



From Technology Users to Sustainability-Oriented Learning Designers: Developing Science Teachers' STEM-IoT Competencies through Professional Development

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ARTICLE INFO	ABSTRACT
Article history: Submitted: July 02, 2026 Final Revised: August 25, 2026 Accepted: September 18, 2026 Published: Oktober 17, 2026	Purpose: This study examined whether an integrated STEM–Internet of Things (IoT)–Education for Sustainable Development (ESD) professional-development program was associated with differences in junior secondary science teachers' competencies at the group level.
Keywords: STEM education; Internet of Things; Education for Sustainable Development; teacher professional development; science teachers; sustainability-oriented learning.	Methods: A quantitative, pre-experimental repeated cross-sectional pretest–posttest design analyzed 29 valid pretest and 33 valid posttest responses from the MGMP IPA teacher community in Sumedang, Indonesia. A researcher-developed assessment comprised 10 multiple-choice items and five constructed-response items (maximum total score = 100). Descriptive statistics, normalized gain based on group means, Welch's independent-samples t-test, Mann–Whitney U, and Hedges' g were reported.
	Findings: The mean total score was higher at posttest (83.24, SD = 11.07) than at pretest (59.34, SD = 16.22); the descriptive normalized gain was 0.588. Welch's $t(48.49) = 6.682$ ($p < .001$), and Hedges' $g = 1.72$ indicated a large group-level separation. The largest multiple-choice differences concerned the Blynk platform and ESP8266/Wi-Fi modules, whereas constructed responses showed higher scores for sensor-data interpretation and IoT–ESD project design.
	Implications: Integrated technical practice, data interpretation, and pedagogical design may provide a useful structure for science-teacher professional development. These cross-sectional comparisons cannot establish within-teacher growth, program causality, or transfer to classroom practice.
	Originality: The study examines factual, interpretive, and design-oriented competencies within a combined STEM–IoT–ESD teacher-learning program.



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INTRODUCTION

Sensor-based technologies can make otherwise invisible environmental changes observable in school science, yet the availability of a digital device does not by itself produce meaningful inquiry. The Internet of Things (IoT) links sensors, communication systems, and digital platforms so that learners can collect and interpret measurements from their surroundings (Almufarreh & Arshad, 2023). In school-based STEAM work, such data become educationally useful when they are connected to questions, explanations, and collaborative design decisions (Liston et al., 2022). A related review of teachers' use of digital-platform data shows why collecting information must be distinguished from using it to plan instruction (Hase & Kuhl, 2024). For science teachers, the central challenge is therefore pedagogical as well as technical: deciding what measurements mean and how learners should reason with them.

Integrated science, technology, engineering, and mathematics (STEM) education provides a context for addressing this challenge because it connects scientific concepts with technological construction, quantitative reasoning, and problem solving. Reviews of K–12 STEM professional development describe active learning, interdisciplinary planning, and sustained instructional support as recurring features, although their outcomes and evaluation practices vary (Huang et al., 2022; Boz, 2023; Surahman & Wang, 2023). Recent international syntheses likewise suggest that effective professional learning involves more than exposure to a new teaching tool (Rehman et al., 2025; Ma et al., 2025). Among STEM teachers, professional learning communities have also been associated with the translation of digital

development opportunities into instructional integration (J. Liu et al., 2024). These findings motivate attention to teachers' capacity to construct teachable STEM experiences rather than merely operate technology.

IoT can give integrated STEM projects a measurable connection to local environmental conditions, including soil moisture, temperature, and pH. Multisensor environmental systems illustrate how observations can be captured across different variables rather than inferred from isolated classroom demonstrations (Băjenaru et al., 2025). Applications in precision agriculture provide a related sustainability context, although a technical monitoring system is not automatically an effective educational activity (Hartono et al., 2025) [PERLU CEK SUMBER ASLI]. In Indonesian teacher education, IoT-supported contextual STEM activities have been examined in relation to digital literacy, demonstrating the relevance of this technological strand to science education (Setyawarno et al., 2025). The instructional task is to transform measurements into meaningful questions, interpretations, and design choices rather than treat the digital display as the learning outcome.

Education for Sustainable Development (ESD) extends this instructional task by asking learners to consider the purposes and consequences of their decisions. Research on teacher education for sustainability identifies professional competences that connect knowledge, pedagogy, values, and action rather than confining ESD to awareness of global goals (Fischer et al., 2022; Bürgener & Barth, 2022). Reviews also indicate that explicit ESD competences are not necessarily embedded systematically in teacher preparation (Imara & Altinay, 2021; Thao & Kieu, 2022). More recent science-teacher education work links teaching practices with the Sustainable Development Goals (Guo et al., 2024), while an integrated STEM–ESD review stresses the need to align activity design, assessment, and sustainability outcomes (Kopbossyn et al., 2025). Combining STEM, IoT, and ESD can therefore provide an organizing rationale for science lessons that move from environmental evidence toward justified action.

Technology-related teacher competence also depends on how technical knowledge interacts with subject content and pedagogical judgment. Reviews of technological pedagogical content knowledge (TPACK) show that professional learning can address these knowledge domains unevenly and that performance-based evidence remains important (González & Bravo, 2023; Fabian et al., 2024). Studies of professional training report the relevance of context-sensitive support, personalized learning, and opportunities to apply technology to a specific teaching task (Chaipidech et al., 2022; Kong et al., 2023). Related research documents the influence of teacher characteristics and prior experience on participation in digital professional development (Charania et al., 2024). Such evidence suggests that teachers need not only familiarity with IoT components but also opportunities to evaluate data, construct learning sequences, and explain the sustainability purposes of their designs.

The local needs analysis that informed the present program identified a distinct preparation gap among junior secondary science teachers in the MGMP IPA professional community in Sumedang, West Java. Approximately 50% of respondents reported familiarity with STEM learning, whereas only about 10% reported experience integrating IoT into science lessons; the initial report did not identify prior experience in the proposed microenvironmental application. This pattern is consistent with the broader distinction between knowing a technology and using it for disciplinary instruction, as discussed in reviews of digital integration and teacher learning (Amemasor et al., 2025; Liu, Z., et al., 2024). Indonesian training reports have addressed particular digital STEM applications (Hadi et al., 2023), while other educational work has examined STEM more generally (Agfiah & Fuada, 2024). What remains less clearly documented in this local setting is the profile of both basic technical knowledge and applied STEM–IoT–ESD design competence before and after an integrated professional-learning program.

This study examined group-level differences in junior secondary science teachers' STEM–IoT–ESD competencies before and after a professional-development program in Sumedang. It addressed two questions: how did overall assessment performance differ between the pretest and posttest groups, and which competency domains displayed the largest differences? The assessment brought together knowledge of IoT systems with constructed responses concerning ESD principles, sensor-data interpretation, project design, and relevant Sustainable Development Goals. Its contribution lies in examining those dimensions within a single program, rather than relying solely on teachers' reported attitudes toward digital innovation. Because the pretest and posttest data were not linked to individual teachers and no comparison group was available, the study was designed to describe program-associated group differences rather than establish individual learning trajectories or causal effects.

METHOD

Research design and scope

The study employed a quantitative, pre-experimental, repeated cross-sectional pretest–posttest design to compare science teachers' STEM–IoT–ESD assessment performance before and after a professional-development program. The

two datasets consisted of 29 valid pretest and 33 valid posttest responses, and individual records could not be matched reliably across measurement occasions. The independent group-level comparison was consequently treated as a description of differences between assessment occasions, not as a paired within-teacher estimate. There was no untreated comparison group, so alternative explanations for the posttest difference could not be excluded. The inquiry focused on total competency scores and the conceptual and applied domains assessed by the instrument.

Participants and Research Context

The study took place within the Science Teacher Professional Association (Musyawarah Guru Mata Pelajaran IPA; MGMP IPA) of junior secondary science teachers in Sumedang, West Java, Indonesia. Participants were drawn from this existing professional-learning community, for which the integrated training activities had been prepared. The preliminary needs assessment indicated variation in teachers' readiness: approximately half were familiar with STEM-based learning and about one tenth had previously integrated IoT into teaching. The available document did not provide the population size, recruitment dates, detailed inclusion criteria, or a verified account of individual participation at both tests; these characteristics therefore cannot be specified further. The analysis used all 29 valid pretest and 33 valid posttest responses reported in the original dataset.

Professional-Development Program

The professional-development program combined STEM pedagogy, IoT practice, and ESD-oriented learning design. Its sequence connected conceptual work on interdisciplinary STEM teaching with hands-on use of microcontrollers, Wi-Fi/IoT communication systems, digital platforms, and environmental sensors. Teachers explored the interpretation of measurements such as soil moisture, temperature, and pH, using soil-related environmental quality as the central instructional context. Subsequent activities addressed ESD principles, the selection of science-learning objectives, the design of STEM–IoT projects, and reflection on their potential classroom relevance. Instructional approaches described in the source included explanations, discussion, practical activities, simulations, guided project-design workshops, and reflection. The available material did not report session duration, the exact training calendar, or a standardized implementation-fidelity measure, so these details are not inferred here.

Research Instrument and Scoring

Competence was measured using a researcher-developed assessment containing 10 multiple-choice items and five constructed-response items, with a maximum total score of 100. The multiple-choice section was worth 50 points, with five points for each correct response; its indicators included IoT concepts, communication modules, cloud platforms, actuators, Blynk, STEM–IoT applications, ESD, and the Sustainable Development Goals. The five constructed responses were also worth 50 points, with each scored from 0 to 10 using a predefined analytic rubric. The domains were distinguishing conventional STEM from IoT-integrated STEM, explaining ESD through IoT, interpreting sensor-generated data, designing an IoT–ESD learning project, and connecting the learning design to SDG 4 and SDG 13. The source labels these five tasks Q14–Q18, although the stated instrument comprises 15 questions; the item numbering should be reconciled with the original test booklet. The original manuscript did not provide quantitative validity, internal-consistency, or inter-rater reliability evidence, and no such values were reconstructed.

Table 1. Constructed-response competency domains and maximum scores

Source item	Assessed competency	Maximum
Q14	Conventional STEM vs STEM integrated with IoT	10
Q15	ESD principles and applications through IoT	10
Q16	Sensor-generated data interpretation	10
Q17	Designing an IoT–ESD learning project	10
Q18	STEM–IoT–ESD links with SDG 4 and SDG 13	10

Data Collection and Research Procedure

Data were collected in three stages. First, the pretest measured the initial group profile in STEM–IoT–ESD concepts, technical IoT knowledge, sensor-data interpretation, and learning design. Second, the training program engaged teachers in conceptual learning, sensor-based practical tasks, project design, and guided reflection. Third, a posttest based on the same competency framework was used to describe the corresponding group profile after training. Multiple-choice answers were scored according to correctness, while constructed responses were evaluated against the original predefined scoring criteria. Because the test records were not individually linked, all subsequent analyses compared aggregate pretest and posttest distributions rather than paired teacher-level scores.

Figure 1. Research procedure for the repeated cross-sectional assessment

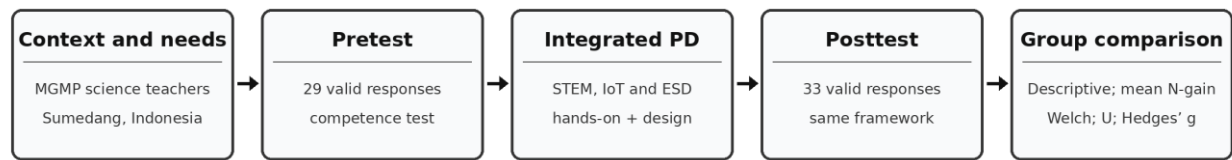


Figure 1. Research procedure for the repeated cross-sectional assessment

Statistical Analysis

Descriptive analyses summarized means and standard deviations for the multiple-choice, constructed-response, and total scores, as well as mean scores for the five constructed-response domains. The reported normalized gain was computed descriptively from the pretest and posttest group means as (posttest mean – pretest mean) / (maximum score – pretest mean). Values below 0.30 were considered low, those from 0.30 to below 0.70 moderate, and those of 0.70 or above high; because the two samples were unpaired, these values must not be interpreted as individual normalized gains. Welch’s independent-samples t-test was used to evaluate the difference in mean total scores across unequal-sized groups at $\alpha = .05$, with the reported 95% confidence interval. A Mann–Whitney U test was used as a nonparametric sensitivity analysis, and Hedges’ g described the standardized difference between the groups. Inferential results refer to group-level differences at two assessment occasions and do not establish program causality.

RESULTS

Overall Group-Level Competency Differences

The pretest total mean was 59.34 (SD = 16.22; $n = 29$), compared with 83.24 (SD = 11.07; $n = 33$) at posttest, corresponding to a 23.90-point difference on the 100-point scale. Multiple-choice means differed by 8.28 points (39.14 vs 47.42, maximum 50), while constructed-response means differed by 15.61 points (20.21 vs 35.82, maximum 50). The reported descriptive normalized gains were 0.763 for multiple-choice knowledge, 0.524 for constructed-response competence, and 0.588 for total competence. Because gain values were calculated from the means of separate groups, they summarize relative differences in aggregate scores rather than individual improvement.

Table 2. Descriptive scores and mean-based normalized gain

Assessment component	Pretest M $\pm$ SD	Posttest M $\pm$ SD	Difference	N-gain	Category
Multiple choice (max. 50)	39.14 $\pm$ 8.25	47.42 $\pm$ 3.09	+8.28	0.763	High
Constructed response (max. 50)	20.21 $\pm$ 10.33	35.82 $\pm$ 10.32	+15.61	0.524	Moderate
Total competency (max. 100)	59.34 $\pm$ 16.22	83.24 $\pm$ 11.07	+23.90	0.588	Moderate

Although the multiple-choice portion displayed a larger normalized gain, the constructed-response portion showed the larger difference in score points. The patterns should not be ranked as though they represented equivalent forms of learning: one measures correct answers to factual and conceptual questions, whereas the other depends on performance on extended tasks. Together, the components describe higher posttest group performance across both forms of assessment.

Inferential Comparison of Total Scores

The reported Welch independent-samples analysis identified a statistically significant difference between total-score distributions, $t(48.49) = 6.682$, $p < .001$. The mean difference was 23.90 points, with a reported 95% confidence interval of [16.71, 31.09]. The standardized difference was Hedges’ $g = 1.72$. The Mann–Whitney sensitivity analysis was also statistically significant (reported $U = 847$, $p < .001$). These analyses converge on a marked group-level separation, but neither the statistical significance nor the effect-size magnitude resolves the lack of paired observations or an untreated comparison group.

Table 3. Reported inference for the total STEM–IoT–ESD competency score

Statistic	Reported value
Pretest	59.34 $\pm$ 16.22 ($n = 29$)
Posttest	83.24 $\pm$ 11.07 ($n = 33$)
Mean difference	23.90
95% CI	[16.71, 31.09]
Welch’s t ; df	6.682; 48.49

Statistic	Reported value
p value	< .001
Hedges' g	1.72
Mann–Whitney U	847
Mann–Whitney p	< .001

Item-Level Differences in Multiple-Choice Knowledge

The multiple-choice items revealed differences concentrated in technical IoT knowledge. Correct responses on the Blynk platform item rose from 31.0% at pretest to 87.9% at posttest, a 56.9-percentage-point difference. The corresponding ESP8266/Wi-Fi module percentages were 31.0% and 78.8%, a 47.8-percentage-point difference. The actuator item differed by 21.5 points. By contrast, SDG-related general knowledge was already high at pretest, limiting the scope for detectable additional correct responses.

Table 4. Correct responses by multiple-choice item

Item	Content assessed	Pretest (%)	Posttest (%)	Change (pp)
1	Concept of IoT	86.2	97.0	+10.8
2	ESP8266/Wi-Fi module	31.0	78.8	+47.8
3	Cloud server/IoT platform	86.2	97.0	+10.8
4	Actuator	72.4	93.9	+21.5
5	IoT platform/Blynk	31.0	87.9	+56.9
6	Application of STEM–IoT	89.7	97.0	+7.3
7	Advantages of STEM–IoT	89.7	100.0	+10.3
8	SDG-related knowledge	100.0	100.0	0.0
9	Purpose of ESD	100.0	97.0	–3.0
10	SDG-related knowledge	96.6	100.0	+3.4

Constructed-Response Competency Domains

All five constructed-response domains had higher mean scores in the posttest dataset. Sensor-data interpretation (Q16) displayed the largest mean difference, from 1.45 to 5.06 (+3.61), closely followed by IoT–ESD project design (Q17), from 4.93 to 8.52 (+3.59). The Q17 posttest mean of 8.52 was the highest among the five applied domains, although the Q16 posttest mean of 5.06 remained relatively modest. Scores for connecting project work with SDG 4 and SDG 13 (Q18) differed by 3.32, for ESD applications (Q15) by 3.07, and for distinguishing conventional STEM from STEM–IoT (Q14) by 2.01.

Table 5. Mean scores for the five constructed-response domains (0–10 each)

Item	Constructed-response domain	Pretest M	Posttest M	ΔM
Q14	Conventional STEM vs STEM–IoT	5.38	7.39	+2.01
Q15	ESD principles and IoT application	4.38	7.45	+3.07
Q16	Sensor-data interpretation	1.45	5.06	+3.61
Q17	Designing an IoT–ESD learning project	4.93	8.52	+3.59
Q18	Links to SDG 4 and SDG 13	4.07	7.39	+3.32

Viewed together, the item profiles indicate a distinction between general conceptual familiarity and applied performance. The initial correct-response rate was high for several broad STEM, ESD, and SDG questions, whereas specific IoT components showed much more room for higher posttest scores. The constructed-response comparisons describe stronger posttest performance on applied tasks, especially project design, but the group-level dataset cannot show how any one teacher progressed from one domain to another.

Discussion

The clearest finding was the size of the difference between pretest and posttest group performance, rather than an established individual learning effect. The 23.90-point mean separation, Welch's t-test result, and Hedges' g indicate that the posttest distribution was substantially higher. This result is compatible with syntheses describing favorable outcomes from structured professional development in STEM and related technological subjects (Zhou et al., 2023; Ma et al., 2025). Yet the available records represented repeated cross-sections with unequal numbers of valid responses rather than a verified matched teacher cohort. Changes in which teachers completed the tests, prior knowledge, practice effects, or other unmeasured influences could have contributed to the contrast. Consequently, the estimates are best understood as program-associated group differences that warrant a more controlled follow-up study.

The multiple-choice and constructed-response results did not follow identical patterns, which helps refine the interpretation of the overall mean difference. Conceptual knowledge had a higher descriptive normalized gain (0.763) than applied responses (0.524), even though the latter showed a larger raw mean-score difference. Several broad STEM and SDG items were near their maximum at pretest, producing a ceiling effect that restricted observed change in those areas. Reviews of STEM teacher professional development emphasize that learning outcomes depend partly on what an assessment measures and how tasks represent the targeted knowledge (Huang et al., 2022; Rehman et al., 2025). In this study, higher posttest factual scores should not be treated as proof that teachers could implement equally strong learning experiences in classrooms. Interpreting knowledge and applying it to a sustained instructional design remain separate and more demanding dimensions.

Technical IoT concepts showed the most conspicuous item-level differences, particularly for Blynk and ESP8266/Wi-Fi communication. The two items began at the same pretest correct-response percentage (31.0%), whereas their posttest percentages reached 87.9% and 78.8%, respectively. This pattern is consistent with the program's hands-on exposure to platforms, sensors, and communications components, although that alignment does not establish that specific activities caused the observed differences. Research integrating IoT-based environmental monitoring into STEAM classrooms similarly draws attention to the practical knowledge required to collect and communicate meaningful data (Liston et al., 2022). Indonesian STEM-IoT work has also connected technology-based applications with science-education competence and digital literacy (Setyawarno et al., 2025). The pedagogical implication is to situate technical instruction within scientific questions so that naming a platform is followed by an explanation of how its outputs can support inquiry.

Interpretation of sensor-generated data was the constructed-response domain with the greatest mean difference (+3.61), but it was not the domain with the strongest posttest performance. The posttest mean of 5.06 out of 10 suggests that interpreting measurements remained difficult even when teachers performed better on several technical knowledge items. Data-use research distinguishes access to information from the capacity to evaluate evidence and make justified instructional decisions (Hase & Kuhl, 2024). The environmental-sensor context can support comparison of measurements, recognition of variation, and discussion of what evidence can or cannot justify (Băjenaru et al., 2025). However, this study did not document whether teachers could assess sensor accuracy, uncertainty, or reproducibility under classroom conditions. Future professional development should therefore devote explicit attention to interpreting noisy or incomplete environmental data, not only operating an IoT device.

The high posttest mean for IoT-ESD project design (8.52) indicates relatively strong assessed performance in planning a sustainability-oriented activity. Such designs can combine learning objectives, scientific measurements, technological choices, classroom procedures, and the intended relevance of environmental questions. This interpretation is compatible with ESD scholarship treating pedagogical competence as the ability to organize action-oriented learning rather than recall sustainability terminology (Imara & Altinay, 2021; Bürgener & Barth, 2022; Guo et al., 2024). At the same time, conceptual reviews caution that linking an activity to an SDG label is not sufficient without coherent learning goals and evidence-based reflection (Fischer et al., 2022; Kopbossyn et al., 2025). The results support the relevance of integrated project-design tasks within assessment, but actual enactment in lessons, student engagement, and sustainability-related behavior were not observed.

Taken together, the domains suggest a plausible conceptual relationship between technical knowledge and pedagogical design, though not a demonstrated developmental sequence. Teachers needed to understand the IoT components, reason with the resulting data, and decide how both belonged in a science lesson connected with ESD. This interpretation is consistent with TPACK scholarship, which distinguishes technical knowledge alone from knowledge integrated with pedagogy and disciplinary content (González & Bravo, 2023; Fabian et al., 2024). Studies of TPACK-oriented professional learning likewise identify the value of application tasks and differentiated support (Chaipidech et al., 2022; Lachner et al., 2021; Zeng et al., 2022). Nevertheless, the assessment did not validate a multi-stage model of teacher learning or follow individuals over time. The theoretical contribution is therefore a candidate set of connected competency domains for future longitudinal and performance-based validation, rather than a confirmed causal pathway.

The MGMP IPA setting also matters for interpreting what the program can contribute beyond its immediate assessment occasion. Working within an established teacher community may provide opportunities for shared problem solving and refinement of classroom projects, but sustained peer support was not directly measured here. Large-scale evidence on STEM teachers associates professional learning communities with stronger connections between digital training and instructional integration (J. Liu et al., 2024). Research also indicates that access, prior experience, and local support conditions can shape participation and take-up of teacher training (Charania et al., 2024; Amemasor et al., 2025). The Sumedang needs assessment shows why training should be sensitive to heterogeneous starting points, especially the

gap between reported STEM familiarity and prior IoT use. It cannot establish whether the same implementation would produce comparable results in schools with different resources or teacher experience.

A central qualification is that strong group-level statistics do not settle questions of instrument validity or long-term instructional effect. The report describes an analytic rubric and distinct test domains but does not document the validation of items, inter-rater agreement, attrition or overlap across samples, or the consistency of training delivery. Evidence from teacher-learning reviews stresses the importance of measuring demonstrated competence rather than assuming that confidence or short-term assessment scores predict classroom transfer (Boz, 2023; Surahman & Wang, 2023; Tang et al., 2023). The present results therefore justify a cautious conclusion: the posttest group demonstrated stronger conceptual and constructed-response performance in the selected STEM–IoT–ESD tasks. A subsequent study could match respondents over time, include an appropriate comparator, evaluate rubric reliability, and examine classroom lesson enactment and student outcomes. Those additions would test whether the proposed shift from technology users to sustainability-oriented learning designers is sustained beyond the training setting.

Implications

For professional-development designers, the findings suggest that technical IoT instruction should be paired with explicit practice in sensor-data interpretation, environmental inquiry, and learning-project design. The contrast between the technical-item scores and the more modest posttest result for interpreting sensor data points to an instructional priority: teachers need structured opportunities to examine evidence, not simply connect devices. The strong assessed project-design result provides a rationale for including a complete instructional artifact in program evaluation, while later classroom observation would be needed to assess implementation. Within MGMP learning communities, collaborative revision of projects could support such transfer, although this mechanism remains a recommendation rather than an outcome measured in the present study.

Limitations and Suggestions for Future Research

This study lacked individually matched pretest and posttest observations and a comparison group, limiting both claims about teacher-level development and causal inference. The available report did not establish the representativeness of the participating teachers, the duration of the intervention, test validity and reliability indices, or agreement among essay scorers. The reused competency framework may also have introduced testing familiarity, while multiple-choice ceiling effects reduced sensitivity for areas in which pretest knowledge was already high. Moreover, the evidence concerns assessment performance rather than observed instruction or student learning. Future work should employ linked repeated measures, document instrument development and rubric reliability, report intervention dosage, and assess subsequent project implementation in actual junior secondary science classrooms.

CONCLUSION

The posttest group of junior secondary science teachers in Sumedang obtained substantially higher STEM–IoT–ESD competency scores than the pretest group, with a total mean difference of 23.90 points, a descriptive normalized gain of 0.588, Welch's $t(48.49) = 6.682$ ($p < .001$), and Hedges' $g = 1.72$. Technical IoT knowledge, particularly concerning platforms and Wi-Fi modules, showed prominent item-level differences; the constructed-response component showed higher scores in sensor-data interpretation and sustainability-oriented project design. These results support further examination of professional development that connects STEM pedagogy, practical IoT work, interpretation of environmental evidence, and ESD purposes. Because different valid responses were available at the two assessment occasions and no comparator was used, the findings describe group-level contrasts rather than proven individual growth or program effects. Evidence of sustained changes in teaching practice and student outcomes remains necessary.

REFERENCES

- Agfiah, U. I., & Fuada, N. A. (2024). Dampak pendekatan STEM dalam pembelajaran matematika. *Jurnal Inovasi Pendidikan Matematika (JIPM)*, 6(2), 82–95.
- Almufarreh, A., & Arshad, M. (2023). Internet of Things (IoT)-based teaching and learning: Modern trends and open challenges. *Sustainability*, 15(21), 15656. <https://doi.org/10.3390/su152115656>
- Amemasor, S. K., Oppong, S. O., Ghansah, B., Benuwa, B.-B., & Essel, D. D. (2025). A systematic review on the impact of teacher professional development on digital instructional integration and teaching practices. *Frontiers in Education*, 10, 1541031. <https://doi.org/10.3389/educ.2025.1541031>

- Boz, T. (2023). Teacher professional development for STEM integration in elementary/primary schools: A systematic review. *International Electronic Journal of Elementary Education*, 15(5), 371–382.
- Bürgener, L., & Barth, M. (2022). Developing ESD-specific professional action competence for teachers: Knowledge, skills, and attitudes in implementing ESD at the school level. *Environmental Education Research*, 28(12), 1691–1729. <https://doi.org/10.1080/13504622.2022.2064973>
- Băjenaru, V.-D., Istrițeanu, S.-E., & Ancuța, P.-N. (2025). Autonomous, multisensory soil monitoring system. *AgriEngineering*, 7(1), 18. <https://doi.org/10.3390/agriengineering7010018>
- Chaipidech, P., Srisawasdi, N., Kajornmanee, T., & Chaipah, K. (2022). A personalized learning system-supported professional training model for teachers' TPACK development. *Computers and Education: Artificial Intelligence*, 3, 100064. <https://doi.org/10.1016/j.caeai.2022.100064>
- Charania, A., Cross, S., Wolfenden, F., Sen, S., & Adinolfi, L. (2024). Exploring teacher characteristics and participation in TPACK-related online teacher professional development in Assam, India. *Computers and Education Open*, 7, 100227. <https://doi.org/10.1016/j.caeo.2024.100227>
- Fabian, A., Backfisch, I., Kirchner, K., & Lachner, A. (2024). A systematic review and meta-analysis on TPACK-based interventions from a perspective of knowledge integration. *Computers and Education Open*, 7, 100200. <https://doi.org/10.1016/j.caeo.2024.100200>
- Falloon, G. (2020). From digital literacy to digital competence: The teacher digital competency (TDC) framework. *Educational Technology Research and Development*, 68, 2449–2472. <https://doi.org/10.1007/s11423-020-09767-4>
- Fischer, D., King, J., Rieckmann, M., Barth, M., Büssing, A., Hemmer, I., & Lindau-Bank, D. (2022). Teacher education for sustainable development: A review of an emerging research field. *Journal of Teacher Education*, 73(5). <https://doi.org/10.1177/00224871221105784>
- Ghani, A. A., Rosli, R., Iksan, Z., Halim, L., Osman, K., Maat, S. M., Mahmud, S. N. D., Mahmud, M. S., Rambely, A. S., & Lay, A. N. (2023). STEM professional development programs for science and mathematics primary school teachers: A systematic literature review. *European Journal of Science and Mathematics Education*, 11(4), 738–753. <https://doi.org/10.30935/scimath/13629>
- González, J. G., & Bravo, G. V. (2023). TPACK in in-service secondary education teachers: A systematic review of the literature. *International Journal of Education in Mathematics, Science and Technology*. <https://doi.org/10.46328/ijemst.3198>
- Guo, C., Huang, Y., & Chen, X. (2024). Research on integration of the Sustainable Development Goals and teaching practices in a future teacher science education course. *Sustainability*, 16(12), 4982. <https://doi.org/10.3390/su16124982>
- Hadi, F. R., Anggrasari, L. A., & Maruti, E. S. (2023). Pelatihan guru SD dalam pembelajaran STEM menggunakan IoT berbasis Canva. *Jurnal SOLMA*, 12(2). <https://doi.org/10.22236/solma.v12i2.12573>
- Hartono, R., Pratama, D. R., Sari, M., & Nugroho, W. (2025). Smart farming for a sustainable future: Implementing IoT-based systems in precision agriculture. *Bulletin of the National Research Centre*, 49(1), Article 8. <https://doi.org/10.1186/s42269-025-01366-8>
- Hase, A., & Kuhl, P. (2024). Teachers' use of data from digital learning platforms for instructional design: A systematic review. *Educational Technology Research and Development*, 72, 1925–1945. <https://doi.org/10.1007/s11423-024-10356-y>
- Huang, B., Jong, M. S.-Y., Tu, Y.-F., Hwang, G.-J., Chai, C. S., & Jiang, M. Y.-C. (2022). Trends and exemplary practices of STEM teacher professional development programs in K–12 contexts: A systematic review of empirical studies. *Computers & Education*, 189, 104577. <https://doi.org/10.1016/j.compedu.2022.104577>
- Hurley, M., Butler, D., & McLoughlin, E. (2024). STEM teacher professional learning through immersive STEM learning placements in industry: A systematic literature review. *Journal for STEM Education Research*, 7, 122–152. <https://doi.org/10.1007/s41979-023-00089-7>
- Imara, K., & Altinay, F. (2021). Integrating education for sustainable development competencies in teacher education. *Sustainability*, 13(22), 12555. <https://doi.org/10.3390/su132212555>
- Kong, S.-C., Lai, M., & Li, Y. (2023). Scaling up a teacher development programme for sustainable computational thinking education: TPACK surveys, concept tests and primary school visits. *Computers & Education*, 194, 104707. <https://doi.org/10.1016/j.compedu.2022.104707>

- Kopbossyn, A., Laiskhanov, S., Aksoy, B., Tokbergenova, A., Nametkulov, M., & Kozybakova, A. (2025). Integrated STEM for sustainability in school and early teacher education: A systematic review (2019–2025). *Frontiers in Education*, 10, 1697058. <https://doi.org/10.3389/educ.2025.1697058>
- Lachner, A., Fabian, A., Franke, U., Preiß, J., Jacob, L., Führer, C., Küchler, U., Paravicini, W., Randler, C., & Thomas, P. (2021). Fostering pre-service teachers' technological pedagogical content knowledge (TPACK): A quasi-experimental field study. *Computers & Education*, 174, 104304. <https://doi.org/10.1016/j.compedu.2021.104304>
- Liston, M., Morrin, A. M., Furlong, T., & Griffin, L. (2022). Integrating data science and the Internet of Things into science, technology, engineering, arts, and mathematics education through the use of new and emerging technologies. *Frontiers in Education*, 7, 757866. <https://doi.org/10.3389/educ.2022.757866>
- Liu, J., Aziku, M., Qiang, F., & Zhang, B. (2024). Leveraging professional learning communities in linking digital professional development and instructional integration: Evidence from 16,072 STEM teachers. *International Journal of STEM Education*, 11, 56. <https://doi.org/10.1186/s40594-024-00513-3>
- Liu, Z., Gearty, Z., Richard, E., Orrill, C. H., Kayumova, S., & Balasubramanian, R. (2024). Bringing computational thinking into classrooms: A systematic review on supporting teachers in integrating computational thinking into K–12 classrooms. *International Journal of STEM Education*, 11, 51. <https://doi.org/10.1186/s40594-024-00510-6>
- Ma, H., Dong, Y., Jing, B., Zeng, Y., & Sun, J. (2025). Effectiveness of in-service computer science teachers' professional development in K–12 education: A systematic review and meta-analysis. *International Journal of STEM Education*, 12, 29. <https://doi.org/10.1186/s40594-025-00548-0>
- Mishra, P., & Koehler, M. J. (2006). Technological pedagogical content knowledge: A framework for teacher knowledge. *Teachers College Record*, 108(6), 1017–1054.
- Rehman, N., Huang, X., Mahmood, A., Zafeer, H. M. I., & Mohammad, N. K. (2025). Emerging trends and effective strategies in STEM teacher professional development: A systematic review. *Humanities and Social Sciences Communications*, 12, 32. <https://doi.org/10.1057/s41599-024-04272-y>
- Setyawarno, D., Rosana, D., Ibrohim, Hamimi, E., & Abdulloh, A. G. (2025). Implementation of IoT-based STEM-contextual learning with the MQTT protocol on the digital literacy skills of pre-service science teacher. *LUMAT: International Journal on Math, Science and Technology Education*, 12(4). <https://doi.org/10.31129/LUMAT.12.4.2277>
- Surahman, E., & Wang, T.-H. (2023). In-service STEM teachers professional development programmes: A systematic literature review 2018–2022. *Teaching and Teacher Education*, 135, 104326. <https://doi.org/10.1016/j.tate.2023.104326>
- Tang, J., Zhou, X., Wan, X., Daley, M., & Bai, Z. (2023). ML4STEM professional development program: Enriching K–12 STEM teaching with machine learning. *International Journal of Artificial Intelligence in Education*, 33(1), 185–224. <https://doi.org/10.1007/s40593-022-00292-4>
- Thao, N. P., & Kieu, T. K. (2022). Teachers' competencies in education for sustainable development in the context of Vietnam. *International Journal of Sustainability in Higher Education*, 23(7), 1730–1748. <https://doi.org/10.1108/IJSHE-08-2021-0349>
- Wohlfart, O., & Wagner, I. (2023). Teachers' role in digitalizing education: An umbrella review. *Educational Technology Research and Development*, 71, 339–365. <https://doi.org/10.1007/s11423-022-10166-0>
- Zeng, Y., Wang, Y., & Li, S. (2022). The relationship between teachers' information technology integration self-efficacy and TPACK: A meta-analysis. *Frontiers in Psychology*, 13, 1091017. <https://doi.org/10.3389/fpsyg.2022.1091017>
- Zhou, X., Shu, L., Xu, Z., et al. (2023). The effect of professional development on in-service STEM teachers' self-efficacy: A meta-analysis of experimental studies. *International Journal of STEM Education*, 10, 37. <https://doi.org/10.1186/s40594-023-00422-x>
- Zuhaida, A., Widodo, A., Prima, E. C., Solihat, R., & Septiyanto, A. (2026). Science teachers' readiness in professional training programs for sustainability-oriented STEM education. *Journal of Science Learning*. <https://doi.org/10.17509/jsl.v9i1.91239>

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AUTHOR CONTRIBUTION STATEMENT

DR: Conceptualization, development of the initial research idea, and supervision of the study. **RR:** Writing – original draft preparation. **HN:** Data curation and formal data analysis. **AS:** Data curation and formal data analysis. **JMS:** Manuscript review. All authors reviewed and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

AI DISCLOSURE STATEMENT

The authors used ChatGpt during the preparation of this work solely for language editing, grammar checking, and improving the clarity of the manuscript. After using the tool/service, the authors thoroughly reviewed and edited the content as needed and take full responsibility for the accuracy, interpretation, and final content of the publication.

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