solving contextual problems instead of managing unnecessary task difficulty. This mechanism may explain why the Employ competency showed relatively high achievement following the intervention. Recent empirical studies have likewise demonstrated that differentiated digital learning environments improve procedural competence because students receive instructional support appropriate to their current level of understanding (Juliana, et al., 2024; Kilpatrick, et al., 2001; Sari, et al., 2024).

Although students demonstrated substantial improvement overall, the Interpret indicator remained the lowest among the three competencies. This finding suggests that many students still experienced difficulty explaining the meaning of mathematical solutions within authentic contexts. Interpretation requires students not only to obtain correct numerical answers but also to evaluate their reasonableness, communicate conclusions logically, and relate mathematical results back to real-world situations. Such competencies involve higher-order reasoning and metacognitive reflection, which are generally more challenging than procedural computation. This finding also suggests that future differentiated digital learning environments should provide more structured opportunities for students to evaluate the appropriateness of mathematical solutions, justify their reasoning, and communicate conclusions within authentic vocational scenarios. These activities may strengthen the interpret competency, which represents the most cognitively demanding dimension of mathematical literacy. Similar findings have been reported by Kolar & Hodnik (2021), Santia and Handayani (2023) and Muhaimin, et al., (2024), who concluded that Indonesian students often perform well in mathematical calculations but encounter difficulties when interpreting solutions and communicating mathematical reasoning in contextual problems. Future instructional interventions should incorporate additional reflective tasks requiring students to justify mathematical reasoning, compare alternative solution strategies, interpret results within authentic vocational scenarios, and communicate mathematical conclusions through collaborative discussion. Such learning activities may further strengthen the Interpret competency, which remained the most challenging dimension of mathematical literacy.

The effectiveness of the differentiated learning-based digital worksheet can also be explained by its interactive digital features. The worksheet integrated multimedia explanations, adaptive learning pathways, scaffolded exercises, and real-time feedback, enabling students to receive immediate information regarding their learning progress. Immediate feedback helps students identify misconceptions during problem solving, whereas scaffolded learning activities gradually increase task complexity according to individual readiness. These features encourage students to engage actively in learning while reducing frustration associated with repeated failure. Previous research has consistently demonstrated that digital learning environments incorporating real-time feedback and scaffolding significantly improve conceptual understanding, mathematical reasoning, and learning engagement (Barana et al., 2021; Cavalcanti et al., 2021; Esen et al., 2023; Hefter et al., 2022; Zakariya, 2022).

The present findings are also consistent with previous studies reporting the positive effects of digital worksheets on mathematics learning. Dewi et al. (2022) and Amaliya et al. (2024) found that interactive digital worksheets improved students' mathematical literacy through contextual learning activities and multimedia integration. Likewise, differentiated instruction has been shown to improve mathematics achievement, classroom participation, and learning motivation by accommodating learner diversity (Bi et al., 2023; Bobis et al., 2021; Pozas et al., 2021). However, most previous investigations examined digital worksheets and differentiated instruction separately. The principal empirical contribution of this study is the evidence that integrating differentiated learning principles into digital worksheets can improve mathematical literacy in vocational mathematics classrooms with heterogeneous student readiness. Unlike previous studies that primarily examined contextual digital worksheets or differentiated instruction separately, this study demonstrates that combining both approaches within a single adaptive learning environment provides a more comprehensive strategy for supporting mathematical literacy in authentic vocational contexts. Unlike previous studies that primarily examined contextual digital worksheets in general mathematics classrooms, this study demonstrates that integrating differentiated learning into digital worksheets can also be effectively implemented within vocational education characterized by heterogeneous learner readiness. This finding therefore extends previous evidence by showing that adaptive digital learning environments can simultaneously accommodate learner diversity while strengthening mathematical literacy in authentic vocational contexts.

Furthermore, the present findings refine previous research by suggesting that the effectiveness of digital worksheets is influenced not only by contextualization and interactivity, as reported in earlier studies, but also by the integration of differentiated learning principles that adapt instructional pathways to students' readiness levels. This finding identifies differentiated learning as a potential mechanism through which digital worksheets can more effectively support the development of mathematical literacy in vocational education. From a practical perspective, the findings suggest that differentiated learning-based digital worksheets can serve as an effective instructional medium for vocational mathematics classrooms characterized by heterogeneous student readiness. The adaptive learning pathways reduce teachers' difficulties in accommodating individual differences because differentiation is embedded directly within the digital learning resources. Furthermore, contextual vocational problems help students recognize the relevance of mathematics to future workplace situations, thereby increasing learning meaningfulness and supporting competency-based vocational education (Rejeki et al., 2023; Sumandya & Widana, 2022; Ubaidillah et al., 2023).Consequently, integrating differentiated instruction into digital learning materials offers a practical strategy for improving mathematical literacy while simultaneously addressing learner diversity in vocational education.

CONCLUSION

This study concludes that the implementation of differentiated learning-based digital worksheets was associated with significant improvements in vocational high school students' mathematical literacy. The statistical findings supported the research hypothesis by indicating that students demonstrated higher mathematical literacy following the learning intervention. These findings suggest the potential of integrating differentiated learning principles into digital instructional media to support students with diverse readiness levels through adaptive learning pathways, contextual vocational problems, scaffolded activities, and interactive feedback. The statistical findings confirmed the research hypothesis by demonstrating a significant improvement in students' mathematical literacy following the learning intervention. The effectiveness of the digital worksheet indicates that integrating differentiated learning principles into digital instructional media enables students with diverse readiness levels to engage in meaningful mathematical learning through adaptive learning pathways, contextual vocational problems, scaffolded activities, and interactive feedback.

The principal contribution of this study is the empirical evidence that integrating differentiated learning principles into digital worksheets has the potential to support mathematical literacy development in vocational mathematics classrooms characterized by heterogeneous student readiness. The findings suggest that adaptive digital learning environments can facilitate opportunities for students to formulate, employ, and interpret mathematics within authentic vocational contexts while accommodating diverse learning needs.

This study has several limitations that should be considered when interpreting the findings. First, the use of a one-group pretest–posttest design without a control group limits the ability to draw definitive causal conclusions regarding the observed improvements. Second, the study was conducted in a single vocational high school with a relatively small sample, which may limit the generalizability of the findings to other educational contexts.

Therefore, the conclusions should be interpreted within the context of these methodological limitations.

Future research is encouraged to employ quasi-experimental or true experimental designs involving control groups, larger samples, and multiple vocational schools to strengthen the generalizability and causal interpretation of the findings. Further studies may also examine the long-term effects of differentiated learning-based digital worksheets on other higher-order mathematical competencies, such as mathematical reasoning, problem-solving, critical thinking, and self-regulated learning. From a practical perspective, vocational mathematics teachers are encouraged to implement differentiated digital worksheets by conducting students' readiness assessments before instruction, designing adaptive learning pathways that accommodate varying readiness levels, integrating contextual vocational problems relevant to students' fields of study, and providing scaffolded learning activities accompanied by timely feedback to support equitable mathematical learning experiences.

DECLARATIONS

Author Contribution

Hertanto, A.T., Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing, review & editing; **Lestari, D**, Conceptualization, Methodology, Supervision, Formal analysis, Writing,review & editing.

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Conflict of Interest

The authors declare no conflict of interest.

Declaration of AI Use

Generative AI tools were used in the preparation of this manuscript. Specifically, ChatGPT was used to assist in improving language clarity, structuring the manuscript, and refining academic writing under the supervision and full responsibility of the authors. All content has been carefully reviewed and validated by the authors to ensure accuracy and originality.

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