



Technology-enhanced STEAM learning through augmented reality digital storybooks: effects on scientific literacy and disaster preparedness in elementary science education

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Abstract

Background: Scientific literacy and disaster preparedness are critical competencies for elementary students, particularly in disaster-prone contexts. However, science education frequently addresses scientific understanding and preparedness as separate learning outcomes, creating a need for an integrated pedagogical approach that connects scientific reasoning with authentic disaster-related decision-making.

Aim: This study investigated the effects of technology-enhanced STEAM learning through augmented reality digital storybooks (DS-AR STEAM) on elementary students' scientific literacy and disaster preparedness.

Method: A quasi-experimental pretest-posttest control-group design involved 60 fourth-grade students from two intact classes, comprising an experimental group ($n = 30$) and a control group ($n = 30$). The experimental group participated in learning that integrated contextual disaster narratives, augmented reality visualization, scientific inquiry, STEAM problem-solving, and preparedness-oriented decision-making, whereas the control group received conventional science instruction. Data were collected using a contextualized scientific literacy test and a nine-item disaster preparedness questionnaire and analyzed using descriptive statistics, normalized gain, and non-parametric between-group comparisons.

Results: The experimental group achieved significantly higher scientific literacy ($M = 94.67$) than the control group ($M = 82.33$; $p < .001$). The corresponding N-Gain values were 0.848 (high) and 0.495 (moderate). Disaster preparedness was also higher in the experimental group (80.37%) than in the control group (67.41%).

Conclusion: Technology-enhanced STEAM learning through augmented reality digital storybooks offers a promising approach for simultaneously strengthening scientific literacy and disaster preparedness by connecting scientific reasoning, interactive visualization, interdisciplinary problem-solving, and preparedness-oriented decision-making in elementary science education.

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INTRODUCTION

Scientific literacy is increasingly recognized as a fundamental competency that enables students to understand scientific phenomena, interpret evidence, evaluate scientific information, and make informed decisions about issues encountered in everyday life. Rather than being limited to the acquisition of factual knowledge, scientific literacy encompasses the capacity to explain phenomena scientifically, evaluate investigations, interpret data and evidence, and apply scientific understanding

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within authentic contexts. Developing these competencies is particularly important in elementary education because early science experiences establish foundations for subsequent scientific reasoning, problem-solving, and responsible participation in society (Bassachs et al., 2020; Darling-Hammond et al., 2020; Erol et al., 2023; Larimore, 2020). International science education frameworks similarly emphasize learners' ability to mobilize scientific knowledge and practices when addressing real-world challenges rather than merely reproducing disciplinary content. Nevertheless, strengthening scientific literacy remains a persistent educational challenge in Indonesia, as reflected in PISA 2022, where Indonesian students performed below the OECD average in science and only approximately 34% reached at least Level 2 proficiency compared with 76% across OECD countries. This pattern suggests that many students still encounter difficulties in recognizing scientific explanations, interpreting evidence, and applying scientific reasoning to meaningful situations. Such difficulties may be reinforced when classroom instruction prioritizes the transmission and memorization of concepts without providing sufficient opportunities to investigate authentic problems and justify evidence-based conclusions. Consequently, elementary science learning requires pedagogical environments that engage students in inquiry, evidence interpretation, contextual reasoning, and active problem-solving. STEAM-project-based learning represents one promising approach because it connects scientific concepts with interdisciplinary activities that require learners to investigate problems, construct solutions, and communicate their reasoning, and previous evidence has demonstrated its potential to strengthen elementary students' scientific literacy (Suryanti et al., 2024). Technology-enhanced STEAM learning may therefore provide an appropriate foundation for creating science learning experiences in which abstract concepts become more accessible, contextualized, and applicable to problems that students may encounter in their lives.

Disaster education provides an especially meaningful context for this approach because understanding environmental hazards requires students to connect scientific explanations with the interpretation of risk, safety considerations, and decisions concerning appropriate responses. This connection is particularly relevant in Indonesia, where exposure to multiple hazards makes disaster risk reduction an important educational concern alongside its broader societal significance. International frameworks emphasize that disaster risk reduction education should equip learners not merely with factual awareness of hazards but also with knowledge and competencies that contribute to preparedness, prevention, and resilience (Cabello et al., 2021; Keswick et al., 2025; Righi et al., 2021; Rokvić & Stanojević, 2024). From a science education perspective, disaster phenomena can function as authentic contexts in which students investigate causal relationships, interpret environmental evidence, assess potential risks, and justify appropriate courses of action. Scientific literacy and disaster preparedness can therefore be viewed as interconnected competencies because understanding the scientific mechanisms underlying hazards may support students in interpreting risk information and making evidence-informed preparedness decisions. Previous work integrating STEM with disaster education has suggested that disaster contexts can provide meaningful opportunities for applying interdisciplinary knowledge while developing disaster literacy, while elementary education research has demonstrated the potential of contextual disaster learning to strengthen disaster literacy and resilience (Cabello et al., 2021; Huang & Chen, 2026). Despite this potential, disaster-related science learning presents a significant pedagogical challenge because floods, strong winds, earthquakes, volcanic eruptions, and other hazards involve dynamic processes that can be difficult, unsafe, or impossible to observe directly in elementary classrooms. Conventional texts and static illustrations may communicate essential information, but they provide limited opportunities for learners to explore spatial relationships, visualize changing processes, examine cause-and-effect mechanisms, or engage with realistic decision-making situations. Augmented reality (AR) can address some of these representational limitations by

providing interactive three-dimensional visualizations of otherwise inaccessible phenomena, and empirical evidence indicates that STEAM-supported AR can contribute positively to scientific literacy and science learning (Asyri & Asyri, 2024). When combined with digital storybooks that contextualize scientific concepts through narratives (Naresti et al., 2024) and STEAM activities that transform visualization into inquiry and interdisciplinary problem-solving (Suryanti et al., 2024), AR has the potential to become part of a broader pedagogical environment connecting scientific understanding with preparedness-oriented action.

Despite growing evidence supporting these individual approaches, the literature reveals important gaps concerning how technology-enhanced STEAM learning can simultaneously develop scientific literacy and disaster preparedness in elementary education. Existing studies have demonstrated the potential of digital storybooks for contextualizing science learning and supporting scientific literacy (Naresti et al., 2024), STEAM-based AR for improving science learning (Asyri & Asyri, 2024), STEAM-project-based learning for strengthening scientific literacy (Suryanti et al., 2024), and contextual disaster education for developing disaster literacy and resilience. However, these strands have largely evolved as separate or partially connected instructional developments, leaving an integration gap regarding a unified learning environment that combines narrative-based contextualization, AR-supported visualization, scientific inquiry, interdisciplinary STEAM problem-solving, and disaster education. An outcome gap is also evident because previous research has commonly examined scientific literacy, science achievement, disaster literacy, or resilience as distinct outcomes rather than investigating scientific literacy and disaster preparedness simultaneously as mutually relevant competencies. This separation limits understanding of whether improvements in students' scientific reasoning can be pedagogically connected with their capacity to interpret risks and make preparedness-oriented decisions. Furthermore, a pedagogical-mechanism gap remains because technology-enhanced learning research frequently emphasizes the effectiveness of particular media while giving less attention to how different technological and pedagogical affordances can be deliberately coordinated within a coherent instructional sequence. In this regard, digital storytelling can establish an authentic narrative context, AR can make complex scientific processes visible and interactive, and STEAM activities can transform these experiences into inquiry, design, interdisciplinary reasoning, and evidence-based problem-solving (Arango-Caro et al., 2025; Chang, 2026). The educational contribution of such integration therefore lies not simply in adding digital technology to conventional instruction but in orchestrating complementary pedagogical functions that guide learners from contextual understanding toward informed action. This perspective is particularly relevant to disaster education because preparedness requires students not only to recognize hazards but also to understand underlying phenomena, evaluate available information, and determine appropriate responses. Accordingly, empirical investigation is needed to determine whether STEAM-integrated augmented reality digital storybooks (DS-AR STEAM) can provide a coherent instructional architecture for strengthening scientific literacy while simultaneously fostering disaster preparedness among elementary students.

Existing literature indicates substantial progress across scientific literacy, STEAM education, augmented reality (AR), digital storytelling, and disaster preparedness, yet these research streams remain largely fragmented. Studies on scientific literacy have emphasized scientific reasoning, model-based learning, socio-scientific issues, and the application of scientific knowledge in authentic contexts (Ke et al., 2021; Osborne & Allchin, 2025; O'Toole et al., 2020), while STEAM research has primarily examined conceptual understanding, creativity, transferable skills, pedagogical frameworks, and the adoption of emerging technologies (Aguilera & Ortiz-Revilla, 2021; Belbase et al., 2022; Filipe et al., 2024; Hsiao & Su, 2021; Leavy et al., 2023; Spyropoulou & Kameas, 2023). In parallel, AR research has demonstrated growing educational potential through interactive and immersive representations, although much of the literature addresses AR broadly rather than its

systematic integration with disaster-oriented science learning (Kamińska et al., 2023; Koumpouros, 2024). Digital storytelling has also been associated with learning engagement, digital literacy, multimodal communication, and learner development, but its application as a narrative scaffold connecting scientific reasoning with disaster-related decision-making remains comparatively underexplored (Churchill, 2020; Kim & Li, 2021; Liang & Hwang, 2023; Wu & Chen, 2020). Meanwhile, disaster preparedness research has predominantly addressed preparedness education, community engagement, preparedness culture, risk management, and contextual determinants of preparedness (Appleby-Arnold et al., 2021; Ayuningtyas et al., 2021; Guo et al., 2025; Ryan et al., 2020; Titko & Ristvej, 2020), leaving limited evidence on its integration into technology-enhanced elementary science education. Collectively, these patterns reveal an integration gap, as STEAM, AR, digital storytelling, and disaster education have largely developed as separate or partially connected pedagogical strands; an outcome gap, because scientific literacy and disaster preparedness are rarely examined simultaneously as interconnected learning outcomes; and a pedagogical-mechanism gap, because limited attention has been given to how narrative contextualization, AR-supported visualization, scientific inquiry, interdisciplinary STEAM problem-solving, and preparedness-oriented decision-making can be systematically orchestrated within a unified learning sequence. Accordingly, the present study addresses these gaps by investigating technology-enhanced STEAM learning through augmented reality digital storybooks as an integrated pedagogical environment for simultaneously strengthening scientific literacy and disaster preparedness among elementary students.

To address these gaps, this study aims to examine the effects of technology-enhanced STEAM learning through augmented reality digital storybooks (DS-AR STEAM) on elementary school students' scientific literacy and disaster preparedness. Specifically, the study investigates whether students participating in the integrated intervention demonstrate stronger scientific literacy than students receiving conventional science instruction. It further examines whether the same instructional environment is associated with higher disaster preparedness, thereby treating scientific understanding and preparedness-oriented action as complementary educational outcomes. Within the proposed framework, digital storytelling serves as a narrative scaffold that situates scientific concepts within authentic disaster-related problems relevant to students' learning experiences. Augmented reality provides interactive representations through which learners can observe and explore scientific phenomena that may be difficult or unsafe to reproduce directly in conventional classrooms. STEAM activities subsequently engage students in scientific inquiry, evidence interpretation, interdisciplinary reasoning, solution design, and evaluation of preparedness-related decisions. Disaster risk reduction therefore functions not merely as supplementary learning content but as an authentic problem context through which scientific knowledge can be interpreted and applied. By coordinating these components within a single instructional sequence, the study seeks to clarify how technology can operate as part of a pedagogical system rather than as an isolated instructional feature. The study consequently extends previous research by simultaneously examining scientific literacy and disaster preparedness while investigating the educational value of integrating narrative contextualization, AR-supported visualization, inquiry, and interdisciplinary STEAM problem-solving. Ultimately, the findings are expected to provide empirical guidance for teachers, curriculum developers, and researchers seeking to design technology-enhanced elementary science learning that connects scientific reasoning with evidence-based and preparedness-oriented decision-making.

LITERATURE REVIEW

Scientific literacy constitutes a multidimensional educational construct concerned with students' ability to mobilize scientific knowledge, practices, and evidence when interpreting phenomena and responding to real-world issues. Contemporary conceptions therefore extend beyond factual recall by emphasizing the abilities to explain phenomena scientifically, evaluate scientific information, interpret data and evidence, and formulate conclusions supported by reasoning (Bao et al., 2022; Janoušková et al., 2023; Masnick & Morris, 2022). In elementary science education, these competencies are particularly important because students begin developing patterns of inquiry and evidence-based reasoning that can support more advanced scientific learning. Scientific literacy also becomes educationally meaningful when learners are required to transfer conceptual knowledge from classroom activities to unfamiliar or contextual situations. Accordingly, learning environments should provide opportunities for students to observe phenomena, formulate questions, interpret information, evaluate evidence, and communicate reasoned explanations rather than positioning them primarily as recipients of scientific facts. Project-oriented and interdisciplinary approaches are relevant to this objective because they situate scientific knowledge within problems that require the integration of concepts, evidence, and practical decision-making. In this regard, STEAM-project-based learning has demonstrated positive potential for strengthening scientific literacy among elementary students by connecting scientific understanding with interdisciplinary problem-solving activities (Suryanti et al., 2024). Digital learning environments may further support this process when technological representations enable students to access scientific phenomena that are difficult to observe through conventional classroom experiences. However, the contribution of technology to scientific literacy depends on how technological affordances are connected with inquiry, reasoning, and meaningful learning tasks rather than on the mere presence of digital media. Scientific literacy in the present study is therefore conceptualized as an applied competency developed through contextual inquiry, interpretation of scientific evidence, interdisciplinary problem-solving, and the use of scientific reasoning to inform decisions.

Disaster preparedness represents a complementary educational outcome because responding appropriately to hazards requires learners to transform knowledge about environmental phenomena into informed judgments and actions. Disaster education should therefore encompass more than recognition of hazard types or memorization of emergency procedures, particularly when the intended learning outcome includes preparedness and resilience. Contemporary disaster risk reduction frameworks emphasize the importance of equipping learners with knowledge and competencies that enable them to understand risks, anticipate consequences, and participate appropriately in preparedness and prevention (Cabello et al., 2021; Righi et al., 2021; Rokvić & Stanojević, 2024; Yang et al., 2025). Within elementary science education, disaster contexts can connect scientific concepts with observable environmental events and decisions that have direct relevance to students' lives. Floods and strong winds, for example, can be examined through scientific concepts concerning environmental conditions, causal processes, forces, weather, and the relationships between natural phenomena and human activities. Contextualizing these phenomena allows disaster education to function as a setting for applying scientific reasoning rather than as an additional body of information detached from science learning. Previous research has indicated that contextual disaster learning can contribute to disaster literacy and resilience among elementary students, supporting the educational value of integrating disaster-related issues into classroom learning (Cabello et al., 2021; Kurt et al., 2026; Shah et al., 2024). From this perspective, scientific literacy can provide a cognitive basis for interpreting hazards and evidence, whereas preparedness reflects students' capacity to translate understanding into awareness, readiness, and appropriate

responses. The relationship between the two constructs is consequently important because scientifically informed understanding does not automatically ensure preparedness unless instruction provides opportunities to connect explanations, risk interpretation, and decision-making. Integrating disaster preparedness into elementary science education may therefore establish an authentic application context in which scientific knowledge is evaluated not only by conceptual understanding but also by its usefulness for reasoning about risk and selecting appropriate actions.

STEAM education provides a pedagogical framework for connecting such authentic problems with interdisciplinary inquiry by integrating science, technology, engineering, arts, and mathematics within purposeful learning activities. Rather than treating these disciplines as independent subjects, integrated STEAM learning encourages students to draw on multiple forms of knowledge while investigating problems, developing ideas, designing solutions, and evaluating outcomes. The inclusion of engineering and design processes is particularly relevant because students can move from explaining a phenomenon toward constructing and testing possible responses to a contextual problem. The arts dimension can additionally support representation, communication, creativity, and narrative meaning, thereby expanding how students express and negotiate scientific ideas. Empirical research has demonstrated the potential of STEAM approaches to support conceptual learning and scientific literacy, including through project-based activities in elementary science contexts (Suryanti et al., 2024). Technology-enhanced STEAM extends this pedagogical architecture by using digital resources to provide representations, interactions, and information that may not be readily available through physical classroom materials. Nevertheless, effective technology-enhanced STEAM learning requires alignment between technological functions and pedagogical purposes because technology that is disconnected from inquiry or problem-solving may provide engagement without necessarily promoting deeper scientific reasoning (Jamba & Chauraya, 2026). In disaster-oriented science learning, such alignment can occur when technology visualizes hazard-related processes, science provides explanatory concepts, engineering structures solution design, mathematics supports interpretation or comparison, and arts contributes to narrative and communication. This interdisciplinary configuration positions learners as active problem solvers who must connect scientific evidence with possible responses rather than simply consume information about disasters. Technology-enhanced STEAM is thus conceptualized in this study as an integrated pedagogical system in which digital affordances support inquiry, interdisciplinary reasoning, design-oriented problem-solving, and the application of scientific understanding to disaster-related situations.

Augmented reality digital storybooks offer a technological and narrative medium through which the principles of technology-enhanced STEAM can be operationalized for elementary learners. AR enables digital information and virtual representations to be integrated with the physical learning environment, providing interactive visualization of objects or processes that may otherwise remain abstract or inaccessible. In science education, this affordance is particularly valuable when students need to examine dynamic, spatial, or hazardous phenomena that cannot be directly reproduced in classroom settings (Akdag et al., 2025; Pallant et al., 2025; Varelas et al., 2022). Evidence from technology-enhanced science learning indicates that AR-supported STEAM activities can contribute to students' science learning and scientific literacy when visualization is embedded within meaningful instructional activities (Asyri & Asyri, 2024). Digital storybooks provide a complementary function because narrative structures can situate scientific information within characters, events, problems, and consequences that are more readily interpreted as meaningful situations. Research on digital picture storybooks has also demonstrated their potential for supporting scientific literacy in elementary education by contextualizing scientific concepts within accessible learning experiences (Naresti et al., 2024). Combining these two affordances allows the storybook to establish the problem context while AR enriches selected narrative events with

interactive representations of relevant scientific phenomena. However, the instructional value of an AR digital storybook should not be attributed solely to technological novelty, because visualization and narrative need to be accompanied by tasks that require students to question, investigate, interpret, design, and justify. Embedding STEAM activities within the narrative can provide this pedagogical progression by moving learners from observing AR-supported phenomena to investigating causes, considering interdisciplinary evidence, developing possible solutions, and evaluating their preparedness decisions. Augmented reality digital storybooks can therefore function as an instructional bridge between contextual narrative, scientific visualization, interdisciplinary inquiry, and evidence-informed action rather than merely as multimedia materials for presenting science content.

The conceptual foundation of DS-AR STEAM emerges from the deliberate orchestration of narrative contextualization, AR-supported visualization, scientific inquiry, interdisciplinary problem-solving, and preparedness-oriented decision-making within a single learning sequence. At the initial stage, disaster narratives provide an authentic problem situation that encourages students to identify relevant phenomena, recognize risks, and formulate questions requiring scientific explanation. AR-supported visualization then makes selected processes and relationships more observable, enabling students to connect narrative events with scientific representations that can be explored during learning. Scientific inquiry extends this visualization by requiring learners to interpret information, examine evidence, construct explanations, and evaluate relationships between causes and consequences. STEAM-oriented problem-solving subsequently broadens the learning process by encouraging students to integrate scientific understanding with technological, engineering, mathematical, and creative considerations when proposing responses to the problem. Preparedness-oriented decision-making represents the applied stage of this sequence, where learners use the knowledge and evidence developed during earlier activities to determine appropriate responses to disaster-related situations. This proposed progression is consistent with the educational potential reported for contextual disaster learning, digital storybooks, AR-supported science learning, and STEAM-project-based scientific literacy instruction, while combining their complementary functions within one pedagogical architecture. The framework consequently assumes that scientific literacy and disaster preparedness can be mutually supported when students are given structured opportunities to move from understanding scientific phenomena to applying that understanding in risk-related judgments and decisions. Such integration distinguishes DS-AR STEAM from approaches in which AR functions primarily as a visualization tool, digital storytelling functions primarily as a presentation medium, or STEAM activities are implemented without an explicit preparedness context. Accordingly, the present conceptual framework positions technology-enhanced STEAM learning through augmented reality digital storybooks as a coherent pathway linking contextualized narrative → AR-supported visualization → scientific inquiry → interdisciplinary STEAM problem-solving → evidence-based disaster preparedness, which provides the theoretical basis for examining its effects on both scientific literacy and disaster preparedness in elementary science education.

METHOD

Research Design

This study employed a quasi-experimental pretest–posttest control-group design to investigate the effects of technology-enhanced STEAM learning through augmented reality digital storybooks (DS-AR STEAM) on elementary students' scientific literacy and disaster preparedness. The quasi-experimental approach was selected because the research was conducted within existing classroom structures in which individual random assignment was not feasible. Two intact and

comparable Grade IV classes participated in the study, with one class assigned as the experimental group and the other as the control group. The experimental group received science instruction through DS-AR STEAM, whereas the control group received conventional science instruction using the learning resources and presentation-based activities normally implemented in the classroom. Both groups studied equivalent science content and were expected to achieve the same curriculum outcomes, thereby maintaining comparability in the instructional content while differentiating the pedagogical approach. Before the intervention, both groups completed pretests measuring scientific literacy and disaster preparedness to establish their initial performance and assess baseline comparability. Following the instructional period, posttests addressing the same constructs were administered to determine changes in learning outcomes. Because the study used intact classes rather than individual randomization, observed between-group differences were interpreted within the inferential boundaries of a quasi-experimental classroom design. The research design is summarized in Table 1.

Table 1. Research Design

Group	Pretest	Intervention	Posttest
Experimental	O ₁	X	O ₂
Control	O ₃	C	O ₄

Participant

The study was conducted at MINU Durungbedug Candi, Sidoarjo, Indonesia, and involved 60 fourth-grade students from two intact classes. Thirty students participated in the experimental group and 30 students constituted the control group. The intact classroom arrangement was retained because reorganizing students through individual random assignment was not feasible within the existing school structure. Students were included in the analysis when they were officially enrolled in Grade IV, participated regularly in the instructional activities, and completed the required assessments. Both groups followed the same grade-level IPAS curriculum and addressed comparable science content and intended learning outcomes during the study. The experimental group participated in technology-enhanced STEAM learning using AR digital storybooks, whereas the control group received conventional science instruction covering equivalent curricular material. This arrangement was intended to minimize differences in curricular exposure while allowing the instructional approach to constitute the principal distinction between the groups. Nevertheless, because the participants were drawn from intact classes without individual randomization, potential pre-existing differences between the groups were considered when interpreting the results. Baseline performance was therefore examined statistically using the pretest data before evaluating post-intervention differences.

Instrument and Data Collection

Two primary instruments were employed to measure the dependent variables: a contextualized scientific literacy test and a disaster preparedness questionnaire, while a structured observation checklist was used to monitor intervention fidelity. The scientific literacy assessment addressed three competencies: explaining scientific phenomena, evaluating or reasoning about scientific investigations, and interpreting scientific data and evidence. The test incorporated selected-response and short constructed-response items situated within flood and strong-wind contexts corresponding to the disaster themes addressed during the intervention. Rather than emphasizing factual recall, the items required students to apply scientific knowledge, interpret contextual information and evidence, and formulate reasoned judgments, with performance subsequently converted to a 0–100 scale. Disaster preparedness was assessed using a nine-item Likert-type questionnaire addressing students' awareness of disaster risk, readiness to take appropriate action, and confidence in responding to disaster-related situations. Each item used a

four-point response scale, producing a maximum possible score of 36, with higher scores indicating stronger preparedness; scores were additionally converted into percentages for categorical interpretation. Prior to the main study, content validity was evaluated by six experts with expertise in scientific literacy, disaster education, and educational technology, who assessed content relevance, construct representation, linguistic clarity, developmental appropriateness, and alignment with the intended learning outcomes. The instruments were subsequently pilot-tested with five students who had characteristics comparable to those of the main participants but were not included in the experimental sample, followed by item analysis examining difficulty, discrimination, and item-total correlation. Internal consistency was assessed using Cronbach's alpha, with a coefficient of at least .70 adopted as the criterion for acceptable reliability, while exploratory factor analysis was considered where appropriate and only items satisfying the predetermined psychometric criteria were retained. Data collection consisted of pre-intervention assessments, classroom observations during implementation, and immediate post-intervention assessments, with all student responses coded using anonymous identifiers before analysis.

Data Analysis

Quantitative data analysis was conducted sequentially to examine baseline characteristics, changes in performance, and differences between the experimental and control groups. Descriptive statistics, including the mean, standard deviation, minimum, and maximum scores, were calculated for scientific literacy and disaster preparedness at the pretest and posttest stages. Before inferential analysis, the Shapiro-Wilk test was used to examine score-distribution normality, while Levene's test was applied to evaluate homogeneity of variance between groups. Baseline equivalence was examined by comparing pretest scores using an independent-samples *t*-test when the relevant parametric assumptions were satisfied or an appropriate non-parametric alternative when those assumptions were violated. Post-intervention differences were then analyzed to determine whether students receiving DS-AR STEAM demonstrated different outcomes from those receiving conventional instruction. When baseline adjustment was required and the relevant assumptions were satisfied, analysis of covariance (ANCOVA) was performed separately for scientific literacy and disaster preparedness, with the posttest score specified as the dependent variable, instructional group as the independent variable, and corresponding pretest score as the covariate. When assumptions required for ANCOVA or other parametric analyses were not satisfied, appropriate non-parametric alternatives were employed, while within-group pretest-posttest changes were examined using paired-samples *t*-tests or Wilcoxon signed-rank tests as appropriate. In addition to statistical significance, effect sizes were considered to evaluate the magnitude of observed intervention effects, with Cohen's *d* interpreted approximately as 0.20 for a small effect, 0.50 for a moderate effect, and 0.80 or greater for a large effect. For ANCOVA, partial eta squared (η^2p) was used to represent the proportion of outcome variance associated with instructional group after accounting for baseline performance, and statistical significance was established at $p < .05$. All quantitative analyses were conducted using SPSS, and interpretation considered the direction, magnitude, and consistency of the observed differences in addition to statistical significance.

Research Procedure

The research procedure was organized into preparation, pretesting, intervention, implementation monitoring, posttesting, and data preparation stages. Before data collection, permission was obtained from the participating school, and the implementation schedule was coordinated with the school principal and classroom teachers. Ethical approval was obtained from KEP Adi Buana under approval number 048/KEP-AB/VI/2026, written informed consent was obtained from parents or legal guardians, and age-appropriate assent was obtained from participating students. Before classroom implementation, the teacher responsible for the

experimental group received an orientation covering the instructional sequence, operation of the AR digital storybook, STEAM activities, and expected classroom procedures. Both groups then completed scientific literacy and disaster preparedness pretests under comparable classroom conditions before receiving instruction on the selected science and disaster-related content. The experimental group subsequently participated in seven DS-AR STEAM instructional sessions conducted over four weeks, with each session lasting approximately 70 minutes, while the control group studied the same science topic and intended curriculum outcomes through conventional presentation-based instruction. In the experimental condition, each learning sequence progressed through a disaster-related narrative, interaction with AR visualizations, scientific questioning and evidence interpretation, integration of science and mathematical concepts, engineering-oriented solution design, artistic or visual communication, and evaluation of preparedness-related decisions. Intervention fidelity was monitored using a structured observation checklist covering the use of disaster narratives, interaction with AR visualization, inquiry activities, integration of STEAM components, evidence-based problem-solving, and preparedness-oriented decision-making, while implementation notes documented relevant technical and instructional conditions. Immediately after the instructional period, both groups completed the scientific literacy and disaster preparedness posttests using the same measurement framework as the pretests. Participation remained voluntary throughout the study, students could withdraw without academic consequences, and personal identities were replaced with research codes to maintain confidentiality during data processing, analysis, and reporting.

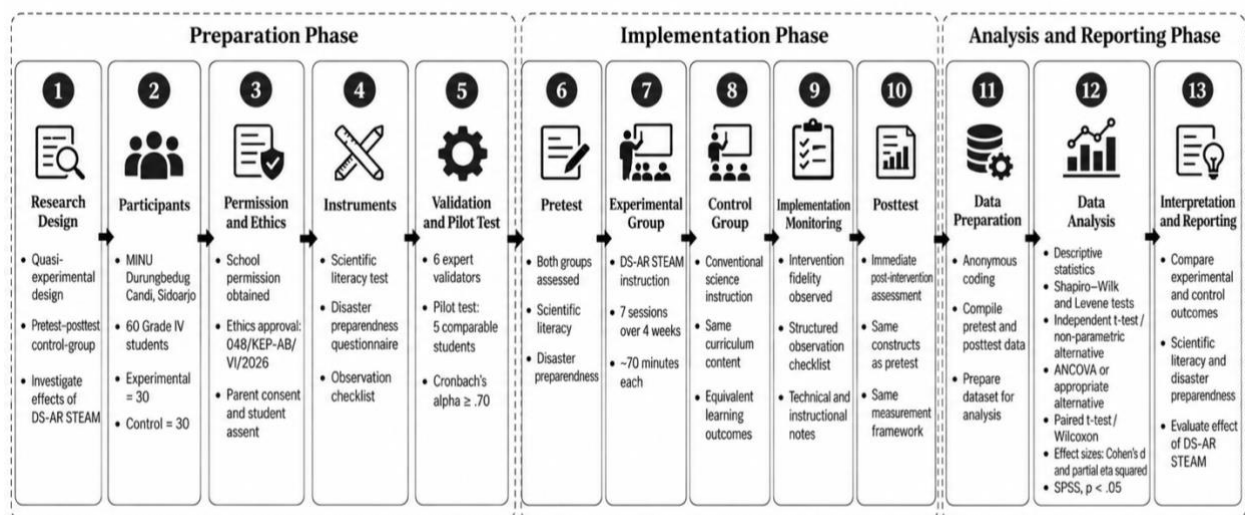


Figure 1. Research Method Flow

RESULTS AND DISCUSSION

Results

The results are presented according to the study's two primary outcomes: students' scientific literacy and disaster preparedness. The analysis focused on differences between students who participated in the STEAM-integrated augmented reality digital storybook (DS-AR STEAM) intervention and those who received conventional instruction. In addition to post-intervention scores, normalised gain (N-Gain) was used to describe improvement in scientific literacy. In contrast, the Mann-Whitney U test was used to examine statistically significant differences between the experimental and control groups.

Scientific Literacy Outcomes

Descriptive analysis showed a clear difference in scientific literacy outcomes between students in the experimental and control groups following the intervention. Students who learned through DS-AR STEAM achieved a mean post-test score of 94.67, whereas students receiving conventional instruction achieved 82.33. Thus, the experimental group demonstrated a post-test mean 12.34 points higher than that of the control group. To examine improvement in scientific literacy relative to students' initial performance, normalised gain scores were calculated for both groups. The experimental group achieved an N-Gain score of 0.848, categorised as high, whereas the control group obtained an N-Gain score of 0.495, categorised as moderate. The difference in N-Gain scores indicates that, although both groups improved, students exposed to DS-AR STEAM demonstrated substantially greater gains in scientific literacy.

Table 2. Scientific Literacy Outcomes in the Experimental and Control Groups

Outcome	Experimental Group	Control Group
Number of students	30	30
Post-test mean	94.67	82.33
Mean difference	12.34	-
N-Gain	0.848	0.495
N-Gain category	High	Moderate
Z	-3.957	
p-value	< .001	

Note. N-Gain was interpreted according to the categories reported in the thesis. Statistical significance was determined at $p < .05$. The inferential analysis further confirmed the difference between the two groups. The Mann-Whitney U test showed a statistically significant difference in post-test scientific literacy scores between the experimental and control groups ($p < .001$). Therefore, the null hypothesis of no difference between the two groups was rejected. Students who participated in the DS-AR STEAM intervention demonstrated significantly stronger scientific literacy outcomes than students receiving conventional instruction.

The combination of post-test and N-Gain results provides two complementary patterns. First, the experimental group achieved a higher level of scientific literacy at the end of the intervention. Second, the magnitude of improvement from initial to final assessment was also greater in the experimental group. Table 3 summarises this contrast.

Table 3. Comparison of Scientific Literacy Outcomes between Experimental and Control Groups

Experimental:	Post-test = 94.67	N-Gain = 0.848	(High)
Control:	Post-test = 82.33	N-Gain = 0.495	(Moderate)

Taken together, these findings indicate that students exposed to DS-AR STEAM not only achieved higher final scientific literacy scores but also demonstrated greater improvement relative to their initial performance.

Disaster Preparedness Outcomes

The second analysis examined whether differences in students' disaster preparedness were associated with the differences observed in scientific literacy. The results again showed an advantage for the experimental group. Students participating in DS-AR STEAM achieved a disaster preparedness score of 80.37%, categorised as Good, whereas students in the control group achieved 67.41%, categorised as Sufficient. The experimental group therefore exceeded the control group by 12.96 percentage points.

Table 4. Disaster Preparedness Outcomes in the Experimental and Control Groups

Outcome	Experimental Group	Control Group
Number of students	30	30
Disaster preparedness	80.37%	67.41%

Difference	12.96 percentage points	—
Category	Good	Sufficient
Statistical test	Mann Whitney U	Mann Whitney U
Interpretation	Higher preparedness	Lower preparedness
Outcome	Experimental Group	Control Group

The descriptive results therefore demonstrate that students exposed to the integrated intervention reached a higher preparedness category than students receiving conventional instruction. While the control group remained within the Sufficient category, the experimental group reached the Good category. The thesis further reports that disaster preparedness in the experimental group was significantly higher than that in the control group. These results indicate that the effect associated with DS-AR STEAM was not confined to students' scientific literacy but was also evident in their disaster-related preparedness.

Table 5. Comparison of Disaster Preparedness between Experimental and Control Groups

Experimental group:	80.37%	Good
Control group:	67.41%	ufficient

The difference between the two groups is consistent with the scientific literacy findings: the experimental group achieved stronger outcomes than the control group on both dependent variables.

Overall Pattern of the Intervention Effects

To provide an integrated overview, Table 6 summarizes the principal outcomes across scientific literacy and disaster preparedness.

Table 6. Summary of the Effects of DS-AR STEAM

Outcome	Experimental	Control	Difference/Pattern
Scientific literacy post-test	94.67	82.33	Experimental +12.34
Scientific literacy N-Gain	0.848	0.495	High vs. Moderate
Disaster preparedness	80.37%	67.41%	Experimental +12.96 percentage points
Preparedness category	Good	Sufficient	Higher category in experimental group

The overall results reveal a consistent advantage for the experimental group. Scientific literacy outcomes were higher among students who experienced DS-AR STEAM, as indicated by both their post-test scores and normalised gains. A similar pattern was observed for disaster preparedness, with the experimental group achieving a higher percentage and category than the control group. Importantly, these results correspond directly with the dual-outcome objective established in the article, which was to determine whether the integrated intervention produced stronger scientific literacy and disaster preparedness simultaneously than conventional science instruction. Thus, three main empirical findings can be identified. First, students participating in DS-AR STEAM achieved higher post-intervention scientific literacy than students in the conventional learning group. Second, the experimental group demonstrated a higher normalised gain (0.848) than the control group's moderate gain (0.495). Third, students in the experimental group demonstrated stronger disaster preparedness (80.37%; Good) than those in the control group (67.41%; Sufficient). Collectively, these findings provide evidence that the experimental group consistently outperformed the control group across both targeted learning outcomes.

Discussion

The findings demonstrate that technology-enhanced STEAM learning through augmented reality digital storybooks (DS-AR STEAM) was associated with stronger scientific literacy and disaster preparedness than conventional science instruction, indicating that the intervention supported both conceptual learning and the application of knowledge in disaster-related contexts. Students in the experimental group achieved a scientific literacy posttest mean of 94.67 compared with 82.33 in the control group, while the corresponding N-Gain values were 0.848 and 0.495, respectively, with the between-group difference reaching statistical significance ($p < .001$). This pattern is consistent with Suryanti et al. (2024), who reported that STEAM project-based learning can strengthen elementary students' scientific literacy by engaging them with meaningful problems requiring investigation, evidence interpretation, and interdisciplinary reasoning. The present findings also correspond with research demonstrating the educational potential of STEAM-supported AR for scientific literacy and science learning (Asyri & Asyri, 2024). However, the current study extends these earlier findings because AR was not implemented as an independent visualization medium but was deliberately embedded within contextual narratives, scientific inquiry, and interdisciplinary STEAM activities. Digital storytelling initially situated scientific concepts within disaster-related events and problems, while AR enabled students to interact with representations of processes that would otherwise be difficult to observe directly in an elementary classroom. This interpretation is compatible with previous evidence that digital picture storybooks can facilitate scientific literacy by embedding science concepts within narratives that are accessible and meaningful to elementary learners (Naresti, 2024). The subsequent STEAM activities required students to move beyond observing digital representations by interpreting evidence, integrating scientific and mathematical ideas, designing possible solutions, and communicating their reasoning. Consequently, the substantially higher N-Gain in the experimental group can be interpreted as evidence that the combination of contextualization, visualization, inquiry, and interdisciplinary problem-solving provided additional learning opportunities beyond those available through conventional instruction. These results therefore reinforce the view that the contribution of DS-AR STEAM to scientific literacy derives from the pedagogical coordination of multiple learning processes rather than from technological exposure alone.

A second important finding concerns disaster preparedness, for which the experimental group achieved 80.37%, categorized as Good, compared with 67.41%, categorized as Sufficient, in the control group. This result indicates that the benefits associated with DS-AR STEAM extended beyond scientific understanding to students' awareness, readiness, and responses concerning disaster-related situations. The finding is consistent with who demonstrated that contextual disaster learning can strengthen disaster literacy and resilience when scientific content is connected with environmental situations meaningful to elementary students. Unlike approaches in which disaster education primarily communicates hazard terminology or recommended procedures, the present intervention required students to interpret disaster situations, investigate underlying phenomena, consider available evidence, and evaluate possible actions. Such a learning sequence may explain why preparedness developed alongside scientific literacy, because students were repeatedly required to translate scientific understanding into judgments about risk and appropriate responses. AR visualization provided an additional representational layer by allowing students to examine disaster-related processes within a safe instructional environment rather than relying exclusively on verbal explanations or static images. This representational function is consistent with the educational potential attributed to AR-supported science learning, particularly when interactive visualization is connected with meaningful instructional tasks (Asyri & Asyri, 2024). Nevertheless, the preparedness findings should not be attributed solely to AR because disaster-related decision-making was explicitly embedded throughout the narrative, inquiry, and STEAM problem-solving sequence. The intervention consequently positioned preparedness as an applied learning outcome

in which students were expected to understand why particular actions were appropriate rather than simply recall predetermined responses. In this respect, DS-AR STEAM extends contextual disaster education by connecting preparedness with scientific explanation, evidence interpretation, interdisciplinary problem-solving, and reasoned decision-making within the same instructional environment.

Interpreting scientific literacy and disaster preparedness together provides a particularly important perspective on the contribution of the study because the experimental group demonstrated advantages across both outcomes rather than improvement in only one domain. Scientific literacy involves explaining phenomena (Morris, 2025), interpreting scientific evidence, and using information to formulate reasoned conclusions, whereas disaster preparedness requires learners to recognize risks and determine appropriate responses within potentially hazardous situations. The simultaneous pattern observed in the present study suggests that these competencies can be pedagogically connected when disaster phenomena are used as authentic contexts for applying scientific knowledge. Conceptually, students first encounter a disaster-related problem through narrative contextualization, then use AR-supported representations to explore relevant phenomena before engaging in scientific inquiry and interdisciplinary problem-solving. This progression is consistent with the benefits of contextualized digital storybooks reported by Naresti (2024), the potential of AR-supported science learning reported by Asyri and Asyri (2024), and the scientific literacy benefits associated with STEAM project-based learning reported by Suryanti et al. (2024). The distinction of the present study lies in combining these pedagogical affordances so that scientific reasoning becomes progressively connected with preparedness-oriented decision-making rather than remaining an isolated academic outcome. Narrative contextualization gives meaning to the problem, AR visualization makes relevant processes more accessible, scientific inquiry structures evidence interpretation, and STEAM activities require students to transform their understanding into possible solutions (Djam'an et al., 2026; Mansour et al., 2025; Pallavicini & Anesa, 2026). Evidence-based decision-making then provides the point at which scientific understanding is applied to evaluating risks and selecting preparedness-related responses. The findings therefore provide empirical support for the proposed instructional pathway of contextualized narrative → AR-supported visualization → scientific inquiry → interdisciplinary STEAM problem-solving → evidence-based disaster preparedness. Although the quasi-experimental design does not establish that improvement in scientific literacy directly caused improvement in preparedness, the parallel advantages across the two outcomes support further investigation of their pedagogical relationship within contextual elementary science education.

The results also contribute to existing literature by addressing the integration and pedagogical-mechanism gaps identified in the conceptual framework of the study. Previous research has provided evidence for digital storybooks in supporting scientific literacy (Naresti, 2024), AR-supported STEAM learning in science education (Asyri & Asyri, 2024), STEAM project-based learning for scientific literacy (Suryanti et al., 2024), and contextual disaster learning for disaster literacy and resilience. These studies collectively establish the educational potential of the individual or partially integrated components, but the present study organizes their complementary functions within a unified instructional architecture. This distinction is important because the educational effectiveness of digital technology cannot be adequately explained by the presence of a particular technological feature when the technology is embedded within a broader sequence of pedagogical interactions. In DS-AR STEAM, the digital storybook was responsible primarily for contextualization, AR supported interactive representation, scientific inquiry structured observation and evidence interpretation, and STEAM activities facilitated interdisciplinary solution development. Disaster risk reduction simultaneously provided an authentic context in which the knowledge generated through these activities could be translated into preparedness-oriented decisions. The observed advantages over

conventional instruction therefore support a pedagogical interpretation in which different affordances become mutually reinforcing when deliberately aligned with the intended learning outcomes. This interpretation moves beyond claims that AR or digital storytelling is inherently effective and instead emphasizes the instructional architecture through which technology is connected to cognitive and problem-solving activities. Accordingly, the novelty of DS-AR STEAM lies less in introducing a new digital tool than in orchestrating narrative, visualization, inquiry, interdisciplinary design, and decision-making as interconnected stages of science learning. This contribution is particularly relevant to technology-enhanced elementary education because it suggests that instructional design should prioritize the relationship between technological affordances and pedagogical processes rather than technological novelty itself.

Taken together, the findings provide evidence that DS-AR STEAM offers a promising instructional approach for connecting scientific reasoning with preparedness-oriented action, although the magnitude and interpretation of the results should remain bounded by the study design. The improvement observed in both groups indicates that conventional instruction also supported learning, while the larger gains in the experimental group suggest that the integrated intervention provided additional pedagogical opportunities rather than rendering conventional approaches ineffective. This balanced interpretation is important because the experimental advantage may reflect the combined influence of contextual narratives, interactive representations, inquiry, interdisciplinary problem-solving, and decision-making rather than any single component of the intervention. The findings consequently complement previous studies on STEAM scientific literacy (Suryanti et al., 2024), contextual disaster learning, AR-supported science education (Asyri & Asyri, 2024), and digital storybooks (Naresti, 2024) by demonstrating how these strands can be brought together around two interconnected educational outcomes. From a pedagogical perspective, the results suggest that disaster contexts can serve a dual function by providing authentic problems for developing scientific literacy while simultaneously creating opportunities to practice preparedness-oriented reasoning. From a technological perspective, AR appears most educationally meaningful when visualization becomes evidence that students must interpret and use rather than digital content that they merely observe. From an interdisciplinary perspective, STEAM provides a structure through which scientific explanations can be connected with mathematical reasoning, technological representation, engineering-oriented design, and creative communication. Nevertheless, because the study involved 60 fourth-grade students from two intact classes at a single school, the findings should not be generalized beyond comparable educational settings without additional evidence. Furthermore, the quasi-experimental design supports an interpretation of intervention-associated differences but does not isolate the independent contribution of storytelling, AR, or individual STEAM components, nor does it establish causal pathways between gains in scientific literacy and disaster preparedness. Future research should therefore replicate the intervention across schools and disaster contexts, employ larger and more diverse samples, examine longer-term retention and preparedness behavior, and use component-based or mediation designs to clarify how the individual and combined mechanisms of DS-AR STEAM contribute to learning outcomes.

Implications

The findings offer several practical implications for elementary science education. First, locally relevant disaster phenomena can be incorporated into science instruction as authentic contexts through which students develop scientific literacy while simultaneously strengthening disaster preparedness, rather than positioning disaster education as an isolated curricular topic. Second, the results emphasize a shift from technology-centered implementation toward pedagogy-centered technology integration, in which AR functions as part of a structured sequence involving contextual problem identification, interactive visualization, scientific inquiry, interdisciplinary

STEAM problem-solving, and preparedness-oriented decision-making. Accordingly, schools adopting AR should prioritize instructional design and teacher readiness alongside the provision of digital applications and devices. Third, the smartphone-based nature of DS-AR STEAM provides opportunities for adaptation in schools with varying levels of technological infrastructure, including collaborative device use when individual access is limited. Such adaptation should nevertheless ensure that students remain actively involved in observing, interpreting evidence, designing solutions, and making informed decisions rather than becoming passive users of digital content. Overall, DS-AR STEAM provides a practical instructional framework for integrating technology, scientific reasoning, interdisciplinary problem-solving, and disaster preparedness within meaningful elementary science learning.

Limitations and Suggestions for Future Research

This study has several limitations that should be considered when interpreting its findings. First, the research was conducted in a single school with 60 fourth-grade students and focused on floods and strong winds, limiting the generalizability of the results to other educational settings and disaster contexts. Future studies should therefore replicate DS-AR STEAM across larger and more diverse samples and extend its application to hazards such as earthquakes, tsunamis, landslides, and volcanic eruptions. Second, the quasi-experimental design did not involve strict randomized assignment, and the pretest used for N-Gain originated from the diagnostic phase of the DBR cycle, which limits the strength of causal inference. Accordingly, the N-Gain results should be interpreted as evidence of learning improvement rather than as an independent basis for causal conclusions. Future research should employ randomized or cluster-randomized designs with prospectively established baseline measures to provide stronger evidence of intervention effects. Third, the relatively short implementation period did not permit examination of long-term retention or the sustainability of students' disaster preparedness. Longitudinal studies incorporating delayed posttests and performance-based preparedness measures are therefore recommended to determine whether the observed gains persist and transfer to new disaster situations. Further research could also examine the relative contributions of digital storytelling, AR visualization, scientific inquiry, and STEAM problem-solving to clarify the mechanisms underlying the intervention. Overall, broader and more rigorous investigations are needed to establish the robustness, transferability, and long-term educational value of DS-AR STEAM in connecting scientific literacy with preparedness-oriented action.

CONCLUSION

This study demonstrates that STEAM-integrated augmented reality digital storybooks (DS-AR STEAM) were associated with stronger scientific literacy and disaster preparedness than conventional science instruction. The experimental group achieved higher scientific literacy ($M = 94.67$) than the control group ($M = 82.33$; $p < .001$), accompanied by a high N-Gain of 0.848 compared with a moderate N-Gain of 0.495 in the control group. Disaster preparedness showed a similar pattern, reaching 80.37% (Good) in the experimental group and 67.41% (Sufficient) in the control group. These findings suggest that DS-AR STEAM can support both scientific reasoning and the application of knowledge to preparedness-related situations. Its principal contribution lies not in AR alone but in the pedagogical integration of narrative contextualization, interactive visualization, scientific inquiry, interdisciplinary STEAM problem-solving, and evidence-based decision-making. This instructional architecture enables students to progress from understanding disaster-related scientific phenomena to interpreting evidence, developing solutions, and considering appropriate

responses to authentic risks. Accordingly, scientific literacy and disaster preparedness can be addressed as interconnected outcomes within contextual elementary science learning. The findings also highlight the importance of positioning technology as part of a coherent pedagogical system rather than merely as a tool for presenting digital content. Nevertheless, the single-school setting, use of intact classes, focus on floods and strong winds, and relatively short intervention period limit the broader interpretation of the findings. Future research should evaluate DS-AR STEAM with larger and more diverse samples, additional disaster contexts, stronger experimental designs, and longitudinal assessments. Overall, DS-AR STEAM represents a promising pedagogical approach for connecting scientific understanding with informed and preparedness-oriented action in elementary science education.

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AUTHOR CONTRIBUTIONS STATEMENT

Cholifah Tur Rosidah contributed to the conceptualization, research design, development of the DS-AR STEAM intervention, instrument development, data collection, data analysis, interpretation of the findings, and preparation of the original manuscript. Deving Eka Misbakhul contributed to the development and implementation of the augmented reality digital storybook, instructional design, data collection, and manuscript review. Danang Prastyo contributed to the development of STEAM learning activities, instrument validation, classroom implementation, data analysis, and interpretation of the results. Reza Rachmadtullah contributed to the research methodology, supervision, validation of the instructional framework, interpretation of the findings, and critical revision of the manuscript. Las Johansen B. Caluza contributed to methodological refinement, interpretation of the results, international scholarly perspectives, and critical review and editing of the manuscript. All authors contributed to the refinement of the study, reviewed the manuscript, and approved the final version for publication.

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