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Exploring Deep Learning in Science Education through the SmartEdu Application among Pre-Service Elementary School Teachers

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Abstract: The rapid advancement of science and technology requires educational systems to address the limited integration of deep learning practices that effectively develop 21st-century competencies in prospective elementary school teachers. This study aims to examine how the SmartEdu application supports the implementation of deep learning in science education. A qualitative exploratory design was employed, involving classroom observations, interviews, and document analysis, with data analyzed through thematic analysis. The results demonstrate that SmartEdu facilitates the integration of theoretical knowledge with authentic problem-solving, structured discussions, and reflective evaluation, significantly enhancing conceptual understanding, higher-order thinking skills, and learner autonomy. In conclusion, SmartEdu effectively promotes meaningful, contextual, and sustainable science learning while strengthening critical, creative, collaborative, communicative, and reflective competencies. These findings imply that technology-supported deep learning frameworks can serve as a strategic model for improving teacher education programs.

Keywords: 21st-Century Competencies; Deep Learning; Prospective Elementary School Teachers; Science Education; SmartEdu Application.

Introduction

The rapid development of science and technology today requires every individual to adapt, innovate, and play an active role in facing global challenges (Zulkarnaen et al., 2020). These changes also influence the direction and policies of education, which are now expected to produce excellent and adaptive human resources equipped with skills relevant to the demands of the 21st century (Giacomazzi, 2024). The paradigm of modern education is no longer solely focused on the mastery of knowledge but also on the development of skills, character, and life competencies. In this context, deep learning emerges as a strategic approach that emphasizes the cultivation of six global competencies: character, citizenship, collaboration, communication, creativity, and critical thinking (Fullan et al., 2016, 2018; OECD, 2016).

Pre-service teachers, as agents of educational change, need to be equipped with 21st-century skills from an early stage, particularly in terms of collaboration and communication (Griffin & Care, 2015). These skills are not only essential from a pedagogical perspective but are also supported by strong theoretical foundations, such as social development theory (Vygotskiĭ et al., 1978), the concept of collaborative problem solving (Roschelle & Teasley, 1995), and team-based learning (Baker, 2015). In the context of science education, collaborative skills become highly relevant since the scientific approach requires processes of exploration, experimentation, and reflection that occur collectively and contextually.

One relevant approach to fostering these skills is Outcome-Based Education (OBE), which emphasizes meaningful and applicable learning outcomes (Shaheen, 2019). Its implementation requires media that can bridge

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the gap between theoretical knowledge acquired at the university and practical applications in schools. The SmartEdu application, developed by the Primary School Teacher Education (PGSD) Study Program at Universitas Perjuangan Tasikmalaya, emerges as an innovative solution to address this need. This application facilitates students in accessing real-world problem data, engaging in virtual discussions with practitioner teachers, and formulating contextual and applicable solutions (Zulkarnaen et al., 2019b, 2019a, 2020). Features such as self-directed learning, discussion forums, and virtual presentations enable students to actively engage in the processes of analysis, evaluation, and reflection on real educational issues (Zulkarnaen et al., 2019b, 2020).

Figure 1. SmartEdu Application Interface

The urgency of this study lies in the need to strengthen technology-based science learning strategies that can genuinely facilitate deep learning. The use of the SmartEdu application serves as a significant innovation in addressing the challenges of integrating campus learning with school practices, while simultaneously enhancing the readiness of prospective primary school teachers to face the dynamics of the educational landscape. The aim of this study is to explore how SmartEdu-assisted science learning can foster deep learning among prospective elementary school teachers.

Method

This study employs a qualitative design with an exploratory approach (Creswell, 2017; Isiaku et al., 2024). Its primary focus is to investigate in depth the practices of science learning assisted by SmartEdu and its impact on the deep learning of prospective elementary school teachers. Semi-structured interviews were used as the main method of data collection (Kallio et al., 2016). This method is highly appropriate for exploratory studies that aim to gain initial insights into a phenomenon (Galletta, 2020). Furthermore, it serves as a valuable approach in building theoretical foundations for emerging topics (Louise Barriball & While, 1994). Figure 2 illustrates the flow of this research.

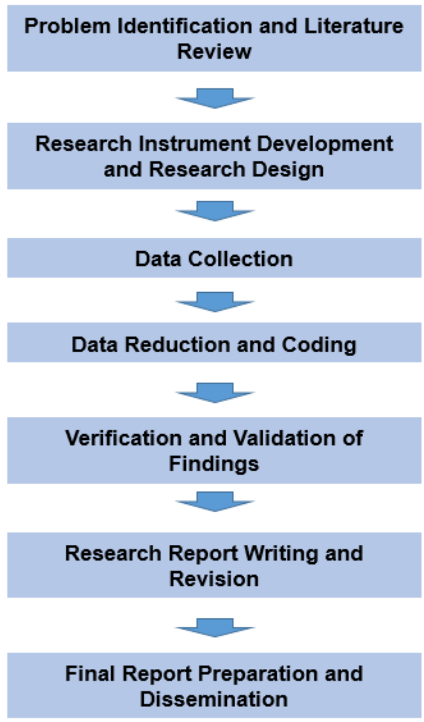

Figure 2. Framework of Exploratory Qualitative Research

The data analysis in this study follows the interactive model of Miles, Huberman, and Saldaña (Miles et al., 2014), which consists of three main stages: data reduction, data display, and conclusion drawing/verification. Data reduction was carried out by selecting, simplifying, and focusing on the relevant information obtained from interviews and documentation, a process that aligns with the principle of "meaning condensation" in qualitative data analysis (Brinkmann & Kvale, 2015). Subsequently, the data were organized and presented systematically in the form of narrative descriptions and matrices to facilitate interpretation, consistent with the use of visual displays to support analytic thinking in qualitative research (Creswell, 2009, 2017). The final stage involved drawing conclusions and verifying them through continuous comparison of the data to ensure validity and credibility, a process supported by the constant comparative logic described by Merriam and Tisdell (Merriam & Tisdell, 2016). To strengthen trustworthiness, member checking was conducted to confirm the accuracy of interpretations with participants, which is a widely recommended strategy for enhancing credibility in qualitative inquiry (Birt et al., 2016; Lincoln, 1990).

The subjects of this study consisted of 32 prospective elementary school teachers enrolled in a science education course supported by the SmartEdu application, along with one course instructor. Student participants were selected using purposive sampling with specific criteria: they had to attend at least six SmartEdu-based learning sessions, provide consent to be interviewed and recorded, and represent different levels of learning activity (high, medium, and low). The use of purposive sampling aligns with Creswell and Poth's (Creswell, 2017) recommendation for selecting information-rich participants in qualitative research. These activity levels were determined through SmartEdu activity logs and initial classroom observations, consistent with the use of digital trace data and observational fieldwork in contemporary educational research (Merriam & Tisdell, 2016; Zulkarnaen et al., 2019b, 2020). The research was carried out within the Elementary Teacher Education (PGSD) Study Program at Universitas Perjuangan Tasikmalaya, ensuring alignment between the research context and the authentic demands of elementary-level instruction, as suggested by Biggs and Tang's (Biggs et al., 2022) principles of constructive alignment.

Multiple data collection techniques were employed using a triangulation approach to achieve depth and credibility. Participant observation enabled the researchers to directly examine SmartEdu-based learning processes, a method consistent with the immersive observation strategies (Silverman, 2021). In-depth interviews with students and the course instructor were conducted to explore their experiences, challenges, and reflections on using the application (Brinkmann & Kvale, 2015). Complementary data were obtained through documentation, including student reflection notes, project outcomes, and SmartEdu activity logs, which align with the use of multiple sources of evidence recommended in case study research (Yin & Campbell, 2018). In addition, an exploratory questionnaire was distributed to capture students' perceptions regarding the extent to which SmartEdu facilitated deep learning, reflecting the mixed-methods integration commonly applied in educational technology research (Johnson & Christensen, 2019). This combination of data collection methods enabled the researchers to obtain rich, comprehensive, and credible insights in line with the objectives of the study and with the triangulation principles emphasized by Lincoln and Guba (Lincoln, 1990). An overview of the research process is illustrated in Figure 3.

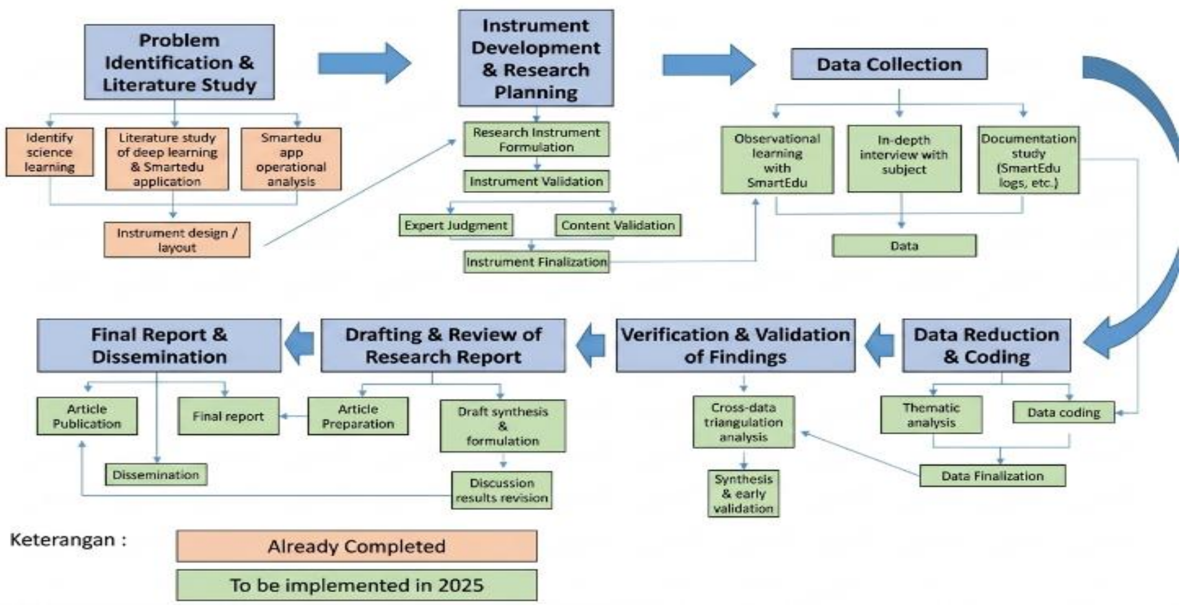

Figure 3. Research Flowchart of the Exploratory Study on Deep Learning Using the SmartEdu Application

Result and Discussion

Analysis of Interview Findings with Lecturers and Students on the Use of the SmartEdu Application in Fostering Deep Learning

Interviews were conducted using an interview instrument that had been developed and prepared prior to the implementation of the study. The instrument was constructed based on the indicators of deep learning that served as the focus of this research. To ensure its validity, the instrument underwent expert judgment by three specialists in the relevant field and was subsequently analyzed using Aiken's V. The results indicated that the instrument possesses adequate validity and is appropriate for use in the data collection process.

Interviews with students and instructors provided rich insights into the role of the SmartEdu application in fostering deeper learning experiences. Students noted that the Problem feature in SmartEdu encouraged them to think critically, as the problems presented were contextual and challenging—an approach consistent with evidence that well-designed problem-based tasks stimulate higher-order thinking and meaningful learning (Hmelo-Silver, 2004; Savery, 2006). This feature enabled students to explore concepts more thoroughly than merely understanding theories, allowing them to connect the knowledge learned with real-world situations, as emphasized in deep learning frameworks (Biggs et al., 2022; Entwistle & Ramsden, 2015). The instructor also stated that the feature facilitated the integration of the Problem-Based Learning model, as the problems could be directly accessed and explored by students both in class and online, aligning with studies showing that digital PBL environments enhance accessibility and inquiry (Amoa-Danquah & Carbonneau, 2025; Fadhilah* et al., 2022). The general overview of SmartEdu application usage throughout the learning sessions can be seen in Figure 4.

Figure 4. SmartEdu Application Usage Throughout the Course Sessions

In addition, the chat feature served as an effective communication tool that supported more intensive academic interactions between students and instructors. Interview findings revealed that students perceived this feature as a safe and flexible space to ask questions and discuss topics they had not yet understood, without being constrained by time or location. This is in line with research demonstrating that online communication tools foster cognitive and social presence in virtual learning environments (Garrison & Cleveland-Innes, 2005; Pratiwi & Wijayanti, 2025). The instructor also confirmed that the feature strengthened student engagement, as questions could be addressed promptly while also fostering deeper discussions, reflecting principles of social constructivist interaction (Vygotskiĭ et al., 1978). Consequently, the learning relationship became not merely unidirectional but evolved into a more meaningful collaborative process.

The Learning feature, which presents materials interactively, was also well appreciated by both students and instructors. Students expressed that the materials provided in various formats—text, multimedia, or interactive modules—made the learning process more engaging and easier to understand. This aligns with Mayer's Multimedia Learning Theory, which shows that well-designed multimedia supports deeper conceptual comprehension (Mayer & Fiorella, 2021). This flexibility allowed students to learn according to their individual preferences, thereby enhancing conceptual understanding, while the instructor noted that the feature supported differentiated instruction—an approach widely recognized for addressing diverse learner needs (Ameko et al., 2025; Tomlinson, 2016). The ability to access materials any time also reflects evidence that flexible digital learning environments promote deeper learning and sustained engagement (Borokhovski et al., 2020).

Furthermore, the evaluation feature in SmartEdu was regarded as one of the essential components that positively contributed to students' learning reflection. Interviews revealed that students benefited from the transparent evaluation system, as their achievement results could be viewed immediately—an approach supported by research showing that timely and transparent feedback enhances metacognition and self-regulated learning (Granberg et al., 2021; Nicol & Macfarlane-Dick, 2006). This transparency enabled them to more easily identify their strengths and weaknesses throughout the learning process. The instructor emphasized that such transparency allowed students to promptly improve their learning strategies, while also helping instructors monitor progress more accurately, consistent with findings in learning analytics research (Pan et al., 2024).

Overall, the interviews indicate that SmartEdu is capable of fostering more meaningful learning through the integration of features that support active engagement, reflection, and collaboration between students and instructors. Its positive impact is evident not only in enhanced conceptual understanding but also in the development of self-directed learning motivation, critical thinking skills, and the ability to make data-informed decisions based on evaluation results—hallmarks of deep learning (Biggs et al., 2022; Biggs & Tang, 2011; Entwistle & Ramsden, 2015). Thus, SmartEdu has proven to be a platform that bridges theory and practice and promotes the realization of deep learning within higher education settings. A more detailed illustration of the data coding and reduction from the interviews can be seen in Table 1.

Table 1. Data Reduction and Coding of Interview Results on Deep Learning Exploration Supported by the SmartEdu Application, Based on Miles & Huberman

Raw Data (Interview/Observation)	Data Reduction (Core Statement)	Codification (Category)	Data Display (Pattern/Relationship)	Conclusion Drawing (Preliminary Conclusion)
"I feel that the chatting feature in SmartEdu helps me ask the lecturer questions at any time, so I can better understand difficult concepts."	The chatting feature facilitates lecturer–student interaction to deepen conceptual understanding.	C1 – Contextual and Deep Understanding		
C4 – Collaboration and Communication	Students use the chatting feature to clarify concepts personally.	The chatting feature enhances lecturer–student connectedness and supports deeper conceptual understanding.		
"The evaluation feature is very transparent because I can immediately see my score and the lecturer's comments, so I can improve my weaknesses."	Evaluation is transparent, provides comments, and promotes reflection and improvement.	C5 – Self-evaluation and Reflective Learning	Transparent evaluation results foster self-awareness and motivation to improve.	The evaluation feature supports reflective learning and continuous improvement toward deeper achievement.
"The problem feature makes me think more critically because I have to find solutions with my friends before the lecturer discusses them."	The problem feature trains students' critical thinking and collaboration.	C2 – Higher-Order Thinking Skills (critical, creative, 4C)	Students actively discuss and seek solutions before receiving guidance from the lecturer.	The problem feature stimulates critical, collaborative, and creative thinking skills in solving real-world problems.
"The learning feature is easy to understand because it includes interactive videos, so I can study more deeply on my own."	The learning feature provides interactive materials for deep understanding.	C3 – Motivation and Autonomy	Interactive videos enhance conceptual understanding and support independent learning.	The learning feature strengthens deep understanding and promotes student autonomy in learning.
"The assignment feature helps me know what to improve because the lecturer gives direct feedback."	The assignment feature provides corrective feedback for comprehensive learning.	C5 – Reflection and Self-evaluation	Lecturer feedback guides students in improving their tasks and learning outcomes.	The assignment feature promotes meaningful and comprehensive learning through continuous improvement cycles.

Analysis of Student Questionnaire Responses on the Use of the SmartEdu Application in Enhancing Deep Learning

The questionnaire instrument was developed and prepared prior to the data collection phase. The questionnaire was constructed based on deep learning indicators that served as the focus of the study. To ensure the validity of the developed instrument, it was assessed by three experts in accordance with their areas of expertise, and the results were analyzed using Aiken's V. The analysis yielded an average Aiken's V value of 0.92, indicating that the instrument was valid and suitable for use. The questionnaire was administered to capture students' perceptions regarding their deep learning practices when using the SmartEdu application. The data obtained from the questionnaire on deep learning supported by SmartEdu are presented in Figure 5.

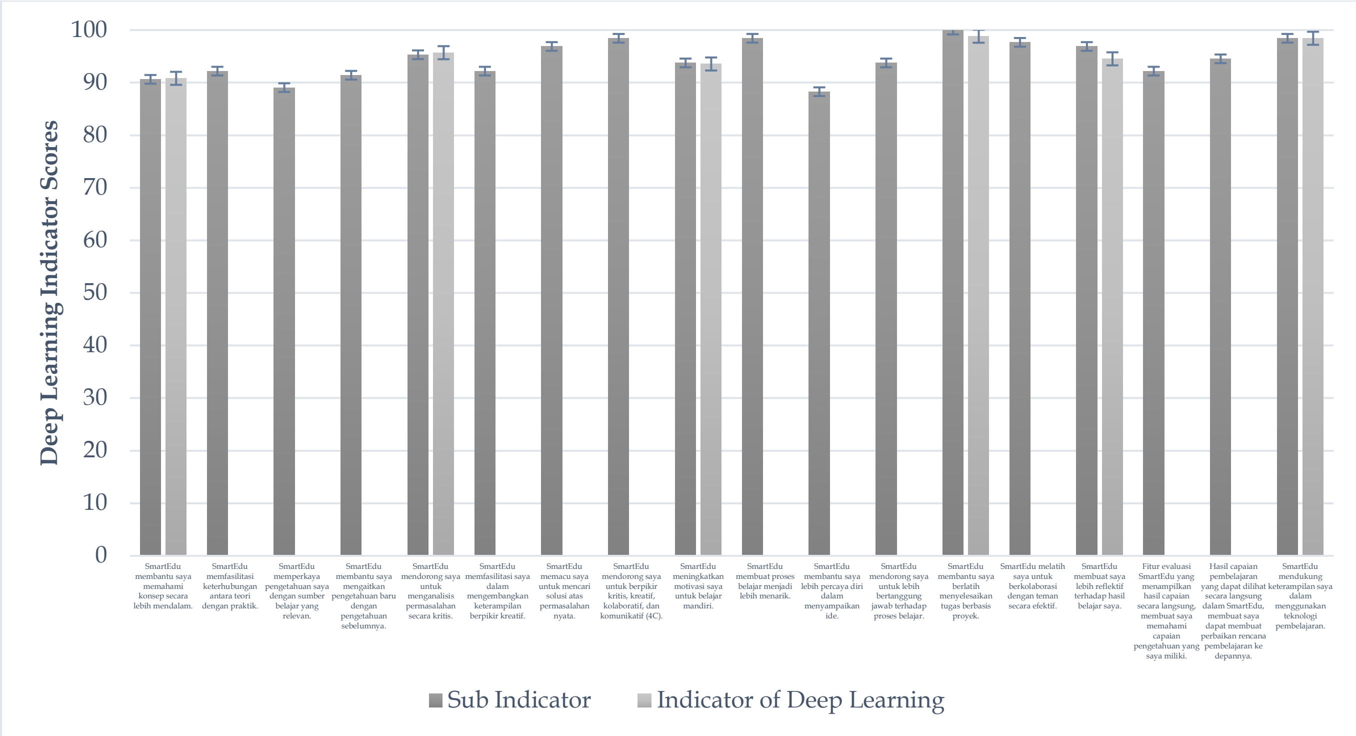

Figure 5. Graph of Deep Learning Questionnaire Score Achievement Using the SmartEdu Application

The questionnaire results indicate that the use of the SmartEdu application contributes significantly to enhancing students' deep learning. This finding aligns with the conceptualization of deep learning, which emphasizes active engagement in higher-order thinking processes such as analysis, evaluation, and reflection (Biggs et al., 2022; Biggs & Tang, 2011). The increased scores across indicators of motivation, cognitive engagement, and reflective ability demonstrate that SmartEdu promotes meaningful learning rather than mere memorization. This reinforces the view that the integration of educational technology can create learning environments that are more constructive and personalized (Mayer, 2021).

The utilization of features such as Problem, Learning, and Chat within SmartEdu facilitates students' interaction with learning materials as well as with their peers, thereby strengthening the internalization of knowledge. Prior studies have shown that interactive learning technologies can foster deeper conceptual understanding compared to conventional approaches (Kirschner et al., 2024). The questionnaire data in this study likewise confirm that students find it easier to analyze problems, connect concepts across topics, and evaluate solutions when using the application. These conditions are consistent with Bernard et al. (Borokhovski et al., 2020), who assert that digital technologies enhance critical thinking and problem-solving skills by supporting collaborative and self-directed learning activities.

Moreover, deep learning is strongly influenced by the quality of social interaction and the degree of learner autonomy. SmartEdu provides a participatory space that enables students to exchange feedback, thereby strengthening self-regulated learning skills. The findings indicate that learners with strong self-regulation abilities tend to achieve higher levels of conceptual understanding. This tendency is reflected in the significant improvements in questionnaire scores related to reflection and self-evaluation. Thus, SmartEdu functions not only as a learning medium but also as a tool that reinforces learner autonomy—an essential component of deep learning.

Overall, the questionnaire data show that students respond positively to SmartEdu-supported learning, particularly in terms of cognitive and metacognitive engagement. The integration of digital literacy with a deep learning approach is believed to foster richer, more meaningful, and more sustainable learning experiences (Laurillard, 2013). These findings support the perspective of digital constructivism, which holds that adaptive technologies such as SmartEdu can optimize experience-based learning processes. Therefore, this study offers a foundation for developing more targeted and effective technology-enhanced instructional innovations in science education. The detailed description of the reduced and coded questionnaire data, analyzed using the Miles and Huberman approach, is presented in Table 2.

Table 2. Data Reduction and Coding of Questionnaire Results on Deep Learning Exploration Supported by the SmartEdu Application, Based on Miles & Huberman

Raw Data (Statements + Percentage)	Data Reduction (Core Meaning)	Codification (Category)	Data Display (Pattern/Relationship)	Conclusion Drawing (Final Interpretation)
SmartEdu helps me understand concepts more deeply (90.63%), facilitates theory–practice connectedness (92.19%), enriches knowledge (89.06%), and links new knowledge with prior understanding (91.41%).	SmartEdu strengthens students' conceptual understanding and knowledge connectivity.	C1 – Conceptual Understanding & Knowledge Connectivity	Students experience more meaningful learning by linking theory, practice, and prior learning experiences.	SmartEdu supports deeper conceptual learning, with a high average achievement score (90.82%).
SmartEdu promotes critical analysis (95.31%), fosters creativity (92.19%), encourages real-world problem solving (96.88%), and cultivates 4C skills (98.44%).	SmartEdu develops critical, creative, collaborative, and communicative thinking skills.	C2 – Higher-Order Thinking Skills (Critical, Creative, 4C)	The Problem and Discussion features strengthen higher-order thinking skills.	SmartEdu is highly effective in promoting critical and creative thinking, with very high achievement (95.70%).
SmartEdu increases independent learning motivation (93.75%), makes learning engaging (98.44%), builds confidence (88.28%), and encourages responsibility (93.75%).	SmartEdu enhances motivation, independence, confidence, and learning responsibility.	C3 – Motivation & Autonomy	Students become more independent and responsible, supported by an engaging learning environment.	SmartEdu fosters motivation and autonomy, with a high achievement score (93.55%).
SmartEdu supports project task completion (100%) and trains effective collaboration (97.66%).	SmartEdu cultivates project-based collaboration and communication skills.	C4 – Collaboration & Communication	Students become accustomed to effective teamwork in project-based tasks.	SmartEdu very strongly develops collaboration and communication, with a very high achievement score (98.83%).
SmartEdu makes students more reflective (96.88%), helps them understand their knowledge attainment through evaluation (92.19%), and improves future learning (94.53%).	SmartEdu supports self-reflection and continuous evaluation.	C5 – Reflection & Self-evaluation	The Evaluation feature encourages awareness of learning progress and improvement.	SmartEdu nurtures students' reflective awareness, with a high achievement score (94.53%).
SmartEdu supports educational technology skills (98.44%).	SmartEdu enhances technological integration skills and problem solving.	C6 – Technology Integration & Problem Solving	Students become accustomed to using technology in learning activities.	SmartEdu develops students' technological competence, with a very high achievement score (98.44%).

Analysis of SmartEdu Application Logs on Student, Lecturer, and Teacher Activities in Supporting Deep Learning

The analysis of SmartEdu application logs provides an essential quantitative complement to the qualitative insights obtained from interviews and questionnaires. Log data offer a real-time, objective record of student, lecturer, and teacher activities throughout the learning process, enabling researchers to observe authentic patterns of interaction, engagement, and task completion within the platform. By examining activity frequency, feature utilization, response patterns, and temporal learning behaviors, this analysis helps uncover how SmartEdu supports the development of deep learning competencies. Such evidence strengthens the overall interpretation of SmartEdu's effectiveness and validates the alignment between users' reported experiences and their actual digital learning behaviors.

The following section provides a more comprehensive overview of the analysis of each SmartEdu application feature in supporting the development of deep learning.

Figure 6. Student Activities in the Problem Feature of the SmartEdu Application

Deep-learning activities supported by the Problem feature in the SmartEdu application occur through the presentation of authentic problems relevant to real-world contexts. Such authentic and complex tasks are widely recognized for their ability to stimulate higher-order thinking, analytical reasoning, and meaningful learning (Hmelo-Silver, 2004; Rahma Hidayati Darwis et al., 2024; Savery, 2006). Through this feature, students are encouraged to analyze the root causes of issues, connect theoretical knowledge with practical situations, and propose alternative solutions in a critical and systematic manner—an approach aligned with principles of deep learning (Biggs et al., 2022; Biggs & Tang, 2011; Entwistle & Ramsden, 2015).

The Problem feature also enables active collaboration among students, instructors, and in-field teachers through interactive discussions and feedback. Recent studies demonstrate that digital Problem-Based Learning (PBL) environments significantly enhance collaborative inquiry, social interaction, and reflective engagement in higher education (Amoa-Danquah & Carbonneau, 2025; Barbara Means, 2009; Pratiwi & Wijayanti, 2025). This collaborative support aligns with the social constructivist view that knowledge is co-constructed through interaction and guided participation (Vygotskiĭ et al., 1978).

Consequently, the learning process facilitated by SmartEdu does not end at conceptual understanding but evolves into a sustained inquiry that cultivates critical thinking, creativity, and reflective problem-solving—competencies highlighted in recent empirical studies on deep learning and digital pedagogy (Borokhovski et al., 2020; Mayer & Fiorella, 2021).

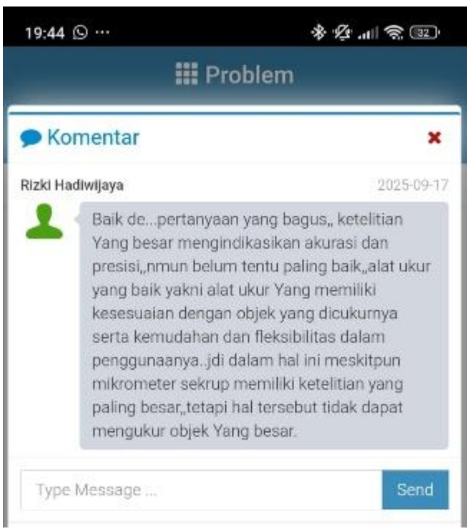

Figure 7. Lecturer responses to the problems presented in the SmartEdu application's problem feature.

The instructor's responses to students' in-depth questions submitted through the Problem feature in SmartEdu serve as an important catalyst for expanding knowledge and deepening conceptual understanding. These responses do not merely provide direct answers but also encourage students to re-examine their assumptions, explore multiple perspectives, and connect theoretical ideas with real-world applications. Such dialogic and reflective feedback has been shown to significantly enhance students' cognitive engagement and promote higher-order thinking and self-regulated learning (Charalampous & Darra, 2024; Ding, 2025; Weidlich et al., 2025).

This process creates a reflective space that stimulates students to think more critically when examining issues, while also generating creative ideas in formulating alternative solutions — outcomes associated with Problem-Based Learning (PBL) environments and collaborative inquiry pedagogies (Listyono et al., 2025). Consequently, the academic interactions facilitated through this feature not only enrich the learning material bu(Means et al., 2013)t also nurture higher-order thinking competencies — a defining characteristic of deep learning (Gong et al., 2025; Means et al., 2013).

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Figure 8. Student Communication Activities in The Smartedu Application's Chatting Feature.

The chat feature in SmartEdu serves as an essential bridge that enables students to engage in in-depth discussions about specific concepts beyond regular class hours, allowing learning to extend beyond the boundaries of the formal classroom. Such extended online interactions are known to promote cognitive presence, deepen conceptual processing, and strengthen social–academic engagement (Garrison & Cleveland-Innes, 2005; Martin et al., 2020). Through these exchanges, instructors function as knowledge facilitators who provide new insights that enrich students' understanding while guiding them to examine issues from multiple perspectives—an approach aligned with recent findings that instructor–student dialogic feedback enhances critical inquiry and conceptual change (David Carless, 2025; Henderson et al., 2019).

The flexible and interactive nature of these discussions fosters more meaningful learning, cultivates strong learning awareness, and creates an enjoyable academic atmosphere without communication barriers, consistent with evidence that synchronous and asynchronous chat tools can reduce transactional distance and promote learner autonomy (Martin et al., 2020; Moore & Diehl, 2019). Consequently, this feature strengthens the development of sustained deep-learning experiences, supporting competencies related to reflective engagement, critical thinking, and collaborative knowledge construction as highlighted in contemporary digital learning research (Baanqud et al., 2020; Kitto et al., 2017; Kleimola et al., 2025).

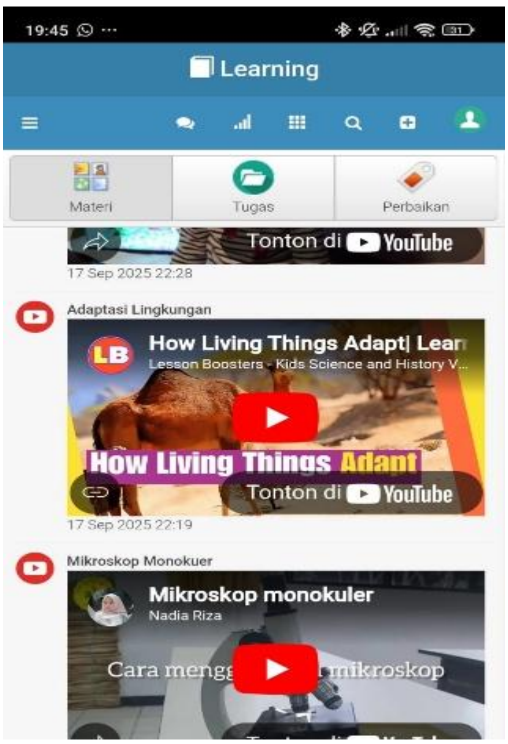

Figure 9. The display of the Learning feature in the SmartEdu application

The Learning feature in SmartEdu presents conceptual visualizations through interactive videos and other supporting materials designed to clarify and enrich students' understanding. Multimodal digital resources of this kind have been shown to enhance conceptual comprehension and promote active cognitive processing (Gijsen et al., 2024; Mayer, 2024; Zhang et al., 2006). With its ease of access and engaging presentation, students are able to learn at their own pace, revisit sections they find difficult, and connect theoretical knowledge with the real-world cases provided in the platform—an approach aligned with principles of self-paced and flexible digital learning environments (Otto et al., 2024; Tullis & Benjamin, 2011).

This multimodal presentation of content not only facilitates students' grasp of core concepts but also encourages them to examine the issues under study more critically and reflectively, supporting the development of deep-learning practices (Biggs & Tang, 2011; Graham et al., 1984). Consequently, the Learning feature contributes significantly to deep-learning experiences, wherein students do not merely receive information but process, connect, and internalize knowledge in meaningful and transformative ways (Tal & Tsaushu, 2017).

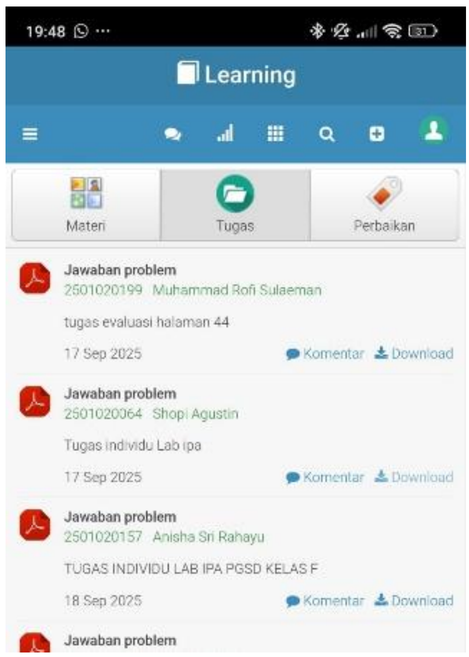

Figure 10. Task Upload Activities in the Assignment Menu of the Learning Feature on the SmartEdu Application

The Assignment feature in SmartEdu serves as a strategic space for fostering deep learning, as it enables students to submit their work directly while receiving transparent evaluations from instructors. Transparent assessment is widely recognized as a key driver of learning accountability, metacognition, and sustained conceptual growth (Panadero et al., 2026; Zulkarnaen et al., 2019b, 2020). Within this feature, instructors can provide detailed feedback in the form of scores, comments on weaknesses, and concrete guidance on aspects requiring improvement—an approach aligned with principles of effective feedback that promote students' self-regulated learning (Zulkarnaen et al., 2019b, 2020).

This transparency not only helps students understand their standing in relation to learning outcomes but also encourages continuous reflection and refinement, strengthening the development of deep learning dispositions (Balloo et al., 2018; Nicol & Macfarlane-Dick, 2006).

Furthermore, SmartEdu provides a task-revision function, allowing students to improve their work until it meets the expected standards. The iterative cycle of feedback and revision has been shown to enhance students' critical thinking, knowledge integration, and perseverance in achieving high-quality performance (Yan et al., 2024; Zeng & Ravindran, 2025; Zulkarnaen et al., 2019b, 2020). This cyclical mechanism promotes more complete and meaningful learning, fully aligned with the goals of deep learning—namely, robust conceptual understanding, critical thinking skills, and sustained engagement toward achieving optimal results (Gijbels, 2026).

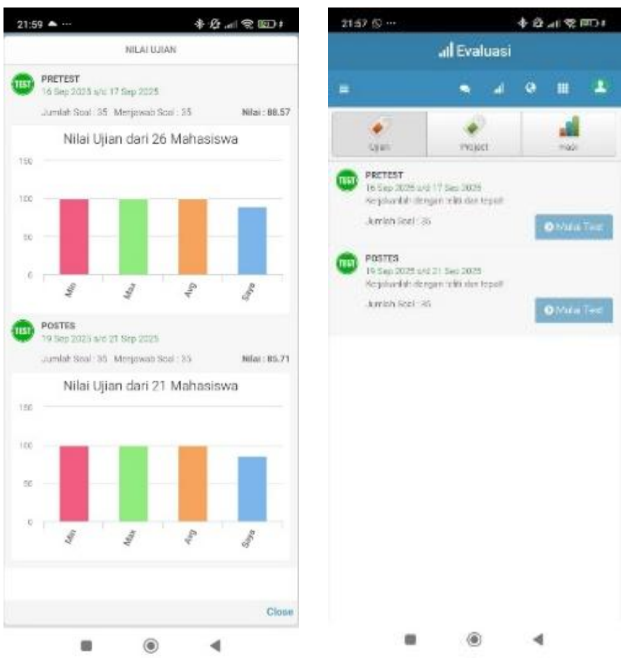

Figure 11. Visualization of Student Achievement Graphs and Questionnaire Reflections in the Evaluation Feature of the SmartEdu Application

The Evaluation feature in SmartEdu is designed with an automated system that allows students' work results to be accessed immediately upon completing a test or evaluative task. The speed and accuracy of this automated assessment system provide full transparency, enabling students to instantly view their scores and learning achievement details (Zulkarnaen et al., 2019b, 2020). Immediate and data-driven feedback has been shown to significantly enhance learners' metacognitive monitoring and performance (Kuklick et al., 2023; Theobald & Bellhäuser, 2022). Moreover, the evaluation feature is directly integrated with the Results feature, which offers a comprehensive overview of students' performance, both individually and in relation to their peers. Such integrated analytics align with recent research indicating that real-time learning dashboards support students in recognizing progress trends and performance gaps (De Vreugd et al., 2024).

Through this mechanism, students not only gain insight into their level of content mastery but also develop awareness of their learning conditions, strengths, and weaknesses. This reflective awareness is essential in fostering self-regulated learning, as students use performance data to adjust their learning strategies and make informed decisions about subsequent learning behaviors (Panadero et al., 2026). Furthermore, reflective feedback loops empower students to identify deficiencies and develop new approaches to improve learning effectiveness, consistent with the principles of formative assessment (Nicol & Macfarlane-Dick, 2006).

Ultimately, this mechanism strengthens the process of deep learning, as students are actively engaged in evaluating and directing their academic progress toward more meaningful and sustained understanding. Studies in digital learning environments show that formative digital feedback and real-time evaluation significantly promote higher-order thinking, conceptual change, and deep learning engagement (Filius et al., 2018; Fleur et al., 2023; McDonald et al., 2017; Wang & Han, 2021). Thus, SmartEdu's evaluation ecosystem aligns with contemporary international standards for technology-enhanced assessment that emphasize immediacy, transparency, adaptivity, and learner agency.

Data Validation and Verification through Triangulation Methods

The processes of verification and validation in this study were carried out to ensure that the findings obtained were truly credible and accurately reflected the actual conditions in the field. Validation was conducted through triangulation of data sources, methods, and researchers, in which data from students, instructors, and SmartEdu application activities were reinforced using observations, interviews, questionnaires, and documentation. Questionnaire results indicating high levels of achievement—such as Critical and Creative

Thinking indicators exceeding 95%—were verified through interviews and documentation that consistently confirmed the benefits of SmartEdu features, particularly in promoting conceptual understanding, critical thinking, and independent learning. Researcher discussions were also conducted to minimize individual bias, thereby producing more objective and trustworthy findings. In addition, member checking served as a crucial step in the validation process, during which interview results and summarized findings were confirmed by participants. The results of the verification and validation analysis are presented in Table 3.

Table 3. Verification and Validation of the Data Summary Analysis Using the Triangulation Method

Main Findings	Data Evidence	Verification Methods	Validation Results
SmartEdu enhances students' conceptual understanding and knowledge connectivity	Questionnaire results for Conceptual Understanding indicators (90.82%); student interview excerpts stating that SmartEdu helps them understand the material; documentation of Learning feature usage	Method triangulation (questionnaire, interview, observation); member checking with students	Valid: consistency between quantitative and qualitative data; students confirmed deeper conceptual understanding through SmartEdu
SmartEdu promotes students' critical and creative thinking	Questionnaire results for HOTS indicators (95.70%); student interviews about analyzing real-world problems; observation of the Problem feature and instructor responses	Source triangulation (students, instructors, and in-app activities); researcher triangulation	Valid: the Problem feature and instructor–student interactions were proven to strengthen critical and creative thinking skills
SmartEdu increases motivation, independence, and learning responsibility	Questionnaire results for Motivation & Independence indicators (93.55%); student statements about being more disciplined and confident; documentation of discussion chats	Method triangulation (questionnaire, interview, observation); member checking	Valid: students reported feeling more motivated, reflective, and responsible for their learning process
SmartEdu strengthens students' collaboration and communication	Questionnaire results for Collaboration indicators (98.83%); observations of chat feature and group assignments; student interviews regarding active discussions	Source triangulation (students, application activities); audit trail of interaction documentation	Valid: effective collaboration was established through chat discussions and project-based tasks
SmartEdu facilitates reflection and self-evaluation	Questionnaire results for Reflection indicators (94.53%); documentation of automatic evaluation features and performance results; student interviews on improving learning strategies	Method triangulation; member checking with students regarding reflection experiences	Valid: transparent evaluation features helped students reflect on their achievements and refine their learning strategies
SmartEdu supports technology integration and contextual problem solving	Questionnaire results for Technology Integration indicators (98.44%); observations of application use inside and outside class; documentation of project-based tasks	Method and researcher triangulation; audit trail of SmartEdu usage	Valid: students were able to use technology as a tool for contextual learning and real-world problem solving

The verification results demonstrate that SmartEdu significantly enhances students' conceptual understanding and knowledge connectivity, aligning with recent findings on technology-supported deep learning (Bond & Bergdahl, 2023; Giacomazzi, 2024). Questionnaire data show a very high achievement score (90.82%), supported by interview statements indicating that the Learning feature deepens conceptual comprehension and links theoretical content with real-world applications, consistent with research on multimodal digital learning (Mayer & Fiorella, 2021). Documentation of interactive materials and instructional videos further confirms that students successfully integrate new knowledge with prior understanding, a process emphasized in cognitive theory and connected learning frameworks (Lang et al., 2017). The consistency of quantitative and qualitative data, reinforced through member checking, validates

SmartEdu's strong contribution to conceptual learning (Creswell, 2017).

Verified findings also indicate substantial improvements in critical and creative thinking (Higher Order Thinking Skills), supporting the notion that digital learning environments can promote higher-order processing. This is evidenced by a 95.70% questionnaire score, interview data showing students' increased ability to analyze authentic problems from multiple perspectives, and observations of active academic dialogue within the Problem feature. Such interactions align with evidence that problem-based and inquiry-supported digital tools strengthen analytical and creative reasoning (Zawacki-Richter & Jung, 2023). Triangulation across sources and researchers confirms the validity of this outcome, highlighting SmartEdu's role in fostering deep-learning characteristics (Biggs et al., 2022).

In the domain of motivation, autonomy, and learning responsibility, verification results remain positive. Students' questionnaire scores averaged 93.55%, supported by interviews describing greater confidence, discipline, and strategic self-regulation—patterns that match contemporary findings on self-regulated learning in digital platforms (Moore & Diehl, 2019). Documentation from chat interactions shows active questioning and clarification-seeking behaviors, indicating strengthened ownership of learning, consistent with research showing that digital communication tools enhance student agency (Zulkarnaen et al., 2020). Methodological triangulation and member checking further validate these findings (Creswell, 2017).

SmartEdu also produces a strong impact on student collaboration and communication, with the highest indicator score (98.83%). Observations of chat interactions and project-based tasks reveal intensive exchanges, constructive peer feedback, and effective teamwork—key characteristics of 21st-century collaborative learning (Zulkarnaen et al., 2019b, 2020). Interviews further confirm that students find collaboration more accessible due to the platform's flexible and interactive communication channels, which is consistent with prior studies on digitally mediated peer learning (Means et al., 2013). Audit trail evidence strengthens the validity of this conclusion.

Finally, verification demonstrates that SmartEdu supports reflective practice, self-evaluation, technology integration, and contextual problem solving. High questionnaire scores (94.53% for reflection; 98.44% for technology integration) indicate that transparent automated assessments help students understand their learning progress and refine future strategies. Documentation of project-based activities shows effective integration of technology in addressing real-world problems, which corresponds to current literature on digital problem-based learning (Zawacki-Richter & Jung, 2023). Triangulation and audit trails affirm that SmartEdu functions not only as a learning tool but also as a platform that cultivates reflective awareness, technological competence, and contextual problem-solving skills essential to deep learning (Mayer, 2021).

Conclusion

This study demonstrates that the SmartEdu application effectively supports the implementation of deep learning in science education for prospective elementary school teachers. By integrating conceptual knowledge with authentic problem-solving activities, structured discussions, and reflective evaluation, SmartEdu facilitates meaningful and contextual learning experiences that enhance students' conceptual understanding, higher-order thinking skills, and learning autonomy. Furthermore, the platform contributes to the development of essential 21st-century competencies, including critical and creative thinking, collaboration, communication, and reflective learning. These findings indicate that technology-supported deep learning environments can play a strategic role in transforming teacher education by promoting more interactive, student-centered, and sustainable learning practices. Therefore, integrating digital learning ecosystems such as SmartEdu offers a promising approach for strengthening the quality of science education and preparing future teachers to address the challenges of contemporary education.

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Conflicts of Interest

The authors declare no conflict of interest.

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