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Development of Deep Learning- and Professional Learning Community (PLC)-Based Digital Science and Social Studies Teaching Materials: An Implementation Study among Elementary School Teachers

***Ika Sukmayanti[1], Neta Dian Lestari[2], Wahid Ibrahim Banul Ngindom[3]**
[1,2,3]Universitas PGRI Palembang, Indonesia
Correspondence Email: sukmaika88@gmail.com

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Abstract

The integration of digital teaching materials, Deep Learning-oriented instruction, and teacher collaboration offers a potential approach to improving the quality of elementary science and social studies (IPAS) learning. This study aimed to develop and evaluate digital IPAS teaching materials integrating Deep Learning and Professional Learning Community (PLC) in elementary schools. The study employed a research and development approach involving needs analysis, product development, expert validation, practicality testing, and preliminary effectiveness testing. Product validation involved two media experts and two subject-matter experts, while practicality testing involved eight teachers from four elementary schools. Preliminary effectiveness testing was conducted with 60 students from four elementary schools using a one-group pretest–posttest design. The product was rated highly valid by media experts (89.70%) and subject-matter experts (86.00%) and highly practical by teachers (M = 4.22). Students' mean learning-outcome score increased from 70.00 to 79.25, with an overall N-Gain of 0.37, categorized as moderate. The reported paired-samples test also indicated a statistically significant pretest–posttest difference (t = 15.004, p = .015). These findings provide preliminary evidence that the developed materials are valid, practical, and potentially beneficial for supporting IPAS learning. Further controlled studies are required to establish their effectiveness across broader educational contexts.

Keywords: *Deep Learning, Digital teaching materials, Elementary education, IPAS, Professional Learning Community.*

I. INTRODUCTION

The quality of education is a critical determinant of a nation's capacity to respond to the demands of the twenty-first century, which are characterized by rapid digital transformation, increasingly complex global challenges, and a growing need for higher-order thinking skills. Contemporary education can no longer be oriented solely toward the acquisition of factual knowledge; it must also foster critical and creative thinking, collaboration, communication, and problem-solving. Accordingly, instructional practices need to promote deep learning, enabling students to construct meaningful conceptual understanding, establish connections across areas of knowledge, and apply what they learn to unfamiliar and real-world situations.

Despite these expectations, international assessments indicate that Indonesia continues to face substantial educational challenges. The 2022 Programme for International Student Assessment (PISA) reported scores of 359 in reading, 366 in mathematics, and 383 in science for Indonesian students, compared with OECD averages of 476, 472, and 485, respectively. These results indicate persistent difficulties in competencies requiring students to understand information, reason with concepts, analyze problems, and apply knowledge in unfamiliar contexts. Although PISA performance should not be interpreted as a direct measure of all dimensions of educational quality, the results underscore the continuing need to strengthen learning environments that support reasoning, conceptual understanding, and knowledge application.

Addressing these challenges requires attention not only to students' characteristics but also to the instructional conditions that shape learning. Teacher competence, the quality of instructional materials, meaningful integration of educational technology, and school instructional leadership are among the factors that can influence the quality of classroom learning. Teacher-centered instruction, extensive reliance on lectures, and static instructional resources may provide limited opportunities for students to investigate problems, construct connections, and engage in higher-order thinking. In contrast, appropriately designed interactive digital materials can provide richer opportunities for students to explore content, receive support, engage with multiple representations, and solve

contextual problems. Digitalization should therefore be understood not simply as converting printed materials into electronic formats, but as redesigning learning resources to facilitate more active and meaningful learning processes.

This need has become increasingly relevant within the implementation of the Kurikulum Merdeka, which emphasizes student-centered, contextualized, differentiated, and technology-supported learning. In Ilmu Pengetahuan Alam dan Sosial (IPAS; Natural and Social Sciences), students are expected to develop an integrated understanding of natural and social phenomena through exploration, investigation, reflection, and problem-solving. Such characteristics make IPAS particularly suitable for learning experiences that encourage students to connect concepts rather than study them as isolated information. Consequently, digital instructional materials for IPAS should extend beyond content presentation by providing opportunities for inquiry, reflection, contextual problem-solving, and differentiated learning according to students' needs.

Recent developments in Artificial Intelligence (AI) offer additional possibilities for designing digital instructional materials that are more adaptive and responsive to learners. AI-supported systems can potentially use information about learners' progress, responses, and levels of mastery to provide differentiated content, feedback, or learning pathways. However, technological sophistication alone does not guarantee meaningful pedagogical innovation. The educational value of AI-supported resources depends substantially on how teachers understand, design, implement, and evaluate their use within authentic classroom settings. Therefore, the development of AI-supported digital materials should be accompanied by mechanisms that strengthen teachers' pedagogical capacity and provide sustained professional support.

In this respect, a Professional Learning Community (PLC) provides an important collaborative framework for continuous teacher professional development. Through collaborative planning, reflection on classroom practices, exchange of experiences, and collective problem-solving, a PLC can position teachers not merely as users of technology but as active designers and evaluators of technology-supported learning. Such collaboration can be particularly valuable when teachers are expected to develop digital instructional materials because the development process requires the integration of subject-matter knowledge, pedagogy, assessment, learner characteristics, and technological competence. A PLC can therefore provide a professional environment in which digital innovation is collaboratively designed, reviewed, implemented, and refined.

Sustaining such innovation also requires instructional leadership that supports teachers' professional growth. Academic supervision that operates primarily as administrative monitoring may provide limited assistance when teachers are confronted with complex instructional-development problems. A more developmental approach can be provided through the TIRTA coaching model, which facilitates goal identification, reflection on current conditions, exploration of possible strategies, commitment to action, and subsequent follow-up. Within the present study, TIRTA coaching is positioned as a reflective support mechanism through which school leaders can assist teachers in identifying instructional needs, examining challenges encountered during development, and determining appropriate actions for improving digital IPAS materials. Thus, PLC and TIRTA coaching represent complementary mechanisms: the former emphasizes professional collaboration among teachers, whereas the latter provides structured reflective support for professional improvement.

The need for such an integrated approach was also identified in elementary schools in Muara Telang District, Banyuasin Regency. Preliminary observations indicated that IPAS instruction continued to rely substantially on textbooks and teacher explanations, while the use of interactive digital instructional materials remained limited. Teachers had incorporated technological devices into instructional administration, but their use of technology for developing digital materials that facilitated deeper conceptual engagement and higher-order thinking was still limited. Moreover, professional collaboration specifically directed toward digital-material development and coaching-based assistance was not yet organized as a sustained process. These conditions suggest that the challenge is not merely the availability of technology but the absence of a systematic professional and pedagogical mechanism through which technology can be transformed into meaningful instructional resources.

The literature and these empirical conditions reveal a more specific research gap. Previous studies have commonly addressed digital instructional-material development, AI-supported learning, PLC-based teacher professional development, and TIRTA coaching as separate areas of intervention. Such fragmented approaches provide valuable evidence regarding individual components but offer limited understanding of how technological development, teacher collaboration, and reflective instructional support can be combined within a single development framework. This gap is particularly evident in elementary IPAS education, where the development of digital resources requires simultaneous attention to curricular content, meaningful learning processes, teacher technological competence, and sustainable professional support. Therefore, the research gap lies not simply in the limited availability of digital IPAS materials but in the lack of an integrated development approach connecting AI-supported digital materials, PLC-based collaboration, and TIRTA coaching.

Accordingly, this study aims to develop AI-supported digital instructional materials for elementary IPAS through an integrated framework involving Professional Learning Community (PLC) and TIRTA coaching. The novelty of the study lies in positioning digital-material development not as an isolated technological activity but as a collaborative and reflectively supported professional process in which technology, teacher learning, and instructional leadership operate within the same development framework. The proposed approach is expected to provide a systematic basis for developing contextually relevant digital IPAS materials while simultaneously strengthening teachers' capacity to design and refine technology-supported instruction. In this way, the study seeks to contribute to the implementation of the Kurikulum Merdeka and to broader efforts to develop meaningful, technology-supported learning appropriate to the competencies required in twenty-first-century education.

II. METHOD

This study employed a Research and Development (R&D) approach using the ADDIE model, which consists of five stages: Analysis, Design, Development, Implementation, and Evaluation. ADDIE was selected because it provides a systematic framework linking needs analysis, product design and development, implementation, and evaluation of educational products (Spatioti et al., 2022). During the Analysis stage, learning needs, student characteristics, teacher readiness, and existing conditions of IPAS instruction were identified. The Design and Development stages involved designing the digital IPAS instructional materials, integrating Professional Learning Community (PLC) activities and TIRTA coaching as professional support mechanisms, preparing supporting instruments, and conducting product validation. Product feasibility was assessed by two media experts and two subject-matter experts, and their feedback was used to revise the product prior to implementation.

The study was conducted with Grade VI students from SD Negeri 5, SD Negeri 7, SD Negeri 13, and SD Negeri 15 Muara Telang, selected purposively according to the study context. The practicality evaluation involved eight teachers, while the preliminary effectiveness test involved 60 students. Data were collected through classroom observations, documentation, expert-validation sheets, teacher-response questionnaires, and pretest and post-test learning-outcome measures. Quantitative and qualitative descriptive analyses were used to evaluate the development process. Product feasibility was determined from expert-validation results, while practicality was examined through teacher responses. Changes in students' learning outcomes were analyzed using Normalized Gain (N-Gain) to quantify pretest–post-test improvement (Nissen et al., 2018; Coletta, 2023), and the statistical significance of the score difference was examined using a paired-samples t-test at $\alpha = .05$.

III. RESULTS AND DISCUSSION

A. Results

The findings are presented according to the major stages of the ADDIE development process, beginning with the needs analysis and product development and followed by the evaluation of product quality. The needs analysis examined existing instructional conditions, teacher and student needs, and contextual issues underlying the development of the digital IPAS instructional materials. The resulting product was subsequently evaluated in terms of feasibility, practicality, and preliminary effectiveness. Changes in student learning outcomes were examined using N-Gain

and a paired-samples *t*-test to determine the magnitude of score improvement and whether the pretest–post-test difference was statistically significant.

1. Needs Analysis for the Development of Digital IPAS Instructional Materials

The needs analysis was conducted with teachers and students across four elementary schools in Muara Telang District. The findings identified several instructional and professional-development needs relevant to the proposed product. Teachers experienced difficulties in developing digital instructional materials, and the available educational technology had not yet been optimally integrated into IPAS instruction. Teachers also demonstrated limited understanding of the Deep Learning pedagogical approach, indicating a need for practical guidance that could support its implementation in classroom learning.

From the student perspective, the needs analysis indicated a preference for visual and interactive learning experiences. The curriculum analysis further identified the importance of providing IPAS learning activities that promote higher-order thinking skills (HOTS), particularly critical thinking, and connect scientific and social concepts with contextual situations. Although technological infrastructure was available, its instructional use remained limited. In addition, professional collaboration among teachers through a Professional Learning Community (PLC) had not yet been optimally implemented. These findings provided the empirical basis for determining the characteristics and components of the digital instructional materials, as summarized in Table 1.

Table 1. Summary of the Needs Analysis

Aspect	Key Finding	Development Implication
Teachers	Difficulties in developing digital instructional materials	Practical and user-friendly digital materials are required
Deep Learning	Teachers' understanding of the approach remains limited	Practical guidance for implementing Deep Learning is required
Students	Preference for visual and interactive learning	Integration of interactive multimedia elements
IPAS Curriculum	Emphasis on HOTS and contextual learning	Integration of critical-thinking and contextual learning activities
Infrastructure	Technological facilities are available but not optimally utilized	Materials should support both online and offline use
PLC	Professional collaboration among teachers remains limited	Integration of Professional Learning Community activities

Taken together, the needs analysis suggests that the development requirement extended beyond simply digitizing existing IPAS content. The product needed to combine accessible multimedia resources, contextual and higher-order thinking activities, implementation guidance, and opportunities for professional collaboration among teachers. These requirements subsequently informed the design and development of the instructional materials.

2. Development of the Digital IPAS Instructional Materials

Based on the needs-analysis findings, digital IPAS instructional materials were developed by integrating the Deep Learning pedagogical approach with a Professional Learning Community (PLC) framework. The product was designed as an interactive multimedia resource using PowerPoint-based animated content and could be accessed through laptops and smartphones. To accommodate variations in technological access identified during the needs analysis, the materials were designed to support flexible use in classroom learning.

The developed product consisted of several interconnected components, including IPAS learning content, interactive learning activities, digital student worksheets (LKPD), quizzes, reflection activities, and a teacher user guide. These components were organized to move beyond the presentation of information by providing opportunities for students to engage with learning content and reflect on their understanding. At the same time, the teacher-support component was intended to facilitate the implementation of the materials within the PLC-oriented professional-development process.

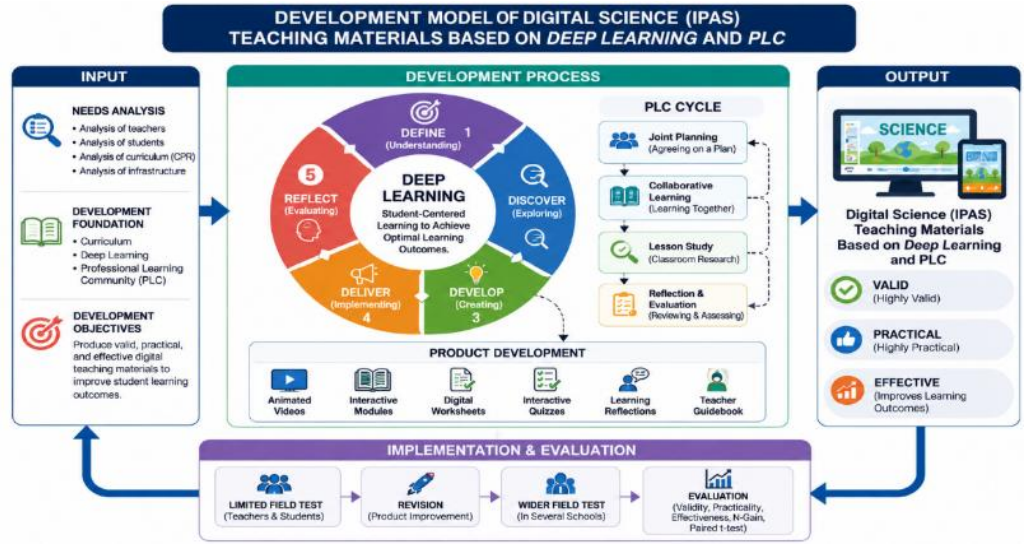

Figure 1. Development Model of Digital IPAS Instructional Materials Based on Deep Learning and Professional Learning Community (PLC)

The resulting development model therefore connected three major elements: the digital IPAS instructional materials as the learning resource, the Deep Learning approach as the pedagogical orientation, and PLC as the collaborative mechanism supporting teachers in implementing and refining the materials. The developed product was subsequently subjected to expert validation and classroom evaluation to examine its feasibility, practicality, and performance during implementation.

3. Product Validation Results

Before field testing, the developed digital IPAS teaching materials were evaluated by two media experts and two subject-matter experts to assess their design quality, visual presentation, usability, and alignment of the content with the intended learning objectives.

Table 2. Product Validation Results

Validator	Mean Score	Percentage	Category
Media Experts	3.62	89.70%	Highly Valid
Subject-Matter Experts	4.30	86.00%	Highly Valid

As shown in Table 2, the media experts assigned a mean score of 3.62 (89.70%), while the subject-matter experts provided a mean score of 4.30 (86.00%). Both assessments fell within the highly valid category according to the predetermined criteria. These results indicate that the developed digital teaching materials met the required standards for content and media quality and were therefore considered appropriate for subsequent field testing.

2. Practicality Test Results

The practicality test involved eight teachers from four elementary schools and was conducted to evaluate the usability and applicability of the developed digital teaching materials in classroom instruction. The assessment covered ease of use, clarity of guidance, time efficiency, and ease of integration.

Table 3. Practicality Test Results

Aspect	Mean Score	Category
Ease of Use	4.38	Highly Practical
Clarity of Guidance	4.25	Highly Practical
Time Efficiency	3.88	Practical
Ease of Integration	4.38	Highly Practical
Overall Mean	4.22	Highly Practical

The overall mean score was 4.22, placing the product in the highly practical category. Ease of use and ease of integration received the highest scores (M = 4.38), followed by clarity of guidance (M = 4.25). Time efficiency received the lowest score (M = 3.88), although it remained within the practical category. These findings indicate that the teachers generally perceived the digital IPAS teaching materials as easy to use, clearly structured, and readily integrated into classroom instruction.

3. Preliminary Effectiveness Results

The preliminary effectiveness of the developed digital IPAS teaching materials was examined by comparing students' learning outcomes before and after product implementation. The evaluation involved 60 students from four elementary schools, with learning outcomes measured using pretest and posttest assessments.

Table 4. Summary of Pretest and Posttest Results

School	Pretest	Posttest	Increase
SDN 5 Muara Telang	66.00	80.00	14.00
SDN 7 Muara Telang	73.00	79.00	6.00
SDN 13 Muara Telang	67.00	78.00	11.00
SDN 15 Muara Telang	74.00	80.70	6.70
Mean	70.00	79.25	9.25

Descriptively, posttest scores were higher than pretest scores across all four schools. The largest increase was observed at SDN 5 Muara Telang, where the mean score increased from 66.00 to 80.00, followed by SDN 13 Muara Telang, from 67.00 to 78.00. SDN 7 Muara Telang increased from 73.00 to 79.00, while SDN 15 Muara Telang increased from 74.00 to 80.70. Overall, the reported mean increased from 70.00 at pretest to 79.25 at posttest, representing a descriptive increase of 9.25 points following implementation of the digital teaching materials.

4. N-Gain Results

N-Gain analysis was conducted to describe the magnitude of improvement in students' learning outcomes following implementation of the developed digital IPAS teaching materials.

Table 5. N-Gain Results

School	N-Gain	Category
SDN 5 Muara Telang	0.41	Moderate
SDN 7 Muara Telang	0.22	Low
SDN 13 Muara Telang	0.33	Moderate
SDN 15 Muara Telang	0.50	Moderate
Mean	0.37	Moderate

The mean N-Gain across the four schools was 0.37, corresponding to the moderate category. Three schools demonstrated moderate gains: SDN 5 Muara Telang (0.41), SDN 13 Muara Telang (0.33), and SDN 15 Muara Telang (0.50). In contrast, SDN 7 Muara Telang obtained an N-Gain of 0.22, categorized as low. These results indicate variation in the magnitude of improvement across implementation settings, with the overall reported gain falling within the moderate range.

5. Paired-Samples *t*-Test Results

A paired-samples *t*-test was conducted to determine whether students' learning outcomes differed statistically between the pretest and posttest measurements.

Table 6. Paired-Samples *t*-Test Results

Measurement	Mean	*t*	*p*
Pretest	70.00	—	—
Posttest	79.25	15.004	.015

The reported results showed an increase in the mean learning-outcome score from 70.00 at pretest to 79.25 at posttest. The paired-samples *t*-test indicated a statistically significant difference between the two measurements (t = 15.004, p = .015). Thus, students demonstrated higher learning-outcome scores following implementation of the developed digital IPAS teaching materials. When considered together with the moderate overall N-Gain (0.37), these findings provide preliminary evidence of improved learning outcomes during product implementation.

B. Discussion

The findings indicate that the developed digital IPAS teaching materials demonstrated strong product quality in terms of validity and practicality, while the implementation stage showed improvement in students' learning outcomes. Expert validation classified the product as highly valid, with scores of 89.70% from media experts and 86.00% from subject-matter experts. The practicality assessment involving eight teachers produced an overall mean of 4.22, categorized as highly practical. These findings suggest that the product was considered appropriate in terms of its content, presentation, usability, and integration into elementary IPAS instruction.

The high validation results indicate that the digital teaching materials achieved an appropriate alignment between instructional content and digital presentation. This alignment is particularly important because digital materials should not merely convert conventional content into an electronic format but should organize information and learning activities in ways that support meaningful learner engagement. From a multimedia-learning perspective, the purposeful combination of textual, visual, auditory, and interactive elements can support learners in processing and integrating information more effectively (Mayer, 2021). The positive evaluations from both media and subject-matter experts therefore provide evidence that the developed product met the intended design and content requirements before classroom implementation.

The practicality findings further demonstrate the feasibility of implementing the product in authentic school settings. Teachers rated ease of use and ease of integration particularly highly (M = 4.38 for both aspects), while clarity of guidance also received a strong evaluation (M = 4.25). Time efficiency received a comparatively lower score (M = 3.88), although it remained within the practical category. This pattern suggests that the product was generally accessible to teachers but that its implementation may require additional instructional time or adjustment to existing classroom routines. This issue is relevant because the successful adoption of digital teaching materials depends not only on their technical usability but also on their compatibility with teachers' instructional workload and classroom conditions.

The implementation results also showed higher learning-outcome scores following the use of the developed materials. Across the four participating schools, the reported mean increased from 70.00 at pretest to 79.25 at posttest, with improvements observed in every school. The overall reported N-Gain of 0.37 fell within the moderate category, although the magnitude varied across schools, ranging from 0.22 at SDN 7 Muara Telang to 0.50 at SDN 15 Muara Telang. This variation is noteworthy because it indicates that implementation outcomes were not uniform across educational settings. Differences in student characteristics, instructional implementation, technological infrastructure, or teachers' familiarity with the developed materials may have contributed to these variations, although the present data do not allow these possible explanations to be tested directly.

Conceptually, the observed improvement is consistent with the principles of Deep Learning, which emphasize meaningful, contextual, and reflective learning rather than superficial acquisition of information. The source manuscript similarly positions the developed materials as a means of facilitating active and contextual learning and relates this orientation to constructivist perspectives and Deep Learning principles. When digital materials provide opportunities for students to connect new concepts with prior knowledge and authentic contexts, they may facilitate deeper conceptual engagement with IPAS content. This interpretation is also consistent with the constructivist perspective that knowledge develops through learners' active interaction with learning experiences rather than through passive reception alone.

An important feature of the present development is the incorporation of the Professional Learning Community (PLC) into the implementation process. PLC provides a collaborative environment in which teachers can jointly plan, implement, evaluate, and reflect on instructional practices. The original discussion emphasizes that PLC functioned not merely as a professional-development forum but also as a mechanism for sharing practices in developing and implementing Deep Learning-based digital teaching materials. This collaborative dimension is relevant because the quality of digital materials alone cannot ensure meaningful classroom implementation; teachers' capacity to adapt the materials, reflect on students' responses, and improve subsequent instructional practices remains essential. The finding is consistent with DuFour (2021), who emphasizes collaborative and reflective professional practice as a central characteristic of PLC.

The findings also correspond with previous studies reporting educational benefits associated with Deep Learning, teacher collaboration, and digital technology. Wulandari (2024) reported improvements in conceptual understanding through Deep Learning-oriented instruction, while Prasetyo and Hidayat (2023) highlighted the contribution of PLC-based teacher collaboration to instructional quality and student learning. Firmansyah et al. (2025) similarly reported that digital technology integration could support student engagement and motivation. The present study extends this line of research by combining these dimensions within the development and implementation of digital IPAS teaching materials rather than examining digital media, Deep Learning, or teacher collaboration independently. This integrated orientation constitutes an important contribution of the study, particularly within elementary IPAS instruction.

The development framework is further strengthened by incorporating TIRTA coaching (Tujuan, Identifikasi, Rencana Aksi, dan Tanggung Jawab) as a mechanism for supporting school principals and teachers during implementation. Within this framework, school principals are positioned not merely as administrative supervisors but as facilitators of professional reflection who can assist teachers in identifying instructional needs, formulating action plans, and following up on the implementation of digital teaching materials. The source manuscript identifies this integration of digital IPAS materials, Deep Learning, PLC, and TIRTA coaching as the principal novelty of the development. Conceptually, this combination broadens the innovation beyond the digital product itself by connecting instructional resources with teacher collaboration and school-level professional support.

Nevertheless, the effectiveness findings require cautious interpretation. Although the paired measurements showed higher posttest scores and the reported paired-samples test indicated a statistically significant difference ($t = 15.004$, $p = .015$), the study did not include a comparison group. Consequently, the observed improvement cannot be attributed exclusively to the developed digital materials, Deep Learning, or PLC because other factors occurring during the intervention period cannot be ruled out. Moreover, the moderate overall N-Gain (0.37) indicates meaningful but not uniformly high improvement across the participating schools. The results should therefore be regarded as preliminary evidence of effectiveness within the implementation context, rather than definitive evidence of a causal treatment effect.

Overall, the study suggests that the value of the developed digital IPAS teaching materials lies not only in their technological characteristics but in their integration with Deep Learning-oriented pedagogy, collaborative professional learning through PLC, and TIRTA-based coaching support. This combination offers a framework in which technology supports rather than substitutes for teachers' pedagogical roles. However, stronger evidence will require future studies employing comparison groups, larger and more diverse samples, student-level statistical analyses, and measures capable of examining whether learning gains are sustained over time. Such research would provide a stronger basis for determining the broader effectiveness and transferability of the developed model across elementary school contexts.

IV. CONCLUSION

This study developed digital IPAS teaching materials integrating Deep Learning and Professional Learning Community (PLC) as an instructional resource for elementary education. The product demonstrated high validity based on evaluations by media experts (89.70%) and subject-

matter experts (86.00%) and was rated highly practical by teachers (M = 4.22). During implementation, students' mean learning-outcome score increased from 70.00 at pretest to 79.25 at posttest, with an overall N-Gain of 0.37, indicating a moderate level of improvement. The reported paired-samples analysis further indicated a statistically significant difference between pretest and posttest scores (t = 15.004, p = .015). The integration of digital materials with Deep Learning-oriented activities and PLC-based teacher collaboration provides a framework that connects technological resources, meaningful learning, and continuous professional reflection. However, because the effectiveness test employed a one-group pretest–posttest design without a comparison group, the observed improvement cannot be attributed exclusively to the developed product. Future studies should employ controlled designs, larger samples, student-level analyses, and longitudinal measurements to establish the effectiveness and sustainability of the learning outcomes more robustly.

CONFLICT OF INTEREST

The authors declare that they have no financial, professional, institutional, or personal conflicts of interest that could have influenced the design, implementation, analysis, interpretation, or reporting of this study.

AUTHOR CONTRIBUTIONS

Ika Sukmayanti: *conceptualization, research design, needs analysis, development of the digital teaching materials, data collection, data analysis, and preparation of the original manuscript.* ***Neta Dian Lestari:*** *methodology, product development, validation process, interpretation of findings, and manuscript review and editing.* ***Wahid Ibrahim Banul Ngindom:*** *research supervision, methodological guidance, evaluation of the developed product, interpretation of findings, and critical revision of the manuscript. All authors reviewed and approved the final version of the manuscript.*

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

Generative artificial intelligence tools were used solely to support language editing, proofreading, translation, and improvement of the manuscript's clarity and readability. AI tools were not used to generate or modify research data, perform statistical analyses, or determine the study findings and conclusions. All AI-assisted revisions were carefully reviewed and verified by the authors, who retain full responsibility for the accuracy, originality, and integrity of the final manuscript.

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