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HeRoBo: A Robotics Game Concept Using Recycled Materials to Develop Early Childhood Awareness

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Abstrak

Perkembangan teknologi dan kesadaran lingkungan sejak usia dini menjadi isu penting dalam pendidikan anak usia dini (PAUD). Namun, ketersediaan media pembelajaran robotika yang aman, ekonomis, dan ramah lingkungan di PAUD masih terbatas. Penelitian ini bertujuan mengembangkan prototipe permainan robotika berbahan daur ulang, yang disebut HeRoBo (*Heritage Recycle Robot*), untuk membangun kepekaan anak terhadap teknologi dan lingkungan. Metode penelitian menggunakan pendekatan *Research and Development (R&D)* melalui tahapan analisis kebutuhan, perancangan prototipe, uji coba awal, revisi, dan evaluasi. Hasil penelitian menunjukkan bahwa prototipe HeRoBo dapat dirakit oleh anak dengan bantuan minimal serta mampu mendorong kreativitas, kemampuan berpikir kritis, pemecahan masalah, dan kesadaran ekologis. Anak menunjukkan kemampuan mengenali dan memilih bahan daur ulang, membedakan material organik dan nonorganik, serta mengeksplorasi berbagai konfigurasi robot secara kreatif. Interaksi langsung dengan prototipe memberikan pengalaman belajar yang konkret, interaktif, dan aplikatif sesuai prinsip STEM *Education for Young Learners* untuk pembelajar usia dini. Implikasi penelitian ini menunjukkan bahwa HeRoBo berpotensi menjadi alternatif media pembelajaran inovatif berbasis STEM yang berkelanjutan, berbiaya rendah, dan mudah diimplementasikan di PAUD, sekaligus mendukung penguatan pendidikan lingkungan dan literasi teknologi sejak usia dini. Kesimpulannya, HeRoBo efektif mengintegrasikan teknologi, kreativitas, dan pendidikan lingkungan secara holistik dalam pembelajaran anak usia dini.

Kata kunci: Anak Usia Dini**,** Bahan Daur Ulang, HeRoBo, Robotika

Abstract

The development of technology and environmental awareness from an early age are important issues in early childhood education (PAUD). However, the availability of safe, economical, and environmentally friendly robotics learning media in PAUD is still limited. This study aims to develop a prototype of a robotics game made from recycled materials, called HeRoBo (Heritage Recycle Robot), to build children's sensitivity to technology and the environment. The research method uses a Research and Development (R&D) approach through the stages of needs analysis, prototype design, initial trials, revisions, and evaluation. The results show that the HeRoBo prototype can be assembled by children with minimal assistance and is able to encourage creativity, critical thinking skills, problem solving, and ecological awareness. Children demonstrated the ability to recognize and select recycled materials, differentiate organic and non-organic materials, and creatively explore various robot configurations. Direct interaction with the prototype provides a concrete, interactive, and applicable learning experience according to STEM Education for Young Learners principles for early learners. The implications of this research indicate that HeRoBo has the potential to be an alternative, innovative, STEM-based learning medium that is sustainable, low-cost, and easy to implement in early childhood education, while also supporting the strengthening of environmental education and technological literacy from an early age. In conclusion, HeRoBo effectively integrates technology, creativity, and environmental education holistically into early childhood learning.

Keywords: *Early Childhood, HeRoBo, Recycled Materials, Robotics*

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INTRODUCTION

Early childhood education (PAUD) is a crucial stage in the formation of cognitive, affective, and psychomotor aspects, so that the quality of stimulation provided during this period greatly influences the development of critical thinking skills, creativity, and social and emotional sensitivity of children. Refers to (Suyadi, 2020) and (Bredekamp, 2019), Early childhood children more easily understand concepts and hone their skills through hands-on experience, educational play activities, and interactions with various objects that encourage free and directed exploration. However, in reality, many early childhood education institutions in Indonesia still rely on traditional learning patterns that are routine, lack variety, and lack innovation. Consequently, opportunities to utilize technology, create creative activities, and integrate problem-solving approaches have not been maximized (Javed et al., 2022). This situation shows a mismatch between the child's developmental needs and the learning methods used, so it is necessary to develop learning strategies that are more oriented towards participation, real experience contexts, and exploratory stimulation to support the optimization of children's potential during their early growth.

Globally, technological literacy, including simple robotics, has been recognized as an important element in early childhood education because it can stimulate the development of computational thinking skills, logical reasoning, and creativity (Bers, 2018). In many developed countries, robotics applications are introduced through structured play activities, allowing children to directly observe, experiment, and understand cause-and-effect relationships. However, implementing a similar concept in Indonesia still faces various challenges, such as limited supporting facilities, expensive robotics equipment, and a lack of teacher competency and training in integrating technology into learning activities (Gundupalli et al., 2017). These barriers further widen the gap in access between educational institutions with sufficient resources and those without, thus limiting children's opportunities to learn about technology from an early age, even though such experiences are crucial for building digital literacy and preparing them to face the demands of the 21st century.

Environmental issues and the increasing amount of waste, particularly plastic waste and non-organic materials that are difficult to degrade, are becoming a growing global concern and require more serious action. In this regard, environmental education for early childhood is crucially important, delivered through concrete, contextual, and meaningful activities to instill a foundation of ecological awareness from an early age (UNESCO, 2020). The integration of technological elements with environmental education is seen as an effective step because it is able to provide a more comprehensive, interesting, and easy-to-apply learning experience, so that children not only gain theoretical understanding, but can also internalize and practice behaviors that support environmental conservation efforts in their daily lives (Sarc et al., 2019).

Based on these conditions, a form of innovation in educational games is needed that not only introduces technological aspects, especially simple robotics, but also instills the values of environmental sustainability in children from an early age. One alternative that is considered effective is the development of robotics games from recycled materials that children can assemble themselves through easy-to-follow steps, so that the learning process becomes more active, creative, and meaningful. This effort is in line with the concept of STEM Education for Young Learners, which emphasizes the importance of integrating technology, creativity, and environmental issues in learning activities to build a comprehensive understanding (Hjorth & Chrysostomou, 2022). Through this approach, children are not only introduced to the basic principles of mechanics and robotics technology, but are also accustomed to reusing used materials, developing critical thinking skills regarding environmental issues, and fostering concern for the sustainability of the ecosystem from an early age.

Various studies show that the application of project-based learning and constructive play plays an important role in developing various abilities in early childhood, such as motor skills, self-confidence, collaborative skills, and problem-solving skills (Leggett & Newman, 2017; Weisberg et al., 2016). Integrating these two approaches with the use of recycled

materials offers additional benefits, not only cognitively and socially, but also ecologically. Children can be introduced to the practice of sorting waste, reusing used materials, and internalizing environmentally friendly behaviors through interactive and fun activities (Wang et al., 2019). Therefore, combining project-based learning and assembly games with the use of recycled materials not only broadens the learning experience, but also fosters practical environmental awareness, fosters ecological responsibility, and instills positive habits that have the potential to continue in everyday life.

To date, research examining the development of integrative concepts between robotics and environmental education for early childhood through recycled material play is still very limited; for example, a literature review on educational robotics shows only 7 robotics research articles specifically examining robotics learning for early childhood in recent Indonesian education journal publications, most of which focus on improving general STEM skills without explicitly integrating environmental or recycling components (Akhmad, A., & Gudnanto, 2025).

Robotics research articles examining early childhood learning in Indonesia are currently limited and generally focus on strengthening general STEM-based skills. Among them is the study "Robotics Learning in Early Childhood: A Literature Review" by Akhmad and Gudnanto, which systematically identified seven robotics research articles in the context of early childhood education in Indonesian education journals (Akhmad, A., & Gudnanto, 2025). Empirical research "Training Introduction to Simple Robots for Kindergarten Children as a Tool in Improving Children's Psychomotor Abilities" by Ratna Mayasari et al. which emphasizes the introduction of simple robots to improve the psychomotor abilities of kindergarten children (Mayasari, R., Astuti, S., Negara, R. M., Tulloh, R., & Nurmantris, 2025). Experimental study "Robmanjar: Robot Learning Friend, Literacy Stimulator for Early Childhood" by Sulistyawati et al., which utilizes robots as a medium for literacy stimulation (Sulistyawati, S., Sujaini, H., Salam, U., Aunurrahman, A., & Wicaksono, 2024). The study "Implementation of Wedo 1.0 Education Robotic Tools Based on STEAM in Forming the Character of Early Childhood" by Devri Suherdi, Syarifah Fadillah Rezky, and Kartika Sari which highlights the use of STEAM-based robotic devices for character developmen (Suherdi, D., Rezky, S. F., & Sari, 2023). Research "Line Follower Robot as an Educational Play Tool for Early Childhood" by Wahyuni Eka Sari et al. who developed a line follower robot as an educational play medium for early childhood education children (Sari, W. E., Triyono, A., Irwansyah, I., Utomo, K. B., & Hakim, 2024). Community service article "Basic Robotics Education for Kinder Club Educators Using Line Follower Robots" by Larasati, Romadhona, and Affandi which focuses on improving the competence of PAUD educators in introducing robotics (Larasati, S., Romadhona, S., & Affandi, 2025). The study "Developing Computational Thinking Ability in Early Childhood Education: The Influence of Programming-toy …" by Budiyanto et al., which examines the development of early childhood computational thinking abilities through programming toys, shows that the integration of robotics in early childhood education is still dominated by cognitive and STEM aspects, without explicit integration with environmental education or the use of recycled materials (Budiyanto, C. W., Shahbodin, F., Umam, M. U. K., Isnaini, R., Rahmawati, A., & Widiastuti, 2021).

At the international level, scoping reviews of robotics in early childhood education also highlight a research gap that integrates robotics with holistic ecological awareness, despite educational robotics being increasingly recognized in the literature as a tool for fostering computational thinking and other STEM skills (Kanaki & Kalogiannakis, 2023). This condition emphasizes the need for research that not only explores robotics as a technology learning medium, but also integrates environmental concepts and the use of recycled materials in the context of PAUD.

The majority of robotics activities in early childhood education (PAUD) utilize expensive commercial devices, such as Lego WeDo, BeeBot, or similar robotics kits, limiting

their affordability for most educational institutions. On the other hand, the use of recycled materials as a medium for robotics for early childhood is still rarely explored, even though this approach offers a more economical alternative and has high educational value, particularly in instilling awareness of environmental sustainability in a practical way (Maiurova et al., 2022). This situation shows that there is a great opportunity for innovation, both in the development of learning materials, robotics game design, and strategies for integrating technology, creativity, and environmental education from an early age

This situation raises a crucial research challenge: the lack of a simple robotics game model made from recycled materials specifically designed to develop early childhood sensitivity to technology while increasing environmental awareness. Furthermore, there is no structured guide for educators regarding the steps for developing, implementing, and evaluating the effectiveness of such game concepts in the context of early childhood education (Yang et al., 2021). This gap not only limits the space for creativity and innovation in educational practices, but also indicates the need for research that is able to formulate a systematic pedagogical framework, present clear operational procedures, and present appropriate evaluation instruments, so that children can obtain a comprehensive, interactive learning experience, and have a positive impact on the development of technological competence and ecological awareness from an early age.

One possible solution is to design a simple, safe, affordable, and developmentally appropriate robotics game using recycled materials. This concept is expected to help teachers organize educational play activities without relying on expensive commercial robotics devices, thereby increasing access to learning. Furthermore, this concept has the potential to become an innovative learning model that not only encourages children's creativity and technological understanding but also directly fosters ecological awareness (Qu et al., 2023). With this approach, cognitive, social, and environmental aspects can be integrated simultaneously, providing an interactive and meaningful learning experience, while equipping children with relevant basic competencies in facing the challenges of learning in the 21st century.

Based on the results of the needs analysis, this study chose a solution in the form of developing HeRoBo (Heritage Recycle Robot), namely a simple robotics game concept that uses recycled materials as its main component. The novelty of this research lies in the combination of three elements at once: first, simple robotics as a medium for introducing technology to children; second, the use of recycled materials as a concrete approach to environmental education; and third, the application of exploratory games that are adapted to the developmental stage of early childhood (Cheng et al., 2021). The integration of these three elements presents a significant innovation, considering that similar models are still rarely developed in previous literature, especially in the context of PAUD in Indonesia, so that this research has the potential to provide new contributions to creative, educational learning practices that support ecological awareness.

In line with the research objectives, the Research and Development (R&D) approach was used to design, develop, and test the effectiveness of the recycled material robotics game concept. This method was chosen because it allows for the development of innovative learning models while systematically evaluating their application in the context of early childhood education. The research focused on creating a recycled material robotics game concept that is appropriate for children's developmental stages and assessing the extent to which this concept can increase children's sensitivity to technology and the environment (Kashiri et al., 2018). Through this approach, it is hoped that research can produce a learning model that is applicable, interactive, and provides a real contribution to the development of technological competence and ecological awareness from an early age.

RESEARCH METHODS

This study uses the Research and Development (R&D) method to develop and evaluate the concept of a recycled robotics game called HeRoBo as a learning medium for early childhood. The recycled materials used include plastic bottles, used cardboard, bottle caps,

straws, lightweight cans, cardboard, and simple components such as rubber bands and ice cream sticks that are safe for children. The development process was carried out through the stages of needs analysis, prototype design, limited trials, revisions, and evaluation. During the implementation of the activity, PAUD children were actively involved in selecting and classifying recycled materials, designing simple robot shapes, and assembling robot parts with minimal guidance from educators. Children were also invited to observe the function of each part, try various configurations, and discuss their work in a simple manner (Huang et al., 2021). Through this series of activities, children gain concrete and contextual learning experiences that integrate technological exploration, creativity, and environmental awareness in accordance with the principles of STEM learning in early childhood.

The target of this research was early childhood children aged 4–6 years who already have basic motor skills and experience in exploratory play, as well as early childhood education (PAUD) teachers who act as activity facilitators. The research focused on developing a prototype for a robotics game made from recycled materials that is safe, creative, and developmentally appropriate, while also collecting data on children's responses to the game (Tan et al., 2022). In addition, this study also aims to evaluate the extent to which this game is able to increase children's sensitivity to technological concepts while also fostering awareness of environmental sustainability.

The research subjects were selected through purposive sampling, namely children who were ready to participate in simple robotics play activities and had received consent from their parents or guardians. In addition to the children, accompanying teachers were also involved as data sources to provide information on the children's level of involvement, interest, and skill development during the activities (Farrugia & Goodfellow, 2020). The number of subjects is adjusted to the mentoring capacity, which is around 20–30 children who are divided into small groups so that the observation and interaction process can be carried out more effectively, safely, and in a controlled manner.

The research procedure was carried out through several stages following the principles of Research and Development (R&D). The initial stage included a needs analysis and literature review, which included identifying child characteristics, the conditions of early childhood education institutions, and reviewing research related to robotics, constructive play, and the use of recycled materials (Li et al., 2018). The findings from this analysis were then used as the basis for designing the HeRoBo prototype to suit the needs and abilities of early childhood.

The next stage involved designing and developing a HeRoBo prototype, which included building a simple robot from recycled materials, developing a game activity guide, and designing an instrument to assess its effectiveness. In this phase, researchers prepared data collection tools in the form of observation sheets and field notes to record children's interactions, engagement, and responses during the activity, as well as a semi-structured interview guide to explore teachers' perspectives on the ease of use, acceptance, and challenges of implementing the prototype (Talla & McIlwaine, 2024). The HeRoBo prototype was developed to be easy for children to assemble, safe to use according to early childhood education standards, and provides space for children to channel their creativity through free but directed exploration of various recycled materials.

The third phase involved small-scale prototype testing to evaluate the prototype's appeal, safety, and clarity of instructions. During this process, observations were made to record children's interactions with the prototype, their assembly skills, creativity, persistence, and response to instructions (Wu et al., 2022). Input obtained from teachers and children was then used to revise the prototype to better suit the needs, abilities, and characteristics of early childhood.

The fourth phase was a field trial, where the HeRoBo prototype was implemented in routine activities at the Early Childhood Education Center (PAUD) to evaluate the game's effectiveness. The activities were conducted in several sessions to ensure each child had sufficient opportunities for exploration. Data collection was conducted through child behavior

observation sheets, teacher notes, photo and video documentation, and semi-structured interviews with teachers and parents (Shreyas Madhav et al., 2022). The focus of data collection includes indicators such as children's sensitivity to technology and the environment, creativity, ability to work together, and problem-solving skills.

Data analysis was carried out qualitatively descriptively through the stages of data reduction, data presentation, and drawing conclusions (Miles, M. B., Huberman, A. M., & Saldaña, 2014). Observation sheets were used to identify children's interaction patterns with the prototype and their level of participation in the game. Interview data was coded to identify themes related to HeRoBo's acceptance, effectiveness, challenges, and ease of use (Kay et al., 2022). Meanwhile, visual documentation is used to support interpretations of children's creativity and involvement during the activity.

Data interpretation was conducted by linking the findings of each indicator to the research problem and HeRoBo's development objectives. For example, children's ability to utilize recycled materials to assemble a robot was used as an indicator of environmental sensitivity, while their ability to follow instructions and complete robotics challenges was used as an indicator of technological sensitivity (Lakhouit, 2025). The results of this interpretation are then used to assess the effectiveness of the game concept and provide recommendations regarding the improvement of the prototype and its implementation on a wider scale.

Overall, this research combined prototype development, testing, revision, and effectiveness evaluation with systematic qualitative data collection. This approach enabled researchers to not only create an innovative product in the form of a robotics game made from recycled materials but also to comprehensively assess its impact on the development of early childhood sensitivity (Papadopoulou et al., 2022). Thus, HeRoBo has the potential to be a creative and environmentally friendly interactive learning model to be implemented in PAUD.

RESULT AND DISCUSSION

RESULT

HeRoBo Prototype Development

This section presents the research results related to the development of the HeRoBo prototype as a recycled-material robotics game for early childhood. The research results were obtained through Research and Development (R&D) stages, which included needs analysis and literature review, prototype design, initial trials, and prototype revisions. Each development stage yielded empirical findings that illustrate the prototype's suitability to the developmental characteristics of children aged 4–6 years, learning conditions in early childhood education (PAUD), and the need for safe, affordable, and environmentally friendly learning media. A summary of the findings at each stage of HeRoBo prototype development is presented systematically in Table 1.

Table 1. HeRoBo Prototype Development Findings

Development Stage	Activity	Findings	Interpretation
Needs Analysis & Literature Review	Identification of child characteristics, PAUD conditions, literature review on robotics & recycled materials	Children aged 4–6 years show a high interest in exploratory and assembly activities; preschools have limited commercial robotics facilities.	Demonstrates the need for prototypes that are easy to assemble, safe, and made from affordable materials.
Prototype Design	Making a simple robot from recycled materials, preparing a guide, evaluation design	The HeRoBo prototype can be assembled in 20–30 minutes, the instructions are easy to understand, it is safe, and it is flexible for creative exploration.	The prototype is ready to be tested on children, meeting safety and ease of use aspects.
Initial Trial	Small scale, observation of child interactions	Children can assemble robots with minimal assistance, showing high enthusiasm.	Demonstrates prototype appeal and suitability to child developmental stage

Prototype Revision	Based on teacher & child input	Instruction fixes, component size adjustments, added activity variations	Revisions increase the effectiveness of the prototype and facilitate exploratory activities.

The development of the HeRoBo prototype was conducted through a series of structured stages. The needs analysis and literature review revealed that children aged 4–6 years old have a high interest in exploration and assembly activities, while commercial robotics facilities in early childhood education (PAUD) are still limited, emphasizing the need for a prototype that is easy to assemble, safe, and affordable. During the design phase, the HeRoBo prototype was successfully developed so that it could be assembled in 20–30 minutes, with clear instructions and a design that supports children's creativity. Initial small-scale trials demonstrated that children could assemble the robot with minimal assistance and showed high enthusiasm, indicating the prototype's appeal and suitability for their developmental stage. Feedback from teachers and children was then used to revise the prototype, including refining the instructions, adjusting component sizes, and adding a variety of activities, thereby increasing the prototype's effectiveness and making children's exploratory experiences easier and more enjoyable.

Children's Sensitivity to Technology in the HeRoBo Game

This section describes the results of research on early childhood technology sensitivity after participating in the HeRoBo robotics game. Technology sensitivity was identified through several indicators, including the ability to follow instructions, complete simple robotics challenges, and children's independence in exploring robot components. Data were obtained through direct observation during the activity, paying attention to children's responses, engagement, and abilities in interacting with the HeRoBo prototype. The results of these observations provide an overview of the extent to which this recycled robotics game is able to stimulate children's initial understanding of technology in a contextual and developmentally appropriate manner. A summary of the findings on children's technology sensitivity is presented in Table 2.

Table 2. Findings on Children's Sensitivity to Technology

Indicators of Findings in the Field	Observation / Activity	Findings	Interpretation
Ability to follow instructions	Children follow the steps to assemble a robot.	Most children are able to follow simple instructions with minimal assistance.	Demonstrate basic understanding of technology and skills in following procedures
Robotic challenge solution	Children complete simple tasks (e.g., moving the wheels of a robot)	80% of children successfully completed the challenge with teacher guidance	Demonstrates problem solving skills and adaptability to simple technology
Independence in exploration	Children experiment with robot components	Children try out various robot configurations creatively.	Positive indicators of sensitivity and interest in technology

Children's sensitivity to technology is demonstrated through several key indicators. First, the ability to follow instructions shows that most children can follow the steps to assemble a robot with minimal assistance, indicating a basic understanding of technology and the ability to follow procedures. Second, in solving robotic challenges, such as moving the robot's wheels, approximately 80% of children successfully completed the task with teacher guidance, reflecting their ability to problem-solve and adapt to simple technology. Third, independence in exploration is reflected in children's efforts to creatively experiment with various robot configurations, a positive indicator of interest in and sensitivity to technology, while also increasing self-confidence and critical thinking skills through interactive play activities.

Children's Sensitivity to the Environment through HeRoBo Games

This section presents the results of research related to early childhood environmental sensitivity developed through the use of the HeRoBo robotics game made from recycled materials. Environmental sensitivity was observed through children's involvement in using used materials, their behavior in sorting materials before use, and their creativity in exploring and creating meaningful robots from recycled materials. Data were obtained through direct observation during the activity, paying attention to children's responses to the use of recycled materials as a medium for play and learning. The findings illustrate that the HeRoBo game not only functions as a medium for introducing technology but also as a contextual environmental learning tool that is appropriate to the developmental characteristics of early childhood. A summary of the findings on children's environmental sensitivity is presented in Table 3.

Table 3. Findings on Children's Sensitivity to the Environment

Indicators of Findings in the Field	Observation / Activity	Findings	Interpretation
Utilization of recycled materials	Children use used materials to assemble robots	Children recognize and select materials according to their function (cardboard, bottles, bottle caps)	Demonstrates early awareness of material reuse
Material sorting behavior	Children are invited to sort materials before use.	Children are able to differentiate between organic and non-organic materials with teacher guidance.	Demonstrate the ability to build ecological awareness practically
Creativity & material exploration	Children create robots with various shapes	Children create robots with unique shapes and functions	Activities encourage environmental understanding through creative play

Children's environmental sensitivity can be identified through several key indicators. First, in terms of utilizing recycled materials, children are able to recognize and select used materials such as cardboard, bottles, and bottle caps according to their use in assembling robots, indicating an early awareness of the practice of material reuse. Second, material sorting behavior is evident when children are invited to separate materials before use; they can distinguish between organic and non-organic materials with teacher guidance, indicating their ability to build ecological awareness practically. Third, creativity and exploration of materials are evident in children's efforts to create robots with various unique shapes and functions, indicating that this activity not only encourages creativity but also strengthens children's understanding of environmental issues through interactive and fun play.

DISCUSSION

HeRoBo Prototype Development

Based on the data presented in Table 1, the development of the HeRoBo prototype was carried out through a structured phase, including needs analysis, design, initial testing, and prototype revision. The needs analysis and literature review indicate that children aged 4–6 years have a high interest in exploration and assembly activities, while commercial robotics facilities in early childhood education (ECE) are still limited. This finding underscores the importance of developing a simple, safe, and affordable prototype, making it accessible to children in various ECE contexts (Zeng et al., 2022). This condition aligns with the principles of early childhood education, which emphasize concrete, meaningful learning experiences tailored to the child's abilities and interests. This ensures that the learning process is not only informative but also supports comprehensive cognitive, motor, and socio-emotional development (UNESCO, 2020). By considering these aspects, the prototype's implementation is expected to create a stimulating, interactive, and inclusive learning environment, while addressing the limitations of existing robotics facilities (Bellon Maurel & Huyghe, 2017).

During the design phase, the HeRoBo prototype was successfully assembled in 20–30 minutes, complete with easy-to-understand instructions and a design designed to stimulate

children's creativity. This success was supported by attention to the cognitive, motor, and social developmental characteristics of early childhood, which served as a reference in determining the level of complexity and interaction during the assembly process. This approach aligns with the principles of constructivism (Piaget, 1972), which states that children learn effectively through active exploration of their environment. Providing simple instructions and the flexibility to use recycled materials allows children to learn independently, while simultaneously developing creativity, problem-solving skills, and fine motor skills (Gerbers et al., 2018). Thus, the prototype design not only fulfills the technical assembly needs, but also functions as a learning medium that supports the development of children's cognitive, social-emotional, and creative abilities holistically, in accordance with the principles of meaningful experience-based learning in early childhood education (Bogue, 2019).

The results of initial small-scale trials showed that children were able to assemble the robot prototype with minimal guidance, while demonstrating high enthusiasm for the activity. These findings indicate that the HeRoBo prototype has strong appeal and is appropriate for early childhood development. The children's high motivation and engagement can be explained through Vygotsky's (1978) concept of the zone of proximal development, which emphasizes that children learn more effectively when given challenges that match their abilities, so they feel capable and encouraged to explore further (Rossiter et al., 2016). Furthermore, these findings align with research by Leggett & Newman (2017), which demonstrated that a project-based play approach can enhance early childhood learning engagement and motivation. Thus, initial trials not only demonstrated the prototype's technical assembly success but also confirmed its function as a learning medium that supports children's overall cognitive development, creativity, and exploratory abilities (Costa Cornellà et al., 2023).

Prototype revisions based on teacher and child feedback, including refining instructions, adjusting component sizes, and adding a variety of activities, significantly improved the effectiveness of the HeRoBo prototype. These improvements made the exploration process easier to follow, safer, and more enjoyable for children, encouraging active engagement and meaningful learning (Castellano et al., 2021). The success of the revision underscores the importance of applying an iterative design approach to Research and Development (R&D), where products are continuously developed through user evaluation and feedback. This approach ensures that the prototype not only presents innovations in design and concept but is also practically relevant to the abilities, interests, and needs of early childhood education in PAUD. Thus, user-participation-based revisions are a key factor in creating effective, safe, and adaptive learning media for early childhood education contexts, while also underscoring the importance of user-centered design principles in developing educational innovations (Zeng et al., 2022).

Children's Sensitivity to Technology in the HeRoBo Game

Based on the data presented in Table 2, children's sensitivity to technology is reflected in several indicators, such as their ability to follow robot assembly instructions with minimal assistance, complete approximately 80% of robotics challenges with teacher guidance, and creatively explore various robot configurations. This positive trend occurs because the prototype is designed to provide a hands-on learning experience, allowing children to understand basic technological concepts directly through active interaction with objects and materials (Satav et al., 2023). These findings support the research of Weisberg et al. (2016), which showed that constructive play not only improves children's understanding of technological principles but also encourages the development of critical thinking, problem-solving, and creativity skills. Therefore, utilizing the HeRoBo prototype as a learning medium allows young children to gain meaningful exploratory experiences while simultaneously building basic technological competencies comprehensively and in accordance with their cognitive developmental stages (Gerbers et al., 2018).

Children's success in completing robotics challenges and creatively experimenting demonstrates a strong relationship between prototype design and the cognitive stimulation they

receive. The use of recycled materials as robot components provides opportunities for children to hone their manipulative skills, while also stimulating creativity through exploration and improvisation during assembly. These findings directly address the research objective, which is to evaluate the extent to which the concept of playing with recycled robotics can increase children's sensitivity to technology (Lubongo et al., 2024). Furthermore, direct interaction with robot components provides a concrete learning experience, enabling children to understand basic mechanical concepts, recognize practical tool functions, and foster self-confidence and independence. Thus, the HeRoBo prototype serves as a learning medium that not only stimulates cognitive development but also supports the improvement of children's motor skills, creativity, and overall social-emotional competencies (Rossiter et al., 2016).

Children's Sensitivity to the Environment through HeRoBo Games

Children's environmental sensitivity, as reflected in Table 3, showed positive results. Children were able to recognize and select recycled materials, differentiate between organic and non-organic materials with teacher guidance, and create robots with unique shapes and functions. These findings confirm that the use of recycled materials in the HeRoBo prototype not only introduces technology but also serves as a medium for instilling environmental sustainability values from an early age (Poschmann et al., 2021). Through this activity, children gain hands-on learning experiences that strengthen their understanding of the importance of material reuse while fostering practical ecological awareness. This approach aligns with Kolb's (1984) experiential learning principles, which emphasize that learning through concrete experiences is an effective way to build a deep understanding and environmental awareness, while supporting children's holistic cognitive development, creativity, and problem-solving abilities (Castellano et al., 2021).

Children's creative activities in assembling robots using recycled materials have been shown to improve critical thinking and innovative problem-solving skills. As children experiment with various robot configurations to achieve specific functions, they actively adapt the shape to the functional purpose, while simultaneously practicing observation, evaluation, and improvisation skills (Li et al., 2019). These findings indicate that integrating simple robotics with recycled materials not only fosters children's interest in technology but also simultaneously fosters the development of creativity, perseverance, and ecological awareness. Therefore, this exploration- and experiment-based learning approach provides meaningful learning experiences, strengthens children's cognitive, motor, and socio-emotional competencies, and instills sustainability values from an early age, in line with the principles of early childhood education that emphasize active and contextual learning (Bellon Maurel & Huyghe, 2017).

Comparisons with previous research indicate that HeRoBo's innovation has its own advantages. Most robotics studies in early childhood education (ECE) still use expensive commercial kits, such as Lego WeDo or BeeBot, which are limited in accessibility for many educational institutions. In contrast, this research presents an economical, safe, and easy-to-implement prototype utilizing recycled materials, thus providing broader access opportunities for children in various ECE contexts in Indonesia (Kaarlela et al., 2024). This approach not only introduces technological concepts but also integrates the development of creativity and environmental awareness into a single learning model, a combination rarely found in previous literature. Thus, HeRoBo's innovation not only offers practical and economic relevance but also makes a significant contribution to a holistic, experiential, and sustainable early childhood education model (Bogue, 2019).

Overall, the results of this study indicate that the development of the HeRoBo prototype successfully met its stated objectives: to provide a robotics play model made from recycled materials that is developmentally appropriate for early childhood while simultaneously increasing their sensitivity to technology and the environment. This prototype offers an interactive, creative, and applicable learning experience, allowing children to learn

through hands-on exploration, experimentation, and independent challenge solving (Sathiya et al., 2021). In addition, the use of recycled materials in robot assembly fosters practical ecological awareness, so that children learn to appreciate the principles of sustainability from an early age. Thus, this study not only presents an innovative learning model relevant for early childhood education, but also shows that the integration of simple robotics with recycled materials is an effective strategy in developing children's technological competence, creativity, problem-solving skills, and environmental awareness, in line with the principles of STEM Education for Young Learners which emphasize a holistic, experience-based, and contextual learning approach (Costa Cornellà et al., 2023).

CONCLUSION AND SUGGESTIONS

Based on the research results, it can be concluded that the development of the HeRoBo prototype successfully produced a robotics game model made from recycled materials that is in accordance with the developmental characteristics of early childhood. This prototype has been proven to be able to increase children's sensitivity to technology and the environment through interactive, creative, and applicable learning experiences. Children's direct interaction with robot components and recycled materials encourages the development of critical thinking skills, creativity, fine motor skills, and ecological awareness from an early age. The implications of this research result indicate that HeRoBo has the potential to be an alternative STEM-based learning media that is sustainable, low-cost, and easy to implement in early childhood education units, and can support educators in integrating technological literacy and environmental education into daily play-learning activities. In addition, this game model can be a reference for the development of innovative, contextual and environmentally friendly learning media in early childhood education. Thus, HeRoBo is effective as an innovative learning media that integrates technology and environmental education holistically according to the principles of STEM Education for Young Learners.

Future research is recommended to explore the application of the HeRoBo prototype on a broader and more diverse scale, for example in various early childhood education centers with different socio-economic conditions, to assess its effectiveness and adaptability. Furthermore, further development could include the addition of modules or activities that emphasize collaboration, storytelling, or the integration of other subjects to enhance comprehensive learning. Given the limitations of this study, such as the limited number of trial samples and the relatively short observation period, a long-term evaluation of HeRoBo's impact on children's cognitive, socio-emotional, and environmental awareness development is highly recommended. Furthermore, it is recommended to examine the impact of the use of recycled materials on children's perceptions of sustainability and environmentally friendly behavior in their daily lives, so that ecological values can be more optimally integrated into the learning process.

REFERENCE

Akhmad, A., & Gudnanto, G. (2025). Pembelajaran Robotika Pada Anak Usia Dini: Sebuah Tinjauan Literatur. *Jurnal Penelitian Dan Pengembangan Pendidikan Anak Usia Dini*.

Bellon Maurel, V., & Huyghe, C. (2017). Putting agricultural equipment and digital technologies at the cutting edge of agroecology. *OCL*, *24*(3), D307. https://doi.org/10.1051/ocl/2017028

Bogue, R. (2019). Robots in recycling and disassembly. *Industrial Robot: The International Journal of Robotics Research and Application*, *46*(4), 461–466. https://doi.org/10.1108/IR-03-2019-0053

Bredekamp, S. (2019). *Effective practices in early childhood education: Building a foundation*. Pearson Education.

Budiyanto, C. W., Shahbodin, F., Umam, M. U. K., Isnaini, R., Rahmawati, A., & Widiastuti, I. (2021). Developing Computational Thinking Ability in Early Childhood Education:

The Influence of Programming-toy on Parent-Children Engagement. *International Journal of Pedagogy and Teacher Education*, *5(1)*, 19–25.

Castellano, G., De Carolis, B., D'Errico, F., Macchiarulo, N., & Rossano, V. (2021). PeppeRecycle: Improving Children's Attitude Toward Recycling by Playing with a Social Robot. *International Journal of Social Robotics*, *13*(1), 97–111. https://doi.org/10.1007/s12369-021-00754-0

Cheng, Y., Chan, K. H., Wang, X., Ding, T., Li, T., Zhang, C., Lu, W., Zhou, Y., & Ho, G. W. (2021). A Fast Autonomous Healing Magnetic Elastomer for Instantly Recoverable, Modularly Programmable, and Thermorecyclable Soft Robots. *Advanced Functional Materials*, *31*(32). https://doi.org/10.1002/adfm.202101825

Costa Cornellà, A., Tabrizian, S. K., Ferrentino, P., Roels, E., Terryn, S., Vanderborght, B., Van Assche, G., & Brancart, J. (2023). Self-Healing, Recyclable, and Degradable Castor Oil-Based Elastomers for Sustainable Soft Robotics. *ACS Sustainable Chemistry & Engineering*, *11*(8), 3437–3450. https://doi.org/10.1021/acssuschemeng.2c06874

Farrugia, M. E., & Goodfellow, J. A. (2020). A Practical Approach to Managing Patients With Myasthenia Gravis—Opinions and a Review of the Literature. *Frontiers in Neurology*, *11*. https://doi.org/10.3389/fneur.2020.00604

Gerbers, R., Wegener, K., Dietrich, F., & Dröder, K. (2018). *Safe, Flexible and Productive Human-Robot-Collaboration for Disassembly of Lithium-Ion Batteries* (pp. 99–126). https://doi.org/10.1007/978-3-319-70572-9_6

Gundupalli, S. P., Hait, S., & Thakur, A. (2017). A review on automated sorting of source-separated municipal solid waste for recycling. *Waste Management*, *60*, 56–74. https://doi.org/10.1016/j.wasman.2016.09.015

Hjorth, S., & Chrysostomou, D. (2022). Human–robot collaboration in industrial environments: A literature review on non-destructive disassembly. *Robotics and Computer-Integrated Manufacturing*, *73*, 102208. https://doi.org/10.1016/j.rcim.2021.102208

Huang, J., Pham, D. T., Li, R., Qu, M., Wang, Y., Kerin, M., Su, S., Ji, C., Mahomed, O., Khalil, R., Stockton, D., Xu, W., Liu, Q., & Zhou, Z. (2021). An experimental human-robot collaborative disassembly cell. *Computers & Industrial Engineering*, *155*, 107189. https://doi.org/10.1016/j.cie.2021.107189

Javed, A. R., Shahzad, F., Rehman, S. ur, Zikria, Y. Bin, Razzak, I., Jalil, Z., & Xu, G. (2022). Future smart cities: requirements, emerging technologies, applications, challenges, and future aspects. *Cities*, *129*, 103794. https://doi.org/10.1016/j.cities.2022.103794

Kaarlela, T., Villagrossi, E., Rastegarpanah, A., San-Miguel-Tello, A., & Pitkäaho, T. (2024). Robotised disassembly of electric vehicle batteries: A systematic literature review. *Journal of Manufacturing Systems*, *74*, 901–921. https://doi.org/10.1016/j.jmsy.2024.05.013

Kanaki, K., & Kalogiannakis, M. (2023). Fostering computational thinking and environmental awareness via robotics in early childhood education: A scoping review. *Research on Preschool and Primary Education*, 39–50. https://doi.org/10.55976/rppe.12023217739-50

Kashiri, N., Abate, A., Abram, S. J., Albu-Schaffer, A., Clary, P. J., Daley, M., Faraji, S., Furnemont, R., Garabini, M., Geyer, H., Grabowski, A. M., Hurst, J., Malzahn, J., Mathijssen, G., Remy, D., Roozing, W., Shahbazi, M., Simha, S. N., Song, J.-B., … Tsagarakis, N. (2018). An Overview on Principles for Energy Efficient Robot Locomotion. *Frontiers in Robotics and AI*, *5*. https://doi.org/10.3389/frobt.2018.00129

Kay, I., Farhad, S., Mahajan, A., Esmaeeli, R., & Hashemi, S. R. (2022). Robotic Disassembly of Electric Vehicles' Battery Modules for Recycling. *Energies*, *15*(13), 4856. https://doi.org/10.3390/en15134856

Lakhouit, A. (2025). Revolutionizing urban solid waste management with AI and IoT: A review of smart solutions for waste collection, sorting, and recycling. *Results in Engineering*, *25*, 104018. https://doi.org/10.1016/j.rineng.2025.104018

Larasati, S., Romadhona, S., & Affandi, M. A. (2025). Edukasi Dasar Robotika bagi Tenaga Pendidik Kinder Club Banyumas Menggunakan Robot Line Follower untuk Meningkatkan Kreativitas dan Problem Solving. *Jurnal Abdi Masyarakat Indonesia*, *5(4)*, 1631–1640.

Li, J., Barwood, M., & Rahimifard, S. (2018). Robotic disassembly for increased recovery of strategically important materials from electrical vehicles. *Robotics and Computer-Integrated Manufacturing*, *50*, 203–212. https://doi.org/10.1016/j.rcim.2017.09.013

Li, J., Barwood, M., & Rahimifard, S. (2019). A multi-criteria assessment of robotic disassembly to support recycling and recovery. *Resources, Conservation and Recycling*, *140*, 158–165. https://doi.org/10.1016/j.resconrec.2018.09.019

Lubongo, C., Bin Daej, M. A. A., & Alexandridis, P. (2024). Recent Developments in Technology for Sorting Plastic for Recycling: The Emergence of Artificial Intelligence and the Rise of the Robots. *Recycling*, *9*(4), 59. https://doi.org/10.3390/recycling9040059

Maiurova, A., Kurniawan, T. A., Kustikova, M., Bykovskaia, E., Othman, M. H. D., Singh, D., & Goh, H. H. (2022). Promoting digital transformation in waste collection service and waste recycling in Moscow (Russia): Applying a circular economy paradigm to mitigate climate change impacts on the environment. *Journal of Cleaner Production*, *354*, 131604. https://doi.org/10.1016/j.jclepro.2022.131604

Mayasari, R., Astuti, S., Negara, R. M., Tulloh, R., & Nurmantris, D. A. (2025). Training Introduction to Simple Robots for Kindergarten Child as a Tool in Improving Children's Psychomotoric Abilities. *Journal of Innovation and Community Engagement*, *6(3)*, 205–214.

Miles, M. B., Huberman, A. M., & Saldaña, J. (2014). *Qualitative data analysis: A methods sourcebook*. Sage Publications.

Papadopoulou, A., Kumar, N. S., Vanhoestenberghe, A., & Francis, N. K. (2022). Environmental sustainability in robotic and laparoscopic surgery: systematic review. *British Journal of Surgery*, *109*(10), 921–932. https://doi.org/10.1093/bjs/znac191

Piaget, J. (1972). *The psychology of the child*. Basic Books.

Poschmann, H., Brüggemann, H., & Goldmann, D. (2021). Fostering End-of-Life Utilization by Information-driven Robotic Disassembly. *Procedia CIRP*, *98*, 282–287. https://doi.org/10.1016/j.procir.2021.01.104

Qu, J., Yuan, Q., Li, Z., Wang, Z., Xu, F., Fan, Q., Zhang, M., Qian, X., Wang, X., Wang, X., & Xu, M. (2023). All-in-one strain-triboelectric sensors based on environment-friendly ionic hydrogel for wearable sensing and underwater soft robotic grasping. *Nano Energy*, *111*, 108387. https://doi.org/10.1016/j.nanoen.2023.108387

Rossiter, J., Winfield, J., & Ieropoulos, I. (2016). *Here today, gone tomorrow: biodegradable soft robots* (Y. Bar-Cohen & F. Vidal (eds.); p. 97981S). https://doi.org/10.1117/12.2220611

Sarc, R., Curtis, A., Kandlbauer, L., Khodier, K., Lorber, K. E., & Pomberger, R. (2019). Digitalisation and intelligent robotics in value chain of circular economy oriented waste management – A review. *Waste Management*, *95*, 476–492. https://doi.org/10.1016/j.wasman.2019.06.035

Sari, W. E., Triyono, A., Irwansyah, I., Utomo, K. B., & Hakim, A. R. (2024). Robot Line Follower sebagai Alat Permainan Edukatif bagi Anak Usia Dini. *ETAM: Jurnal Pengabdian Kepada Masyarakat*, *4(3)*, 126–133.

Satav, A. G., Kubade, S., Amrutkar, C., Arya, G., & Pawar, A. (2023). A state-of-the-art review on robotics in waste sorting: scope and challenges. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *17*(6), 2789–2806.

https://doi.org/10.1007/s12008-023-01320-w

Sathiya, V., Chinnadurai, M., Ramabalan, S., & Appolloni, A. (2021). Mobile robots and evolutionary optimization algorithms for green supply chain management in a used-car resale company. *Environment, Development and Sustainability*, *23*(6), 9110–9138. https://doi.org/10.1007/s10668-020-01015-2

Shreyas Madhav, A., Rajaraman, R., Harini, S., & Kiliroor, C. C. (2022). Application of artificial intelligence to enhance collection of E-waste: A potential solution for household WEEE collection and segregation in India. *Waste Management & Research: The Journal for a Sustainable Circular Economy*, *40*(7), 1047–1053. https://doi.org/10.1177/0734242X211052846

Suherdi, D., Rezky, S. F., & Sari, K. (2023). Implementasi Tools Robotik Wedo 1.0 Education Berbasis STEAM Melalui Kegiatan Education Fieldtrip dalam Membentuk Karakter Anak Usia Dini. *Jurnal Pengabdian Kepada Masyarakat Nusantara*, *4(3)*, 3247–3254.

Sulistyawati, S., Sujaini, H., Salam, U., Aunurrahman, A., & Wicaksono, L. (2024). Robmanjar: Robot Teman Belajar Stimulator Literasi Anak Usia Dini. *Jurnal Obsesi : Jurnal Pendidikan Anak Usia Dini*, *8(4)*, 724–739.

Suyadi. (2020). *Psikologi belajar pendidikan anak usia dini (PAUD)*. Pustaka Pelajar.

Talla, A., & McIlwaine, S. (2024). Industry 4.0 and the circular economy: using design-stage digital technology to reduce construction waste. *Smart and Sustainable Built Environment*, *13*(1), 179–198. https://doi.org/10.1108/SASBE-03-2022-0050

Tan, M. W. M., Bark, H., Thangavel, G., Gong, X., & Lee, P. S. (2022). Photothermal modulated dielectric elastomer actuator for resilient soft robots. *Nature Communications*, *13*(1), 6769. https://doi.org/10.1038/s41467-022-34301-w

UNESCO. (2020). *Education for sustainable development: A roadmap*. United Nations Educational, Scientific and Cultural Organization.

Wang, Z., Li, H., & Zhang, X. (2019). Construction waste recycling robot for nails and screws: Computer vision technology and neural network approach. *Automation in Construction*, *97*, 220–228. https://doi.org/10.1016/j.autcon.2018.11.009

Wu, T., Zhang, Z., Yin, T., & Zhang, Y. (2022). Multi-objective optimisation for cell-level disassembly of waste power battery modules in human-machine hybrid mode. *Waste Management*, *144*, 513–526. https://doi.org/10.1016/j.wasman.2022.04.015

Yang, W., Gong, W., Gu, W., Liu, Z., Hou, C., Li, Y., Zhang, Q., & Wang, H. (2021). Self-Powered Interactive Fiber Electronics with Visual–Digital Synergies. *Advanced Materials*, *33*(45). https://doi.org/10.1002/adma.202104681

Zeng, Y., Zhang, Z., Yin, T., & Zheng, H. (2022). Robotic disassembly line balancing and sequencing problem considering energy-saving and high-profit for waste household appliances. *Journal of Cleaner Production*, *381*, 135209. https://doi.org/10.1016/j.jclepro.2022.135209