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The Use of Educational Robots and Pedagogical Deep Learning Approach to Enhance Critical Thinking in Early Childhood Education

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ABSTRACT

Purpose: This study aims to examine the implementation of Educational Robots using a Pedagogical Deep Learning Approach as a learning medium to foster critical thinking skills in early childhood education. **Methods:** This study employed a descriptive qualitative approach. Data were collected through observations and semi-structured interviews involving children aged 5–6 years. The data were analyzed using coding, category development, and thematic analysis to identify patterns and themes emerging from the learning process. **Findings:** The findings indicate that Educational Robots were implemented through learning activities emphasizing exploration, problem-solving, and collaborative play, in line with the principles of meaningful, mindful, and joyful learning. The results suggest that the use of Educational Robots facilitated children's critical thinking skills, as reflected in their ability to analyze shapes, make decisions, predict outcomes, identify errors, and revise construction strategies. In addition, increased engagement, collaboration, and curiosity were observed throughout the learning process. **Research Implications:** This study suggests that Educational Robots integrated with a Pedagogical Deep Learning Approach can facilitate meaningful and accessible learning experiences that support the development of critical thinking skills in early childhood. The findings also offer an innovative, affordable, and sustainable learning medium that can assist early childhood educators in implementing meaningful learning practices. **Originality:** The originality of this study lies in integrating Educational Robots constructed from recycled materials with a Pedagogical Deep Learning Approach to foster critical thinking skills in early childhood education. This study offers an innovative, affordable, sustainable, and contextually relevant learning medium to support the implementation of meaningful learning in Indonesian early childhood education settings.

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INTRODUCTION

The Sustainable Development Goals (SDGs 4) are a set of global goals to address social, economic, and environmental challenges worldwide. One of the 13 SDGs emphasizes that access to quality education must include integrating technology to enhance children's learning experiences from an early age (Mursyidah & Mardiana, 2023). Deep learning in early childhood education encourages the development of critical thinking and complex problem-solving skills and fosters a positive attitude towards curiosity and exploration, which are the foundations of lifelong learning (Zhao et al., 2023). The use of STEM Educational Robots to stimulate critical thinking and problem-solving skills in children from an early age is in line with the National Association for the Education of Young Children, which emphasizes that critical thinking in early childhood develops through meaningful, exploratory, and developmentally appropriate learning experiences, including the use of technology that encourages children's curiosity and reflection (National Association for the Education of Young Children, 2020). Globally, critical thinking skills are seen as a key 21st-century competency that needs to be developed from early childhood education because they support analytical skills, problem-solving, and readiness to learn in the context of science- and technology-based learning (OECD, 2016; Trilling &

Fadel, 2009). In this context, integrating learning media such as Educational Robots (Robot Edukasi) is an innovative effort to improve the quality of education, particularly in science and technology.

Educational robots have been implemented in various countries to help children learn programming and logical thinking from an early age (Williams et al., 2019). Robotics can enhance creativity, engage children in science, engineering, and technology, and provide suggestions for using robotics in Early Childhood Education (S. D. Park et al., 2019; Zviel-Girshin & Rosenberg, 2021). Although it has been widely implemented in various countries, the use of educational robots in Early Childhood Education in Indonesia still faces various challenges. Some of the main obstacles faced are a lack of supporting resources, limited access to educational robot devices designed specifically for early childhood education, and a lack of effective strategies for integrating this technology into the early childhood education curriculum (Merry et al., 2024). The application of deep learning in early childhood education, which emphasizes the development of critical thinking, problem-solving, and reflective skills, is an important approach to reforming PAUD education to make it more effective and personalized. However, the integration of technology, such as educational robots, is still not optimal because it has not fully adopted this deep learning strategy (Ding & Li, 2024; Su et al., 2023). In this digital age, children are growing up in an environment increasingly influenced by technology, yet many early childhood education institutions lack effective strategies to integrate technology into learning (Aryani et al., 2023; Helena et al., 2023; Liu & Pange, 2015; Sugiyono, 2019).

Research shows that deep learning is one of the most effective learning methods for developing children's analytical and cognitive abilities. Through the application of deep learning techniques, children can be stimulated to hone their critical thinking and problem-solving skills in depth (Misirli & Komis, 2023; Tariq et al. 2025). Deep learning also plays an important role in supporting the understanding of complex concepts through a repetitive, adaptive learning process, thereby gradually strengthening children's cognitive abilities. Therefore, the application of deep learning in early childhood education is highly relevant and requires a specialized approach tailored to children's developmental characteristics, including the selection of appropriate learning methods and media to achieve optimal results (Hermita et al., 2023; Kumala et al., 2023).

Educational robots have demonstrated potential to enhance learning outcomes, particularly when they are implemented as co-teachers rather than as replacements for human teachers (Winter et al., 2026). Children can learn through exploration, experimentation, and direct interaction with technology (Helena et al., 2023). Educational robots with a deep learning approach are urgently needed in kindergartens, as many schools have not yet implemented them in their learning. The problem-solving approach was carried out through research on the design of Educational Robots with a deep learning approach that directly involved early childhood, so that Educational Robots not only functioned as learning aids but also increased children's interaction with technology, problem-solving abilities, and critical thinking (Aryani et al., 2020, 2024; Hermita et al., 2023).

Based on this research gap, this study aims to examine the implementation of Educational Robots integrated with a Pedagogical Deep Learning Approach in early childhood education. Specifically, the study seeks to describe how Educational Robots are implemented in the learning process and to explore how their use facilitates the development of young children's critical thinking skills through exploration, problem-solving, and reflective learning activities. The findings are expected to provide an innovative, accessible, and contextually relevant STEM learning alternative for early childhood educators in supporting meaningful learning experiences.

METHOD

This study uses a descriptive qualitative approach to gain an in-depth understanding of the application of Educational Robot (Robot Edukasi) learning media, based on a deep learning approach, to stimulate critical thinking skills in early childhood. This approach was chosen because it allows researchers to explore the learning process in a natural, contextual manner, in accordance with the characteristics of early childhood education (Creswell & Poth, 2018; Merriam & Tisdell, 2016). The research was conducted at a partner kindergarten that has integrated Educational Robot into its learning activities. The research subjects included early childhood children directly involved in the learning process, as well as classroom teachers who served as the main facilitators. The subjects were selected purposively based on their active involvement in the implementation of Educational Robot (Miles et al., 2014). The participants consisted of 24 children aged 5–6 years from three partner kindergartens in Pekanbaru, Indonesia, along with 3 classroom teachers. The selection was based on purposive sampling criteria, including active participation in Educational Robot learning activities and teacher willingness to collaborate in the research process.

The learning intervention was implemented in eight classroom sessions over a four-week period, with each session lasting approximately 60–90 minutes. The Educational Robot used in this study was constructed from low-cost recycled materials and designed to support hands-on STEM learning activities appropriate for children aged 5–6 years.

Each learning session followed the stages of the Pedagogical Deep Learning Approach, including understanding, exploration, application, collaboration, and reflection. Children's critical thinking was observed using indicators adapted from early childhood critical thinking frameworks, including identifying problems, asking questions, predicting outcomes, making decisions, testing alternative solutions, explaining ideas, and revising strategies. Classroom observations were guided by a structured observation protocol documenting children's verbal responses, collaborative interactions, problem-solving processes, and reflective behaviours. Throughout the study, the researchers acted as participant observers, documenting learning activities while minimizing interference with the natural classroom environment.

Chronologically, the research was conducted in several stages. The initial stage was preparation, which included preliminary studies, the development of observation and interview guidelines, and the design of learning activities based on Educational Robots, oriented towards stimulating critical thinking and the principles of deep learning (Fullan et al., 2018). The next stage was the implementation of learning, in which teachers carried out activities using Educational Robots in a natural classroom setting, while the researchers conducted participatory observations of the children's interactions, exploration, and problem-solving.

Data collection was conducted through participatory observation, semi-structured interviews with teachers, and documentation in the form of photos of activities, learning notes, and children's artifacts (Spradley, 2016). The collected data were analyzed using thematic analysis, involving coding, category grouping, and theme discovery, to represent children's critical thinking patterns and teachers' responses to the use of Educational Robots (Braun & Clarke, 2006). Data validity was ensured through source triangulation and member checking with teachers to ensure the accuracy of data interpretation (Lincoln & Guba, 1985). The analysis focused on how the Educational Robot facilitated deep learning through interactions that encouraged children to independently and collaboratively explore, question, and reflect on their learning experiences. Each observation session lasted approximately 60–90 minutes and was conducted over a period of four weeks. Interviews with teachers were conducted at the end of each implementation cycle to capture reflective insights on children's learning processes and challenges. To enhance the trustworthiness of the findings, methodological triangulation was applied by comparing data from observations, interviews, and documentation. In addition, data source triangulation was conducted across different classrooms and participants. Peer debriefing among researchers was also carried out to minimize bias in data interpretation. This study was conducted with the approval of the participating schools, and written informed consent was obtained from teachers and parents or legal guardians of all participating children prior to data collection.

RESULTS

The results of the study were obtained from the implementation of learning using the Education Robot (Education Robot) media with a deep learning approach in children aged 5–6 years in three kindergartens. Data analysis was conducted thematically to identify patterns of learning behavior, forms of critical thinking stimulation that emerged, and teachers' responses to the use of Educational Robots in early childhood learning. The findings identified four major themes related to the implementation of Educational Robots integrated with the Pedagogical Deep Learning Approach: (1) identifying problems through exploration, (2) decision-making and predicting outcomes, (3) strategy revision through reflection, and (4) meaningful collaborative learning supported by teacher facilitation. These themes emerged consistently from participatory observations, teacher interviews, and learning documentation conducted in three partner kindergartens.

Theme 1. Children Identified Problems through Exploration

During classroom observations, children actively explored the Educational Robot by manipulating geometric components and observing the consequences of their actions. Rather than simply following teacher instructions, children demonstrated the ability to identify simple problems, such as recognizing why the robot could not stand properly or why certain structures became unstable. They compared different component arrangements before deciding how to modify their constructions.

Observation Note 1: One child repeatedly rearranged the robot's supporting blocks after noticing that the robot collapsed several times. The child remarked, "Maybe this one should be here," before replacing the rectangular block with a triangular piece and testing the new arrangement.

Teacher interviews supported these observations. *"During the initial learning sessions, most children tended to wait for instructions before taking action. As the activities progressed, they became more willing to identify problems independently and attempted to solve them before asking for assistance." (Teacher 1)*

These findings indicate that Educational Robots created opportunities for children to engage in active exploration while recognizing simple cause-and-effect relationships.

Theme 2. Children Demonstrated Decision-Making and Prediction Skills

Observation data showed that children made decisions by selecting geometric components, predicting possible outcomes, and evaluating whether their constructions functioned as intended. The repeated trial-and-error process encouraged children to compare alternative solutions and determine the most appropriate construction strategy.

Observation Note 2: During one learning activity, several children discussed whether a square or triangular component would provide better balance for the robot. They agreed to test both alternatives before deciding which arrangement produced a more stable structure.

Teacher interviews also confirmed these findings : *"After several learning sessions, the children no longer relied solely on teacher instructions. They discussed ideas with their peers, predicted what might happen if they changed the robot's structure, and tested those ideas independently." (Teacher 2)*

These observations suggest that the learning activities encouraged children to make reasoned decisions based on direct exploration and collaborative discussion.

Theme 3. Reflection Supported Strategy Revision

Children demonstrated reflective thinking by evaluating unsuccessful constructions and revising their strategies accordingly. Rather than abandoning the activity after failure, they attempted different arrangements based on previous experiences and peer discussions.

Observation Note 3: One child modified the robot's base after observing that the previous arrangement repeatedly collapsed. After making several adjustments, the child explained, "Now it can stand because I changed this part."

Teachers described similar behaviors: *"When the robot did not function properly, the children rarely stopped working. They observed what had happened, discussed possible causes with classmates, and tried another strategy before asking the teacher." (Teacher 3)*

These findings illustrate that reflection became an integral part of children's problem-solving process throughout the learning activities.

Theme 4. Educational Robots Fostered Meaningful and Collaborative Learning

Teacher interviews and classroom observations consistently indicated that Educational Robots supported a more meaningful, collaborative, and child-centred learning environment. Children actively exchanged ideas, justified their decisions, and participated in collaborative problem-solving while teachers assumed the role of facilitators rather than direct instructors.

One teacher explained, *"The Educational Robot transformed the classroom atmosphere. Children became more engaged, asked more questions, expressed their opinions confidently, and collaborated naturally while solving problems together." (Teacher 2)*

Another teacher added: *"Instead of providing immediate answers, I encouraged children to think by asking questions such as 'Why do you think this happened?' or 'What could you try differently?' This allowed them to construct their own understanding." (Teacher 3)*

Learning documentation further demonstrated that children connected their play experiences with concepts such as balance, movement, geometric shapes, and structure. As they gained experience, they developed increasingly systematic strategies for constructing Educational Robots, reflecting the characteristics of meaningful, mindful, and reflective learning promoted within the Pedagogical Deep Learning Approach.

Overall, the thematic analysis demonstrated consistent patterns across observations, teacher interviews, and learning documentation. The four themes identified represent interconnected aspects of children's learning experiences while interacting with Educational Robots within the Pedagogical Deep Learning Approach. Rather than occurring as separate processes, problem identification, decision-making, strategy revision, and collaborative learning emerged simultaneously throughout the learning activities. The convergence of evidence from multiple data sources strengthens the credibility of these findings and illustrates how Educational Robots supported active, reflective, and meaningful learning experiences that encouraged the emergence of critical thinking behaviours among young children. Table 1 summarizes the identified themes, the corresponding data sources, and the key evidence observed across the three partner kindergartens.

Table 1. Summary of Themes and Supporting Evidence from the Implementation of Educational Robots within the Pedagogical Deep Learning Approach

Theme	Data Sources	Evidence
Identifying problems through exploration	Observation, Interview	Children recognized problems, explored causes, and tested different arrangements.
Decision-making and predicting outcomes	Observation, Interview	Children selected alternatives, predicted outcomes, and evaluated results collaboratively.
Reflection and strategy revision	Observation, Interview	Children revised unsuccessful constructions based on previous experiences.
Meaningful collaborative learning	Observation, Interview, Documentation	Teachers facilitated inquiry while children collaborated and constructed understanding.

As presented in Table 1, the four themes were supported by converging evidence from observations, teacher interviews, and learning documentation. The findings indicate that children's problem identification, decision-making, reflection, and collaborative learning were not isolated processes but occurred as interconnected aspects of their learning experiences with Educational Robots. This convergence across multiple data sources provides a consistent representation of the learning processes observed during the implementation.

DISCUSSION

The findings of this study suggest that integrating Educational Robots with the Pedagogical Deep Learning Approach created learning experiences that encouraged the emergence of critical thinking behaviours among children aged 5–6 years. Rather than demonstrating causal effectiveness, the qualitative evidence indicates that children increasingly engaged in identifying problems, predicting outcomes, making decisions, testing alternative solutions, and revising construction strategies while interacting with Educational Robots. These behaviours emerged consistently across classroom observations, teacher interviews, and learning documentation, suggesting that Educational Robots functioned as learning media that supported exploration, reflection, and collaborative inquiry within authentic classroom contexts. One important contribution of this study is the explanation of the learning mechanism through which Educational Robots appeared to facilitate critical thinking. The findings indicate that children's critical thinking did not emerge solely because they interacted with robotic media. Instead, the observed behaviours resulted from the interaction of three complementary elements: hands-on manipulation of Educational Robots, collaborative dialogue with peers, and teacher scaffolding implemented through the Pedagogical Deep Learning Approach. During classroom activities, children repeatedly observed the consequences of their actions, compared alternative solutions, evaluated unsuccessful constructions, and modified their strategies accordingly. This learning process reflects constructivist perspectives that emphasize knowledge construction through active interaction with objects and social experiences rather than passive transmission of information (Fullan et al., 2018). Similarly, the deep learning framework emphasizes meaningful learning experiences in which learners actively construct understanding through exploration, collaboration, and reflection (Ding & Li, 2024; Zhao et al., 2023).

The results also demonstrate that Educational Robots supported inquiry-oriented STEM learning experiences appropriate for early childhood. Throughout the learning sessions, children manipulated geometric components, explored balance and movement, discussed possible solutions with peers, and refined their constructions through repeated trial and error. These activities resemble engineering design processes commonly promoted within STEM education, where children develop understanding through experimentation and iterative problem solving rather than predetermined procedures (Aryani et al., 2024; Hermita et al., 2023). Similar patterns were reported by (Misirli & Komis, 2023), who found that tangible robotics activities encouraged debugging processes, exploration, and computational thinking among young children. Likewise, (Ruangtip et al., 2025) reported that robotics-based STEM learning promoted computational thinking and problem-solving through experiment-based learning. Although the present study did not directly examine computational thinking, the observed behaviours—including identifying problems, predicting outcomes, evaluating alternatives, and revising strategies—represent comparable forms of higher-order thinking appropriate to early childhood learning contexts.

Another important finding concerns the role of teacher facilitation. Teacher interviews consistently indicated that children became more willing to explore independently when teachers shifted from giving direct instructions to facilitating inquiry through open-ended questions and reflective dialogue. Rather than immediately correcting children's mistakes, teachers encouraged them to observe what happened, explain their reasoning, and test different solutions independently. Such scaffolding appears to have created opportunities for children to regulate their own

thinking while maintaining ownership of the learning process. This finding supports the view that meaningful technology integration depends not only on the learning media but also on pedagogical practices that encourage children's active participation (Gao et al., 2022; Helena et al., 2023). Therefore, Educational Robots should be viewed as pedagogical tools whose educational value depends largely on how teachers facilitate exploration and reflection during learning.

The collaborative dimension of learning also emerged as an important mechanism supporting critical thinking. Classroom observations showed that children frequently exchanged ideas, negotiated construction strategies, justified their choices, and evaluated outcomes together before making decisions. Through collaborative interactions, children were exposed to multiple perspectives that encouraged them to reconsider previous assumptions and refine their solutions. These findings are consistent with previous studies reporting that educational robotics promotes communication, collaborative problem solving, and inquiry-based learning in early childhood STEM education (H. J. Park et al., 2016; Zviel-Girshin & Rosenberg, 2021). The present findings extend this literature by illustrating how collaboration became integrated into the Pedagogical Deep Learning Approach through sequential stages of exploration, application, and reflection.

Unlike many previous studies that employed commercially manufactured educational robots, this study implemented Educational Robots constructed from recycled materials. Although technologically simple, these robots provided meaningful opportunities for children to investigate relationships among geometric shapes, balance, structure, and movement through direct manipulation. This finding suggests that the pedagogical design of learning activities may play a more important role than technological sophistication alone. Such an approach may offer a practical alternative for early childhood education settings with limited financial resources, while supporting broader efforts to integrate STEM learning into Indonesian early childhood education (Merry et al., 2024). Nevertheless, the findings should be interpreted within several contextual limitations. This study involved only 24 children from three partner kindergartens and adopted a descriptive qualitative design; therefore, the findings are intended to provide contextual understanding rather than evidence of general effectiveness. Children's engagement may also have been influenced by several contextual factors that were not examined separately, including the novelty of interacting with Educational Robots, differences in teacher facilitation styles, and collaborative dynamics among peers during classroom activities. Future studies employing longitudinal, mixed-methods, or comparative research designs across more diverse educational settings may provide a deeper understanding of how these factors influence children's critical thinking development over time.

Overall, this study contributes to the growing body of literature on educational robotics in early childhood education by illustrating how Educational Robots integrated with the Pedagogical Deep Learning Approach may support meaningful, reflective, and collaborative learning experiences. Rather than positioning Educational Robots as a stand-alone technological solution, the findings suggest that their educational value lies in their capacity to facilitate inquiry-oriented learning in which children actively construct understanding through exploration, dialogue, and reflection. These findings provide contextual evidence that affordable educational robotics may represent a feasible pedagogical alternative for supporting STEM learning and the development of critical thinking behaviours in early childhood education.

CONCLUSION

This study explored the implementation of Educational Robots integrated with the Pedagogical Deep Learning Approach in learning activities involving children 5–6 years old from three partner kindergartens. The findings suggest that the learning activities provided opportunities for children to demonstrate critical thinking behaviours, including identifying problems, predicting outcomes, making decisions, testing alternative solutions, and revising strategies through exploration, collaboration, and reflection. The findings also indicate that Educational Robots constructed from low-cost recycled materials can serve as a contextually relevant pedagogical medium to support meaningful STEM learning experiences when combined with appropriate teacher facilitation.

However, these findings should be interpreted within the context of this qualitative study and should not be generalized to broader early childhood education settings. Because the study involved a limited number of participants and focused on a specific learning context, it cannot be interpreted as evidence of causal effectiveness. Future studies involving larger and more diverse samples, longitudinal observations, or mixed-methods approaches are recommended to further examine the potential contribution of Educational Robots and the Pedagogical Deep Learning Approach in supporting children's critical thinking development across different educational contexts.

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AUTHOR CONTRIBUTION STATEMENT

All authors contributed to the development and completion of this study. The contributions included the formulation of the research idea and objectives, development of the research design and methodology, implementation of the research activities, data collection and analysis, interpretation of the findings, and preparation of the manuscript. All authors were involved in reviewing and revising the manuscript to ensure the clarity, accuracy, and consistency of the content. All authors have read and approved the final version of the manuscript and agree to be accountable for the integrity and accuracy of the work.

AI DISCLOSURE STATEMENT

The authors used AI solely to assist in generating and developing ideas during the preparation of this manuscript. AI was not used to generate research data, conduct data analysis, determine research findings, or formulate conclusions. The authors reviewed and verified all content and remain fully responsible for the accuracy and integrity of the manuscript.

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