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Development of an Ethno-STEAM-adapted Physics e-Module using a Deep Learning Approach to Improve Disaster Mitigation Literacy in Sikka Regency, Indonesia

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Abstract: This study aimed to develop, validate, and evaluate the effectiveness of a Deep Learning (DL) Physics Teaching e-Module, adapted through an Ethno-STEAM approach, to enhance disaster-mitigation literacy regarding earthquakes and volcanic eruptions among senior high school students in Sikka Regency, East Nusa Tenggara. A Research and Development design based on the Borg and Gall model was employed, integrated with a non-equivalent control group quasi-experimental design for the effectiveness phase. Participants comprised 285 students and 6 teachers from four senior high schools, selected through purposive sampling. Instruments included validation sheets (5 experts), student response questionnaires, observation sheets, and a 30-item achievement test (KR-20 = 0.84). Data were analyzed using descriptive statistics, independent t-tests, ANCOVA, exploratory factor analysis, and thematic analysis. The e-module demonstrated strong validity (mean CVI = 0.86, ICC = 0.84) and practicality (91.2% Perceived Pedagogical Relevance factor). Experimental classes achieved significantly higher post-test scores ($M = 81.2$, $SD = 7.4$) than control classes ($M = 68.9$, $SD = 8.2$), with ANCOVA confirming a large adjusted group effect ($F(1,218) = 142.6$, $p < 0.001$, partial $\eta^2 = 0.395$). Descriptive cross-school patterns indicated that implementation conditions differed in teacher ICT competency, principal support, and student access to technology; these school-level factors were not treated as inferential moderators because only three schools were included in the operational test. Thematic analysis of teacher interviews indicated that the e-module supported contextual negotiation between indigenous *pire tanah* knowledge and modern physics concepts (mechanical waves and Archimedes' principle). Among the Sikka schools studied, the Ethno-STEAM-adapted DL Physics e-Module was a viable, practical, and effective instructional resource for disaster-mitigation literacy. Its implementation should be interpreted in light of differences in teachers' ICT capacity and school infrastructure. The proposed Synergistic Pedagogical Model (SPM-ESDL) offers a framework for further testing in other cultural and disaster contexts rather than a universally established model.

Keywords: ethnophysics, STEAM, deep learning, disaster mitigation, Sikka regency.

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INTRODUCTION

Flores Island, including Sikka Regency, is exposed to complex seismic and tsunami hazards, making disaster literacy a substantive educational need (Pranantyo, Heidarzadeh, & Cummins, 2021). School-based disaster education is generally associated with improved preparedness when it is contextual, sustained, and supported by adequate instructional resources (Seddighi et al., 2022; Yildiz, Dickinson, Priego-Hernández, Teeuw, & Shaw, 2024). In the local Sikka context, previous analysis of physics teaching modules also indicated weaknesses in the implementation of student-centered learning principles (Elizabeth, Agung, & Debrito, 2024). The preliminary needs assessment in the present development study involved the broader sample of 285 students and included diagnostic items, interviews, and analysis of five physics modules. Only 28.3% of students were able to explain the relationship between wave concepts and earthquakes, and none of the five modules integrated local disaster contexts with Sikka cultural knowledge. Importantly, this needs-assessment sample is reported separately from the operational quasi-experimental baseline: the pre-test mean of 56.4 (SD = 8.7) shown later in Table 2 pertains specifically to the 108 students in the experimental group during operational field testing, not to the entire 285 students.

Ethno-STEAM offers a plausible response to this gap, as culturally grounded STEM instruction can connect formal scientific concepts with familiar community knowledge and practices. Systematic reviews indicate that Indigenous knowledge can strengthen relevance, engagement, and conceptual access in STEM when it is integrated carefully rather than treated as decoration (Jin, 2021; Matindike & Ramdhany, 2025). Similar work in geoscience education also shows that centering traditional knowledge can help students see cultural knowledge and Western science as complementary rather than mutually exclusive (Todd, Towne, & Clarke, 2023).

In disaster education, digital and culturally contextualized resources are particularly relevant because they can combine scientific explanations, local experiences, and active problem-solving. An ethnoscience-based digital disaster module has shown that locally grounded content can support disaster-preparedness learning (Bachri et al., 2024), while recent STEAM research emphasizes that the sequencing and integration of STEAM components influence students' conceptual understanding (Corrigan, Wong, Grove, Andersen, & Hughes, 2025). Indigenous STEM curricula have likewise been proposed specifically for disaster-prevention education (Chen & Wu, 2024). Within the Emancipated Curriculum and the Deep Learning (DL) approach, the present study therefore develops a DL Physics Teaching e-Module that connects Sikka local knowledge with physics concepts and disaster-mitigation problems.

Operationally, the Ethno-STEAM-adapted DL Physics Teaching e-Module is defined as a digital teaching resource built on the Canva Pro platform that integrates the four learning experience frameworks of Fullan's Deep Learning (pedagogical partnerships, learning environments, leveraging digital, and learning partnerships) with the five components of Ethno-STEAM (Science, Technology, Engineering, Art, Mathematics) and Sikka local wisdom (*pire tanah*). The pedagogical framework referenced throughout this study is the Fullan et al. (2020) Deep Learning framework, which emphasizes meaningful learning through higher-order cognitive engagement, reflection, and learning partnerships.

The *pire tanah* ritual, a communal practice in which groups of Sikka community members rhythmically and synchronously stamp the earth, is particularly relevant to physics and disaster mitigation. The ritual embodies four physics principles: (1) synchronous stamping generates mechanical surface waves that propagate through the soil medium, fundamentally analogous to seismic surface waves (Rayleigh waves); (2) resonance occurs when the stamping frequency approaches the natural frequency of the soil, providing empirical understanding of why resonance is dangerous for buildings during earthquakes; (3) the distribution pattern of vibrations can be modeled as wave interference from multiple sources; and (4) Archimedes' principle becomes relevant when *pire tanah* is performed on muddy terrain, where buoyant force and soil pressure come into play. These principles serve as starting points for learning about earthquake mitigation: students learn how seismic waves propagate, why resonance is hazardous, and how earthquake-resistant structural design mitigates these effects. A concrete example of this integration in the e-module is the "*Pire tanah* Wave Laboratory" activity, where students: (a) use smartphone sensors (Technology) to measure vibration frequency and amplitude during simulated *pire tanah*; (b) calculate wavelength, frequency, and wave speed (Mathematics); (c) design earthquake-resistant structural models (Engineering); (d) analyze the rhythmic pattern of *pire tanah* as both cultural art and periodic wave manifestation (Art); and (e) connect these observations to seismic wave concepts (Science).

Previous research provides three relevant lines of evidence. First, ethnoscience-based digital disaster modules have been developed to connect local practices with disaster preparedness (Bachri et al., 2024). Second, an ethnoscience e-module on vibration and waves has demonstrated the feasibility of embedding local knowledge in science learning materials (Damayanti, Supeno, & Asyiah, 2025). Third, international research on Indigenous STEM and culturally sustaining science education shows that local knowledge can function as a meaningful context for science learning when cultural and scientific explanations are handled explicitly (Chen & Wu, 2024; Jin, 2021; Todd et al., 2023).

The present study differs from those strands in its combination of three elements within a single physics teaching resource: (a) Fullan's Deep Learning framework as the pedagogical process; (b) Ethno-STEAM as the interdisciplinary design structure; and (c) Sikka's *pire tanah* as the local cultural context for learning mechanical waves, resonance, and disaster mitigation. Bachri et al. (2024) focused on ethnoscience-based disaster learning but not on the DL framework; Damayanti et al. (2025) focused on vibration and wave content, but not disaster-mitigation literacy; and broader Indigenous STEM studies do not operationalize the specific Sikka context. The novelty claimed here is therefore the pedagogical integration and contextual transformation of established approaches, rather than the invention of Ethno-STEAM or the integration of Indigenous knowledge itself.

The conceptual framework assumes a complementary relationship between Ethno-STEAM and Deep Learning. Fullan, Quinn, Drummy, and Gardner (2020) provide the pedagogical emphasis on meaningful learning, learning environments, partnerships, and purposeful use of digital tools. In contrast, Ethno-STEAM provides the contextual and interdisciplinary structure through which those experiences are enacted. In this study, Sikka local knowledge functions as a contextual bridge rather than as a substitute for scientific explanation. This position is consistent with cross-cultural science education, which emphasizes explicit movement between knowledge systems (Aikenhead, 2001; Cobern, 1996), and with recent systematic evidence recommending deliberate, culturally responsive integration of Indigenous knowledge in STEM (Matindike & Ramdhany, 2025).

These studies indicate that previous research has not yet fully produced comprehensive teaching materials that span from planning to learning resources, specifically integrated with the four frameworks of learning experience in the Deep Learning (DL) approach within the *Independent Curriculum*. Specifically, three comprehensive aspects are missing from prior studies: (1) the integrative aspect, no study has holistically integrated the DL framework (Fullan's four learning experiences) with the Ethno-STEAM approach (five components) in a single teaching resource; this aspect is crucial because meaningful learning requires both cognitive depth (DL) and cultural-scientific contextualization (Ethno-STEAM), and the separation of the two in prior research has resulted in partial pedagogical innovations; (2) the contextual aspect, no study has adapted Sikka local wisdom (*pire tanah*) into physics learning for disaster mitigation literacy; this aspect is crucial because the effectiveness of contextual learning depends on cultural relevance that can only be obtained from specific local wisdom; (3) the multi-hazard aspect, prior studies typically focus on a single hazard type (earthquake OR volcanic), whereas Sikka faces dual risks (earthquake AND volcanic eruption) requiring an integrated approach; this aspect is crucial because effective mitigation literacy must reflect the real hazard spectrum faced by students. The chosen solution for this study is the development of a holistic, dynamic, flexible, responsive, student-centered, and digitally leveraged Ethno-STEAM-adapted Physics Teaching e-Module.

Accordingly, the research questions guiding this study are reformulated to focus on evaluation rather than development: (RQ1) How effective is the Ethno-STEAM-adapted DL Physics e-Module in enhancing students' disaster mitigation literacy compared to conventional instruction? (RQ2) To what extent is the e-module perceived as practical by teachers and students across different school contexts in Sikka? (RQ3) What contextual factors are associated with variations in e-module effectiveness across schools, and how does the integration of *pire tanah* local wisdom contribute to pedagogical innovation? The objective of this research is to evaluate the effectiveness, practicality, and unique pedagogical contribution of the Ethno-STEAM-adapted DL Physics Teaching e-Module for earthquake- and volcanic-eruption disaster-mitigation literacy among senior high school students in Sikka.

METHOD

This study employed a Research and Development (R&D) design based on the Borg and Gall model, which outlines ten systematic steps of product development. The research focused on the design, development, and validation of a Physics Deep Learning (DL) e-Module that integrates an Ethno-STEAM approach to support disaster mitigation related to earthquakes and volcanic eruptions. The final product was designed as a digital learning resource for high school physics that contextualizes scientific concepts with the local wisdom of the Sikka community.

Participants

The population comprised all grade XII science-stream students in six senior high schools in Sikka Regency ($N \approx 1,245$). The development sample consisted of 285 students and 6 physics teachers from four purposively selected senior high schools based on disaster-risk context, availability of certified physics teachers, and minimum classroom infrastructure. The main field testing at SMAN 1 Talibura involved 2 physics teachers and 64 students. Operational Field Testing involved 221 students from SMAN 1 Waigete, SMAN Bola, and SMAN Waiblama: 108 in the experimental group (51 males, 57 females, mean age = 17.2 years, SD = 0.4) and 113 in the control group (54 males, 59 females, mean age = 17.1 years, SD = 0.4). Initial semester-1 physics grades were comparable (experimental M = 68.4, SD = 7.8; control M = 67.9, SD = 8.1; $t(219) = 0.47$, $p = 0.638$). Technology access was documented at the school level before the intervention: regular student smartphone access was 89% at SMAN 1 Waigete, 67% at SMAN Bola, and 64% at SMAN Waiblama. Experimental and control classes were assigned within the same schools, so each pair shared the same school-level technology environment. However, no individual pre-intervention digital literacy test or prior platform use history was collected; therefore, equivalence of individual technical skills cannot be claimed from these data alone. Class assignments within each school were drawn from available Grade XII science classes, yielding six operational classes (3 experimental and 3 control).

Research Design and Procedures

The research design combined the Borg and Gall (1983) R&D model with a non-equivalent control group quasi-experimental design (Campbell & Stanley, 1963) to evaluate effectiveness. The quasi-experimental design was chosen because random assignment at the individual student level was not feasible in school settings, but class-level random assignment was implemented. The study was conducted over eight months (March-October 2025).

The product development followed the systematic steps of the Borg and Gall model, adapted into ten stages: (1) Research and Information Collecting, identifying students' learning needs through interviews on Sikka's cultural heritage, literature review, technology analysis, and stakeholder consultation; (2) Planning, designing the e-module based on needs analysis, determining ethno-physics content, formulating learning objectives, integrating STEAM components, and aligning with the four DL frameworks; (3) Develop Preliminary Form of Product, creating the initial Canva Pro version; (4) Preliminary Field Testing, expert validation using validation sheets; (5) Main Product Revision, refining based on expert feedback (transition criterion: Content Validity Index (CVI) e" 0.78 from at least five experts, following Polit & Beck, 2006); (6) Main Field Testing, implementing the e-module in three physics classes at SMAN 1 Talibura with pre-test/post-test design; (7) Operational Product Revision, refining based on main field testing results (transition criterion: e" 80% student responses in "good" or "very good" categories and no substantive teacher criticism); (8) Operational Field Testing, testing in two physics classes across three additional schools with experimental and control groups; (9) Final Product Revision, finalizing the product; (10) Dissemination and Implementation, limited dissemination to 40 senior high schools across Sikka Regency. Each transition decision was documented in a research log and reported transparently.

Threats to internal validity were addressed as follows: (1) selection bias, reduced through comparable initial physics grades and class assignment within each school; (2) history, reduced through parallel treatment schedules; (3) maturation, reduced by the four-week duration; (4) testing effects, reduced through the pre-post interval and parallel test items; (5) instrumentation, reduced through identical achievement-test procedures and trained observers; and (6) attrition, with no attrition during operational testing. Two residual threats remain relevant: possible treatment diffusion between classes within the same school and unmeasured individual differences in digital literacy. The latter is especially important because the intervention required smartphones and Canva-based access; school-level device access cannot substitute for an individual baseline measure of digital competence (Falloon, 2020).

Implementation procedure: The experimental group used the Ethno-STEAM-DL e-module on the Canva Pro platform, accessed via an LCD projector and student smartphones, across four 90-minute sessions (360 minutes total) over four weeks. Session sequence: Session 1, *pire tanah* phenomenon and mechanical wave concepts; Session 2, seismic waves and earthquake mitigation; Session 3, Archimedes' principle and tsunami; Session 4, disaster-resistant structural design (STEAM project). The control group used the conventional printed physics module already used by the school (chapter on Vibration and Waves) taught with the conventional lecture-discussion method by the same teacher, for the same duration (four 90-minute sessions over four weeks). Both groups received the pre-test in week 1 and the post-test in week 4.

Instruments

Four instruments were employed: (1) Validation Sheets, used by a panel of five experts to measure content, construct, and presentation validity. The panel comprised: two physics content experts (PhDs in Physics Education, 12 and 15 years of experience, respectively), one instructional media expert (PhD in Educational Technology, 10 years), one ethno-science expert (PhD in Cultural Anthropology of NTT, 18 years), and one disaster education expert (PhD in Disaster Science, 8 years). Inter-rater reliability was calculated using Cohen's Kappa for each expert pair (mean pairwise ê = 0.82, "almost perfect agreement" per Landis & Koch, 1977) and the Intraclass Correlation Coefficient (ICC) for the whole panel (ICC single measures = 0.84, 95% CI [0.71, 0.94]; ICC average measures = 0.96).

(2) Student Response Questionnaire. For the between-group comparison, both experimental and control students completed a matched 30-item common-core questionnaire using the same three constructs: Perceived Pedagogical Relevance (12 items), Engagement & Interactivity (10 items), and Perceived Learning Effectiveness (8 items). The stems were deliberately module-neutral so that both groups could answer the same construct-level questions. For example, control-group items used wording such as: "The learning material used in this class helps me connect physics concepts with real situations," "The learning activities encourage me to participate actively," and "The learning material helps me explain disaster-related physics concepts." The experimental form used equivalent wording with "e-module" replacing "learning material" where appropriate. Items that specifically evaluated Canva navigation, smartphone-sensor functions, multimedia features, or the *pire tanah* content were treated as treatment-specific descriptive feedback and were not included in the inferential experimental-versus-control comparison reported in Table 1. All common-core items used a 4-point Likert scale (1 = Strongly Disagree to 4 = Strongly Agree).

(3) Observation Sheets were used by trained observers to assess learning implementation and classroom atmosphere using a 4-point scale (1 = Poor, 2 = Fair, 3 = Good, 4 = Very Good). (4) Achievement Test. A 30-item test, developed for the study, measured disaster-mitigation literacy across four domains: physics concepts relevant to disasters (8 items), understanding of local risks (7 items), preparedness and mitigation actions (8 items), and analysis of disaster scenarios (7 items). Content validity was evaluated by five experts; the mean Content Validity Ratio was 0.78, and all retained items met the study's predefined content-validity criterion. Internal consistency for the dichotomously scored items was KR-20 = 0.84. A 20-item Disaster Preparedness Attitude Questionnaire (5-point Likert scale) was also administered before and after the intervention. The use of expert-based content validity indices followed the reporting principles outlined by Polit & Beck (2006).

Data Analysis

Data analysis combined quantitative and qualitative techniques. Validity analysis used expert ratings, Content Validity Index (CVI), and Intraclass Correlation Coefficient (ICC). Student-response analysis used descriptive statistics, exploratory factor analysis (principal-axis factoring with oblimin rotation), and independent-samples t-tests only for the matched common-core questionnaire dimensions shared by both groups. Treatment-specific ratings for Canva, multimedia, smartphone sensor functions, and *pire tanah* integration were excluded from the between-group t-tests. This distinction was made to preserve construct comparability between experimental and control students.

Effectiveness analysis used: (1) normalized gain (N-gain) scores from pre-test and post-test results, interpreted using Hake's (1998) categories (low: $g < 0.30$; medium: 0.30 d" g d" 0.70; high: $g > 0.70$); (2) independent samples t-tests comparing post-test scores between experimental and control groups, with Cohen's d effect size; (3) one-way ANCOVA with pre-test as covariate to control for initial differences, with partial eta-squared (ç^{2}) effect size, after verifying assumptions of linearity, homogeneity of regression slopes, normality of residuals (Shapiro-Wilk), and homoscedasticity (Levene's); (4) per-item analysis to identify physics concepts with the most significant improvement and those remaining difficult; (5) Pearson correlation and simple linear regression to examine the relationship between student perceptions and N-gain; (6) descriptive cross-school comparison of teacher ICT competency, principal support, and student technology access alongside N-gain. Because only three schools were included, these school-level variables were not tested as inferential moderators.

Teacher interviews and student reflections were analyzed using Braun and Clarke's (2006) six-phase thematic analysis. Trustworthiness was strengthened through methodological triangulation, member checking with three teachers, contextual description, an audit trail, independent review by two researchers, and documented reflexivity, consistent with recommendations for transparent thematic analysis (Nowell, Norris, White, & Moules, 2017). Quantitative and qualitative findings were integrated using an explanatory sequential mixed-methods logic and a joint-display matrix (Creswell & Plano Clark, 2018).

RESULT AND DISCUSSION

Needs Analysis

The initial stage identified students' learning needs for disaster mitigation related to earthquakes and volcanic eruptions. Interviews with teachers, students, and local stakeholders revealed that students had limited awareness that physics concepts represent natural phenomena in daily life. Consequently, they found it difficult to apply physics knowledge to real-world problems such as disaster mitigation. Teachers emphasized the need for contextual teaching modules that could guide instruction and train students to apply physics concepts relevant to their regional and cultural contexts. Essential physics content related to disaster mitigation was identified as the concept of waves, as stated in the F phase physics curriculum. To address these needs, the integration of local wisdom, STEAM approaches, and digital technology (Canva) was determined as the foundation for developing the e-module.

The quantitative needs assessment is reported separately from the operational experimental baseline. Across the broader development sample (N = 285), 28.3% of students could explain the relationship between wave concepts and earthquakes, and analysis of five existing physics modules showed that none integrated local disaster contexts with Sikka cultural knowledge. These indicators were used to justify product development, not as the baseline mean for the quasi-experiment. The operational pre-test statistics are reported only in Table 2: among the 108 experimental students, M = 56.4 (SD = 8.7), whereas the 113 control students had M = 55.8 (SD = 8.5). This separation prevents the development-sample needs data from being conflated with the operational experimental baseline.

Product Development and Validation

The preliminary product was developed using Canva Pro, incorporating physics concepts, local wisdom (*pire tanah*), and STEAM elements. Expert validation yielded an average score of 86%, with content clarity at 91%, media display at 85%, and ease of use at 82%. Validation was conducted iteratively in two rounds. Round 1 yielded 82.3%, with revisions focused on clearer tsunami examples for Archimedes' principle, improved seismic-wave visualization, and step-by-step guidance for the *pire tanah* activity. Round 2 yielded 86.4% after the addition of three sub-activities, interactive wave animations, and the 1992 Sikka tsunami case. Inter-rater agreement was strong (mean pairwise Cohen's $\kappa = 0.82$; ICC single measures = 0.84; ICC average measures = 0.96), supporting progression to classroom testing. Agreement interpretation followed Landis & Koch (1977), while content-validity reporting followed Polit and Beck (2006).

Main Product Revision

Revisions were made to various disaster mitigation domains related to community cultural heritage and scientific concepts embedded in local wisdom associated with wave phenomena in the learning activities presented in the teaching e-module.

Main Field Testing

Field trials were conducted in two classes (XII IA 1 and XII IA 2) at SMAN 1 Talibura. The results are as follows:

Student Responses: Class XII IA 1: average score of 92% (very good) across media display, usability, and learning benefits. Class XII IA 2: average score of 89% (very good) across the same aspects. These findings indicate high levels of student acceptance and practicality of the e-module.

Learning Outcomes: Class XII IA 1: pre-test (59) → post-test (83), N-gain = 0.62 (medium effectiveness). Class XII IA 2: pre-test (56) → post-test (80), N-gain = 0.54 (medium effectiveness). The increase in learning outcomes demonstrates that the e-module effectively enhanced students' understanding of physics concepts in the context of disaster mitigation.

Observations: Classroom implementation and atmosphere were categorized as good, with average scores of 3.69–3.70 across both classes. Teachers successfully managed learning activities aligned with the deep learning framework, and students actively engaged in discussions, reflection, and cultural integration.

Student Engagement: Students expressed strong interest: 80% were very interested in learning materials and applications, 90% in worksheets (LAPD) and classroom atmosphere, and 100% in simple experiments. This high level of engagement confirms that the e-module was novel and motivating for learners.

Interviews: Teachers noted that the module introduced a contextual innovation in physics learning, enabling students to connect physics concepts to real-life disaster challenges. It also served as a best practice reference for planning deep learning in alignment with the national curriculum.

Operational Product Revision

Improvements were implemented in the descriptions of student activities related to the selected disaster mitigation projects.

Students' Responses

Student responses were analyzed using the matched 30-item common-core questionnaire described in the Instrument section. Table 1 presents the three-factor solution (KMO = 0.87; Bartlett's $\chi^2(435) = 2847.3$, $p < 0.001$; total variance explained = 68.4%): Factor 1, Perceived Pedagogical Relevance (12 items, $\alpha = 0.89$, 31.2% variance); Factor 2, Engagement & Interactivity (10 items, $\alpha = 0.85$, 22.7% variance); and Factor 3, Perceived Learning Effectiveness (8 items, $\alpha = 0.82$, 14.5% variance).

Because these dimensions were assessed with parallel, module-neutral items, the inferential comparison reflects students' perceptions of the learning experience rather than control students' evaluations of e-module-specific features they did not receive.

Table 1. Per-Dimension student responses (EFA-Based)

Dimension	Group	Mean (%)	SD	t (df=219)	p	Cohen's d
Perceived Pedagogical Relevance	Experimental	91.2	6.4	23.4	<0.001	3.02
	Control	67.8	9.1			
Engagement & Interactivity	Experimental	88.7	7.2	21.8	<0.001	2.82
	Control	64.3	10.1			
Perceived Learning Effectiveness	Experimental	87.4	7.9	19.4	<0.001	2.55
	Control	65.1	9.7			
Overall	Experimental	89.1	7.2	22.5	<0.001	2.79
	Control	65.7	9.6			

All three common-core dimensions differed significantly between groups, with very large standardized mean differences (Cohen's $d > 2.5$). These results indicate that experimental students rated pedagogical relevance, engagement, and perceived learning effectiveness more highly than control students; they should not be interpreted as evidence that control students evaluated Canva, smartphone sensors, or *pire tanah* features. Within the experimental group, the total common-core questionnaire score correlated with N-gain ($r = 0.62$, $p < 0.01$), and simple regression yielded $R^2 = 0.38$, $F(1, 106) = 65.8$, $p < 0.001$. More broadly, meta-analytic evidence suggests that digital tools are most beneficial when they support specific learning activities and pedagogical goals rather than merely replacing non-digital materials (Hillmayr, Ziernwald, Reinhold, Hofer, & Reiss, 2020; Major, Francis, & Tsapali, 2021; Wu, 2024).

Learning Outcomes

Effectiveness was measured using N-gain scores, independent-samples t-tests, and ANCOVA. Table 2 reports the per-school means and standard deviations. At the same time, Figure 1 presents the same pre-test and post-test means as an interaction (profile) plot, allowing the different score trajectories of the experimental and control groups to be read directly across schools.

Table 2. Students' learning outcomes with statistical tests

School	Group	Pre-test M (SD)	Post-test M (SD)	N-gain	t (df)	p	Cohen's d
SMAN 1 Waigete	Exp	59.2 (8.4)	83.1 (7.1)	0.62	6.42 (72)	<0.001	1.49
	Ctrl	58.1 (8.6)	70.3 (8.0)	0.28			
SMAN Bola	Exp	55.4 (8.7)	80.2 (7.5)	0.56	5.83 (70)	<0.001	1.37
	Ctrl	54.3 (8.9)	68.5 (8.4)	0.25			
SMAN Waiblama	Exp	56.1 (8.5)	80.3 (7.6)	0.54	5.91 (75)	<0.001	1.35
	Ctrl	56.7 (8.3)	69.1 (8.2)	0.23			
Overall	Exp	56.4 (8.7)	81.2 (7.4)	0.58	11.87 (219)	<0.001	1.60
	Ctrl	55.8 (8.5)	68.9 (8.2)	0.25			

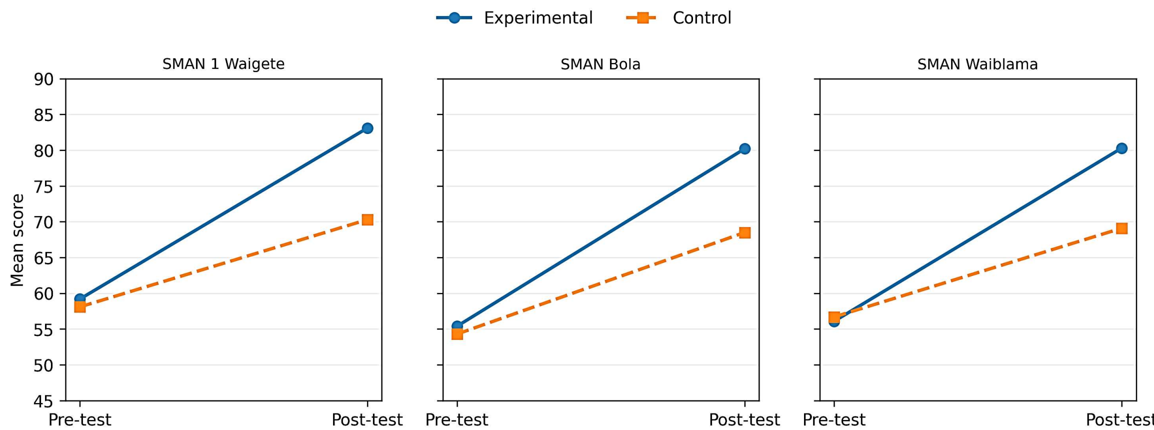

Figure 1. Interaction profile plot of mean pre-test and post-test scores by group and school

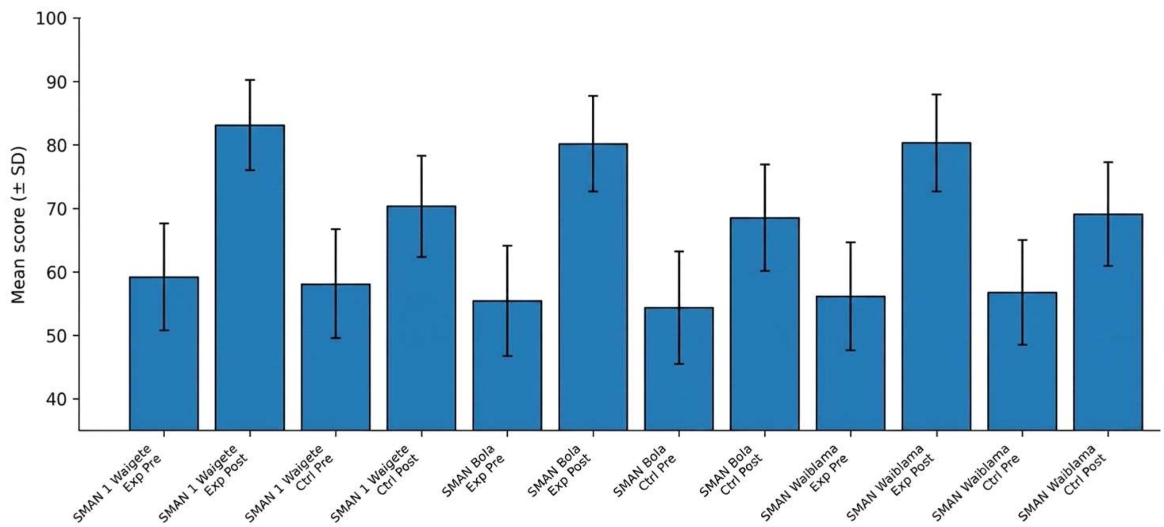

Figure 2. Pre-test and post-test mean scores with SD error bars by school and group

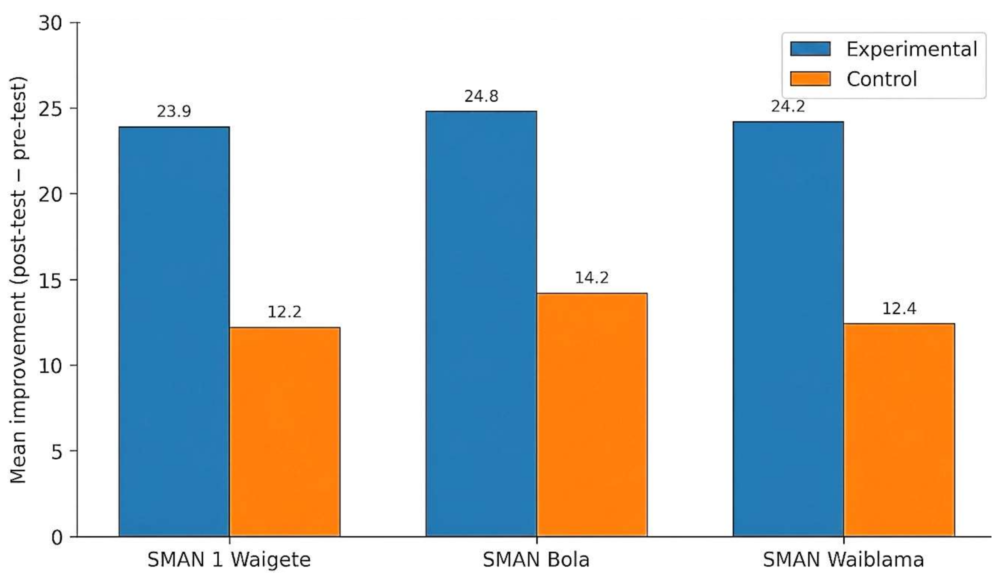

Figure 3. Mean score improvement (post-test minus pre-test) by school and group

ANCOVA with pre-test as covariate confirmed a statistically significant adjusted group difference favoring the experimental group: $F(1, 218) = 142.6$, $p < 0.001$, partial $\eta^2 = 0.395$. Assumptions were verified: linearity (pre-test vs post-test $r = 0.62$, $p < 0.001$), homogeneity of regression slopes ($F(2, 217) = 1.42$, $p = 0.243$), normality of residuals (Shapiro-Wilk $W = 0.99$, $p = 0.21$), and homoscedasticity (Levene's $F(1, 219) = 1.87$, $p = 0.173$). Effect-size reporting is retained to distinguish statistical significance from practical magnitude (Lakens, 2013). Using Hake's (1998) categories, all experimental classes achieved medium N-gain (0.31–0.70), while control classes remained in the low category ($g < 0.30$).

Per-item analysis identified the greatest improvement in surface-wave concepts ($\Delta = +42.8\%$, $p < 0.001$) and Archimedes' principle in a tsunami context ($\Delta = +38.5\%$, $p < 0.001$), while wave interference remained the most difficult concept (experimental post-test = 61.2%). Figure 2 displays the means from Table 2, with SD error bars, for each school and group. Figure 3 displays the mean score improvement (post-test minus pre-test) derived directly from the same aggregate data: experimental gains were 23.9, 24.8, and 24.2 points across the three schools, compared with 12.2, 14.2, and 12.4 points in the control classes. A box plot was not reported because individual-level raw scores were not available in the manuscript dataset used for this revision; constructing medians, quartiles, or outliers from means and SDs would be statistically invalid. The observed pattern is consistent with evidence that appropriately integrated digital tools can improve science learning outcomes (Sung, Yang, & Lee, 2017; Zhai, Zhang, Li, & Zhang, 2019).

Attitude Change and Disaster Preparedness

The Disaster Preparedness Attitude Questionnaire showed a larger pre-post change in the experimental group (pre-test $M = 42.3$, $SD = 6.8$; post-test $M = 78.5$, $SD = 5.9$; N-gain = 0.63) than in the control group (pre-test $M = 41.8$, $SD = 7.1$; post-test $M = 48.2$, $SD = 6.5$; N-gain = 0.11). ANCOVA yielded $F(1, 218) = 98.4$, $p < 0.001$, partial $\eta^2 = 0.311$. Post-intervention disaster-scenario problem-solving scores also favored the experimental group ($M = 76.4$, $SD = 8.2$) over the control group ($M = 52.7$, $SD = 10.4$), $t(219) = 20.3$, $p < 0.001$, $d = 2.60$. This direction is consistent with evidence from school-based disaster education showing that structured educational interventions can improve preparedness knowledge and protective responses (White-Lewis, Beach, & Zegers, 2021; Widowati, Istiono, & Husodo, 2021; Yildiz et al., 2024).

Classroom Observations

Observations: Classroom observations assessed learning implementation and the classroom atmosphere.

Classroom observations showed consistently higher implementation ratings in experimental classes than control classes. These

Table 3. Learning observation results

School	Class	Mean Observation Score	Category	Product Success Indicator
SMAN 1 Waigete	Experimental	3.70	Good	Very Good Implementation
	Control	3.10	Fairly Good	Standard Implementation
SMAN Bola	Experimental	3.65	Good	Good Implementation
	Control	3.05	Fairly Good	Standard Implementation
SMAN Waiblama	Experimental	3.69	Good	Good Implementation
	Control	3.00	Fairly Good	Standard Implementation

observational differences should be interpreted as part of the intervention package (digital resource, instructional structure, and teacher facilitation) rather than as an isolated 'technology effect.' This interpretation is consistent with evidence that digital resources produce stronger outcomes when coupled with appropriate instructional support and purposeful learning activities (Bond, Bedenlier, Marín, & Händel, 2021; Hillmayr et al., 2020; Major et al., 2021).

Student Engagement

Engagement was measured by students' interest in three learning components using a 4-point Likert questionnaire (1 = Strongly Not Interested, 4 = Strongly Interested), converted to the percentage of students who responded "Interested" or "Strongly Interested." Figure 4 (heatmap) visualizes engagement across components and schools. The heatmap uses color gradients from yellow (low, 50-60%) to dark green (high, 90-100%), revealing: (1) experimental cells are consistently greener than control cells; (2) the "simple experiments" column is consistently the greenest for experimental groups; (3) the SMAN Waiblama control cell is the yellowest (lowest). It is important to clarify that the 100% interest figure for simple experiments applies only to the experimental classes at SMAN 1 Waigete and SMAN Waiblama; for SMAN Bola, the figure was 98%.

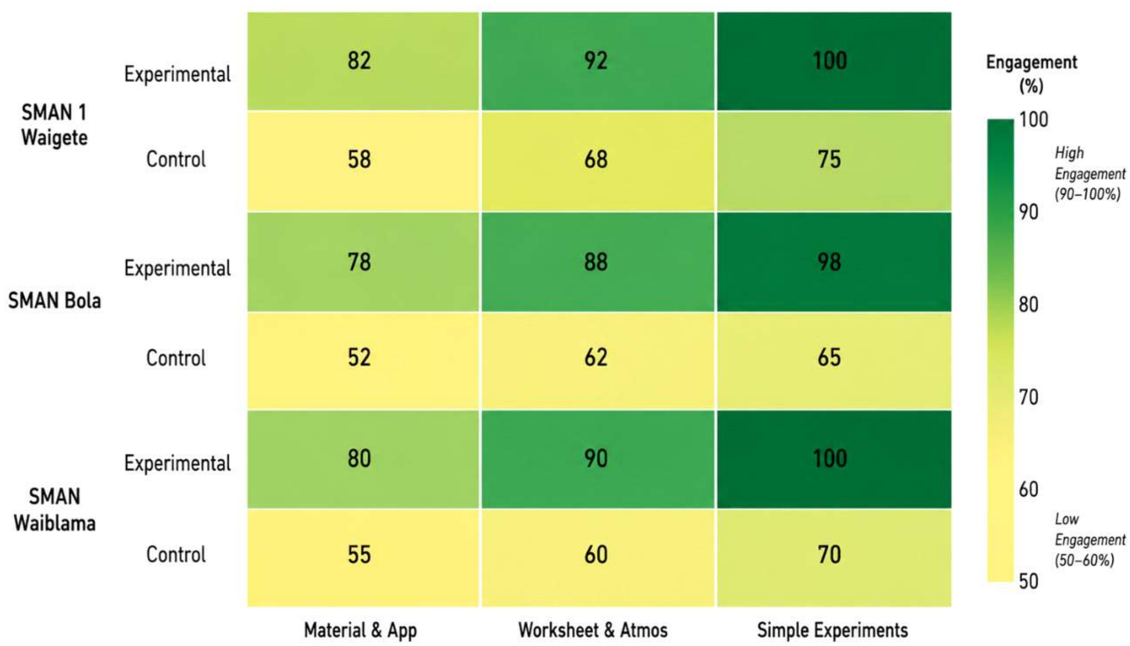

Figure 4. Heatmap of student engagement

The engagement pattern suggests that interactive, activity-centered digital learning can support attention and participation, but the result should not be reduced to novelty or screen exposure alone. Meta-analytic evidence indicates that the effects of digital game-based and mobile-supported learning depend on the structure of the learning activity and the collaborative process (Barz, Benick, Dörrenbächer-Ulrich, & Perels, 2024; Sung et al., 2017; Wang, Chen, Hwang, Guan, & Wang, 2022). In the present study, the stronger interest in simple experiments is therefore interpreted together with the contextual tasks and classroom observations rather than as a direct effect of Canva itself.

Thematic Analysis

Teacher interviews across the three schools were analyzed using Braun and Clarke's (2006) six-phase thematic analysis. Four themes emerged:

(Theme 1) Pedagogical Innovation and Changing Teaching Practice, four of six teachers reported a shift from lecture-based to facilitation of critical discussion, consistent with Fullan et al.'s (2020) DL framework; (Theme 2) Implementation Challenges, technical barriers (internet access, smartphone limitations), time constraints, and teacher digital literacy gaps (particularly at SMAN Bola and SMAN Waiblama); (Theme 3) Cultural Resonance and Perception of Local Wisdom, five of six teachers reported that *pire tanah* integration increased relevance and student engagement, while one teacher expressed concern about potential epistemic conflict; (Theme 4) Comparative Reflection from Control Group Teachers, control teachers reported dissatisfaction with conventional modules and expressed desire to adopt the e-module in subsequent semesters. Table 4 presents the joint display matrix contrasting themes between experimental and control teachers.

To illustrate higher-order cognitive processes, transcript excerpts from experimental class discussions were analyzed using Bloom's Revised Taxonomy. Example from SMAN 1 Waigete Session 2 (seismic waves): Student A: "If *pire tanah* involves synchronized stamping, the waves are constructive, right? Like in earthquakes..." Student B: "*But if the frequency matches the natural frequency of the soil, resonance occurs, like buildings collapsing*..." Student C: "So earthquake-resistant building design must avoid that natural frequency." This exchange demonstrates the cognitive levels of analysis (C4), evaluation (C5), and creation (C6). A student-written reflection further illustrates metacognitive engagement: "*Initially I thought pire tanah was just tradition. However, after the experiment, I understood that our stamping creates measurable waves. Science helps me see tradition in a new way, and tradition makes science feel close*." Analysis using Schraw and Dennison's metacognition rubric indicated a "proficient" metacognitive level.

Table 4. Joint display matrix: experimental vs control teacher perspectives

Theme	Experimental Group Perspective	Control Group Perspective
T1: Pedagogical Innovation	Shift from lecture to critical discussion facilitation; e-module as best-practice reference for DL planning.	Lecture-dominated; difficulty engaging students meaningfully with disaster contexts.
T2: Implementation Challenges	Technical barriers (internet, smartphones), time constraints, teacher digital literacy gaps at two schools.	Limited interactivity of conventional modules; student passivity and note-taking behavior.
T3: Cultural Resonance	*Pire tanah* integration increased relevance and engagement; one teacher noted potential epistemic tension.	No cultural integration in conventional modules; perceived disconnect between physics and local life.
T4: Comparative Reflection	E-module recognized as contextual innovation addressing limitations of conventional instruction.	Dissatisfaction with conventional materials; desire to adopt e-module in subsequent semesters.

Mixed-Methods Integration

Integration of quantitative and qualitative findings provides a contextual explanation of the between-school pattern. SMAN 1 Waigete had the highest experimental N-gain (0.62) and the highest recorded school-level teacher ICT competency (78.3), principal support score (82.4), and regular student smartphone access (89%). SMAN Bola recorded corresponding values of 62.1, 71.3, and 67%, while SMAN Waiblama recorded 60.5, 68.7, and 64%. These values are presented descriptively because only three schools were included; school-level correlations or multiple-regression ‘moderator’ models would not be statistically defensible with n = 3 schools. The data therefore support a contextual interpretation: implementation conditions varied alongside outcomes, but not a causal moderation claim. This distinction also reinforces the need to measure individual baseline digital literacy in future trials (Falloon, 2020).

Mechanisms of Effectiveness

The observed learning mechanisms can be interpreted in terms of three linked processes. First, *pire tanah* provided a familiar cultural phenomenon through which students could approach the abstract idea of mechanical waves; systematic research on Indigenous knowledge in STEM similarly emphasizes the value of culturally familiar contexts as conceptual scaffolds (Jin, 2021; Matindike & Ramdhany, 2025). Second, smartphone sensing and engineering tasks turned digital technology into a tool for investigation rather than presentation only, a distinction supported by meta-analytic evidence on technology-enhanced learning (Hillmayr et al., 2020; Wu, 2024). Third, the combination of discussion, measurement, design, and reflection created multiple routes for conceptual processing. The component-level correlations reported in this study remain associative and should not be read as isolated causal effects of individual STEAM components.

Epistemic Negotiation in Ethno-STEAM Integration

A critical examination of how the integration of *pire tanah* local knowledge with modern physics unfolded in classrooms revealed three patterns of epistemic negotiation, analyzed using Aikenhead’s (2001) border-crossing framework and Cobern’s (1996) encapsulation theory: (Pattern 1) Compatible Harmony (53% of students), students viewed *pire tanah* as a cultural illustration of modern physics concepts without epistemic tension; these students integrated without difficulty; (Pattern 2) Productive Tension (32% of students), students experienced cognitive dissonance between the cultural-spiritual explanation (*pire tanah* as ritual) and the scientific explanation (*pire tanah* as mechanical wave source), but successfully negotiated through written reflection distinguishing the spiritual and physical functions of the same ritual; (Pattern 3) Unresolved Tension (15% of students), students struggled to accept the dualism of explanations and tended to reject one. Implications: the e-module needs to provide explicit epistemic scaffolding for Pattern 3 students, acknowledging that border-crossing between indigenous and modern science is not automatic.

Theoretical Contributions

This study offers three theoretical contributions. First, the proposed Synergistic Pedagogical Model: Ethno-STEAM × Deep Learning (SPM-ESDL) treats Ethno-STEAM as the provider of content and context (WHAT and WHERE) and Deep Learning as the pedagogical process (HOW). Second, the findings extend the cross-cultural science education discussion by identifying three observed patterns of epistemic negotiation, Compatible Harmony, Productive Tension, and Unresolved Tension, within this specific classroom context (Aikenhead, 2001; Cobern, 1996). Third, the study adds empirical evidence that Indigenous or traditional knowledge can function as a legitimate contextual resource in science learning when epistemic boundaries are made explicit rather than collapsed (Matindike & Ramdhany, 2025; Todd et al., 2023).

CONCLUSION

This study developed, validated, and evaluated the effectiveness of a Deep Learning Physics Teaching e-Module, adapted using an Ethno-STEAM approach, to enhance disaster mitigation literacy regarding earthquakes and volcanic eruptions among senior high school students in Sikka Regency. Drawing on the Borg and Gall R&D model integrated with a non-equivalent control group quasi-experimental design, the study provides the following synthesis addressing the three research questions:

(RQ1) The e-module is statistically and practically effective in enhancing disaster mitigation literacy, with experimental classes achieving significantly higher post-test scores than control classes (ANCOVA $F(1,218) = 142.6$, $p < 0.001$, partial $\eta^2 = 0.395$, large effect), consistent across all three schools, and accompanied by significant attitude change (DPAQ N-gain attitude = 0.63 vs 0.11).

(RQ2) The e-module was perceived positively across school contexts. On the matched common-core questionnaire, Perceived Pedagogical Relevance was 91.2% in the experimental group versus 67.8% in the control group. This comparison reflects the perceived relevance of the learning experience using parallel items; treatment-specific features such as Canva navigation and pire tanah integration were evaluated descriptively within the experimental group and supported qualitatively through teacher and student accounts, rather than by asking control students to rate features they had not received.

(RQ3) Implementation outcomes varied across schools, alongside teacher ICT competency, principal support, and student access to technology. Because the operational test included only three schools, these school-level variables are interpreted descriptively rather than as statistically tested moderators. The integration of *pire tanah* local knowledge contributed to pedagogical innovation through three observed patterns of epistemic negotiation (Compatible Harmony, Productive Tension, and Unresolved Tension), indicating that cultural-scientific integration can be productive but is not automatically accessible to every learner.

In synthesis, the Ethno-STEAM-DL e-Module served as both a teaching resource and a context-specific pedagogical design to connect Indigenous and modern science within the Deep Learning framework. The present findings support its use in the schools studied, while broader transferability requires replication across different levels of teacher ICT capacity and school infrastructure.

Six limitations are acknowledged. First, the non-equivalent control-group quasi-experimental design cannot fully eliminate selection bias despite baseline checks. Second, the operational sample (N = 221) limits broad generalization. Third, the geographic scope was restricted to one regency, so transfer to other cultural-disaster contexts requires replication. Fourth, the four-week intervention did not assess long-term retention. Fifth, student-response measures remain vulnerable to self-report bias despite triangulation. Sixth, individual baseline digital literacy and prior use of digital learning platforms were not measured. School-level smartphone-access data (89%, 67%, and 64% across the three schools) describe access conditions but do not establish equivalence of individual technical competence between groups. Future studies should administer a validated pre-intervention digital-literacy measure and include it as a baseline covariate or matching variable.

Five directions for future research are proposed: (1) longitudinal effectiveness studies measuring retention of disaster-mitigation literacy at 6 and 12 months; (2) adaptation of the e-module for junior-high and university levels; (3) multi-region replication in other NTT regencies to test the transferability of the SPM-ESDL framework; (4) comparative cultural studies using different local-knowledge contexts while holding physics content constant; and (5) teacher professional-development studies focused on ICT competency and Ethno-STEAM-DL pedagogical content knowledge.

In closing, the study provides three context-bound insights into physics instructional design based on local knowledge. First, *pire tanah* can function as a cognitive bridge to mechanical-wave concepts when students investigate it as an observable phenomenon rather than encounter it only as an illustration. Second, the combination of digital measurement, engineering tasks, cultural context, and reflection provides multiple routes into the target concepts. Third, implementation outcomes differed across schools with varying levels of technology access and teacher capacity; these contextual differences should be examined explicitly in larger multi-school studies rather than treated as proven causal moderators.

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