KUPAS SENI
Jurnal Seni dan Pendidikan Seni

ISSN 2289-4640 • eISSN 0127-9688

Integrating Local Culture and Sustainability in Educational Play Tools: Conceptual Design of a Punokawan Puzzle with PLA-Based 3D Printing

Pengintegrasian Budaya Tempatan dan Kelestarian dalam Alat Permainan Pendidikan: Reka Bentuk Konseptual Puzzle Punokawan Berasaskan Percetakan 3D PLA

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ARTICLE HISTORY
Received: 10th December 2025
Revised: 13rd Mac 2026
Accepted: 23rd April 2026
Published: 27th April 2026

KEYWORDS
Educational Play Tools
Punokawan
PLA
3D Printing
Local Culture

ABSTRACT - Educational Play Tools (EPT) hold significant importance in fostering young children’s cognitive, motoric, social, and emotional growth, while simultaneously functioning as instruments for cultural transmission. Nonetheless, the global toy industry continues to rely heavily on conventional plastic-based materials that contribute to environmental degradation and lack integration of indigenous cultural values in their designs. This research seeks to formulate a conceptual prototype of a contemporary EPT that synthesizes sustainable materials, technological innovation, and cultural contextualization. The study adopts a Qualitative Conceptual Design Research framework encompassing literature synthesis, design evaluation, and conceptual visualization through Blender 3D, followed by prototype fabrication using 3D printing methods. The developed prototype features a puzzle inspired by the Punokawan figures, embodying Javanese philosophical wisdom; it is designed to stimulate children’s cognitive and motor abilities while reinforcing cultural identity formation. The results demonstrate that polylactic acid (PLA) presents a viable eco-friendly substitute with substantially reduced carbon emissions, though its implementation remains challenged by factors such as material resilience, production cost, and regional availability. Moreover, 3D printing enables the creation of customizable, precise, and pedagogically responsive educational designs. This study contributes to theoretical discourse on sustainable and culturally integrated EPT design while offering practical insights for educational institutions and commercial development. Despite being limited to conceptual modeling, the research establishes a foundational framework for future innovations in environmentally responsible, educationally sound, and culturally embedded play-based learning tools.

https://doi.org/10.37134/kupasseni.vol14.sp.9.2026

INTRODUCTION

Play-based learning media are globally recognized as essential components in promoting the comprehensive development of early childhood. Educational Play Tools (EPT) serve not only as effective aids for teachers in facilitating instructional delivery but also as catalysts for children's physical, motoric, cognitive, social, and emotional growth (Rawanti et al., 2023). Empirical research consistently indicates that the proper utilization of EPT enhances learning enjoyment and produces measurable improvements in children's overall developmental outcomes (Rawanti et al., 2023).

From a theoretical standpoint, constructivism posits that knowledge is actively constructed by children through direct engagement with their social and physical surroundings rather than through passive absorption of information (Wibowo et al., 2025). Numerous studies have validated the efficacy of play-based learning in advancing cognitive competencies, social interaction skills, emotional regulation, and academic achievement (Sakib, 2022). Recent meta-synthesis analyses have further demonstrated that this pedagogical approach significantly fosters intrinsic motivation and sustained participation among learners (Dean & Wenner, 2025). Concurrently, education functions as a critical medium for cultural transmission, facilitating the intergenerational transfer of values, traditions, and local wisdom. This process enables children to internalize their cultural identity from an early stage of development (Shih, 2022).

Despite these pedagogical and cultural benefits, the global toy industry continues to grapple with pressing environmental issues. Findings from life cycle assessment (LCA) research reveal that conventional plastic toys contribute substantially to greenhouse gas emissions and solid waste accumulation across their entire production and disposal phases. Nearly 80 percent of these products ultimately end up in landfills, are incinerated, or enter marine environments, exacerbating global plastic pollution (Levesque et al., 2022). This condition highlights the urgent necessity for adopting eco-innovative materials in the development of EPT.

Polylactic acid (PLA) has emerged as one of the most promising alternatives. As a biodegradable, plant-based polymer, PLA exhibits a significantly lower environmental footprint than petroleum-derived plastics (Salma et al., 2023). Yadou et al. (2025) report that the application of PLA in EPT manufacturing can reduce greenhouse gas emissions by up to 40 percent when compared with materials such as acrylonitrile butadiene styrene (ABS) or polyvinyl chloride (PVC), while maintaining satisfactory mechanical performance. Since PLA is sourced from renewable resources including cassava starch, corn, and sugarcane, it is widely recognized as a sustainable substitute for conventional plastic in the production of educational materials (Agrawal & Bhat, 2025).

Nevertheless, existing scholarship reveals a notable research gap in the exploration of EPT designs that merge eco-friendly materials like PLA with local cultural identity, while simultaneously adhering to constructivist and play-based learning paradigms. Addressing this gap, the present study aims to conceptualize a modern EPT model that not only supports holistic cognitive, motoric, and socio-emotional development but also strengthens cultural awareness and environmental responsibility among children. The study's originality lies in its proposal of an integrative design framework that combines PLA's sustainability attributes with the philosophical essence of local cultural traditions, an interdisciplinary approach that remains underexplored in prior literature.

https://doi.org/10.37134/kupasseni.vol14.sp.9.2026

Figure 1. Punokawan Wayang (Wayang Indonesia)

Within this research, the Punokawan figures were selected as the central motif for the Educational Play Tool (EPT) puzzle. These iconic characters were intentionally chosen because they embody Javanese philosophical virtues such as wisdom, humility, and humor, qualities that can be easily comprehended and appreciated by children. Their engaging and comical nature allows moral lessons to be communicated in a way that is both entertaining and relatable. Through the design of this puzzle, children are encouraged to develop cognitive skills like problem-solving and fine motor coordination while simultaneously being introduced to local cultural values that reinforce their sense of identity from an early age. Consequently, the incorporation of cultural elements within this EPT fulfills a dual objective: it not only supports children's cognitive growth but also contributes to the preservation and transmission of cultural heritage in a contemporary educational context.

PROBLEM STATEMENT

Although the benefits of play-based learning and the developmental value of Educational Play Tools (EPT) for early childhood are well established, several research gaps persist. Environmentally, the majority of EPT continue to rely on conventional plastic materials, which contribute to ecological degradation (Levesque et al., 2022). Culturally, the integration of local values into EPT design remains limited, even though such contextual elements have been shown to enhance children's engagement and reinforce cultural identity (Güven et al., 2025; Wahyuni, 2024). Technologically, the potential of utilizing polylactic acid (PLA) and 3D printing as sustainable and adaptable design approaches has not been extensively examined within the context of culturally inspired EPT development (Salma et al., 2023). In response to these gaps, this study aims to formulate a conceptual framework for EPT design that harmoniously integrates eco-sustainable materials, cultural representation, and foundational learning theories such as constructivism and play-based pedagogy.

OBJECTIVE

This study seeks to address the limitations of conventional Educational Play Tools (EPT), which largely depend on non-biodegradable plastic materials and have yet to meaningfully integrate elements of local culture. In doing so, it explores the potential of incorporating sustainable materials, specifically polylactic acid (PLA), alongside 3D printing technology to develop environmentally responsible EPT. The research focuses on creating a conceptual prototype inspired by the Punokawan figures from the Javanese wayang tradition, reinterpreted as a contemporary puzzle format. This design aims not only to enhance children's cognitive growth, fine motor coordination, and problem-solving abilities but also to cultivate cultural awareness and appreciation of indigenous wisdom. By merging these aspects, the study promotes a learning experience that is both contextually relevant and environmentally sustainable.

METHODOLOGY

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This research employs a Qualitative Conceptual Design Research methodology, emphasizing the formulation of a conceptual framework rather than empirical validation. The investigation was conducted through two principal stages. The first stage comprised an in-depth literature review and design analysis that explored foundational learning theories, previous research on Educational Play Tools (EPT), the integration of local cultural values, the utilization of polylactic acid (PLA) as a sustainable material, and the application of 3D printing technology. This phase also included a comparative assessment between conventional plastic-based EPT and culturally oriented EPT to identify their respective advantages, limitations, and potential areas for synthesis.

The second stage focused on design conceptualization, encompassing the development of preliminary sketches, the creation of 3D digital models using Blender software, and the conceptual preparation of a prototype employing PLA-based 3D printing techniques. This methodological framework was chosen for its suitability in achieving the study's objective: to construct a coherent and systematic conceptual model of EPT that integrates educational, cultural, and environmental sustainability dimensions within a unified design process.

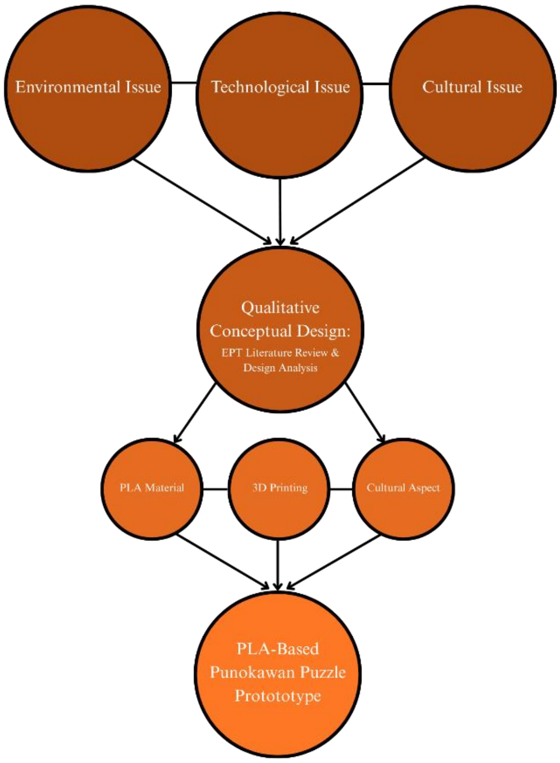

Figure 2. Conceptual Framework

RESULT

The Punokawan character designs featured in this prototype were fully developed as original creations within the scope of this research. Each figure (Gareng, Semar, Petruk, and Bagong) was reinterpreted through a visual redesign process tailored to meet the pedagogical and aesthetic requirements of early childhood educational media, while maintaining the essential attributes that define their traditional identities. The creative workflow involved generating preliminary sketches, refining character proportions, and selecting a color palette that is both engaging and child friendly. This design strategy ensures that the resulting Educational Play Tool (EPT) embodies cultural authenticity while offering a contemporary, safe, and inclusive visual appeal suitable for young learners.

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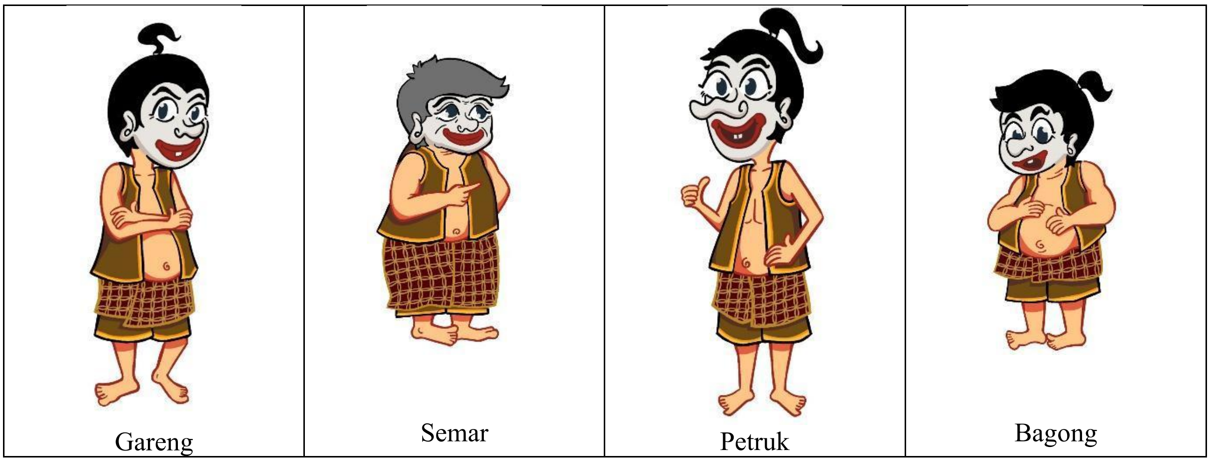

Figure 3. Punokawan Characters

The conceptualization phase of this Educational Play Tool (EPT) design had materialized through the creation of a puzzle inspired by the Punokawan characters, figures deeply embedded in Javanese cultural tradition and imbued with philosophical meaning (Irsyad, 2023). The initial step involved developing detailed character sketches to capture the defining visual traits of Semar, Gareng, Petruk, and Bagong, each symbolizing virtues such as wisdom, humor, and constructive social critique. These sketches were subsequently transformed into three-dimensional models using Blender software, where each figure was divided into modular parts (head, torso, and legs), allowing children to reassemble them during play. This modular configuration was purposefully designed to enhance fine motor coordination, spatial reasoning, logical thinking, and problem-solving skills in an engaging, interactive format.

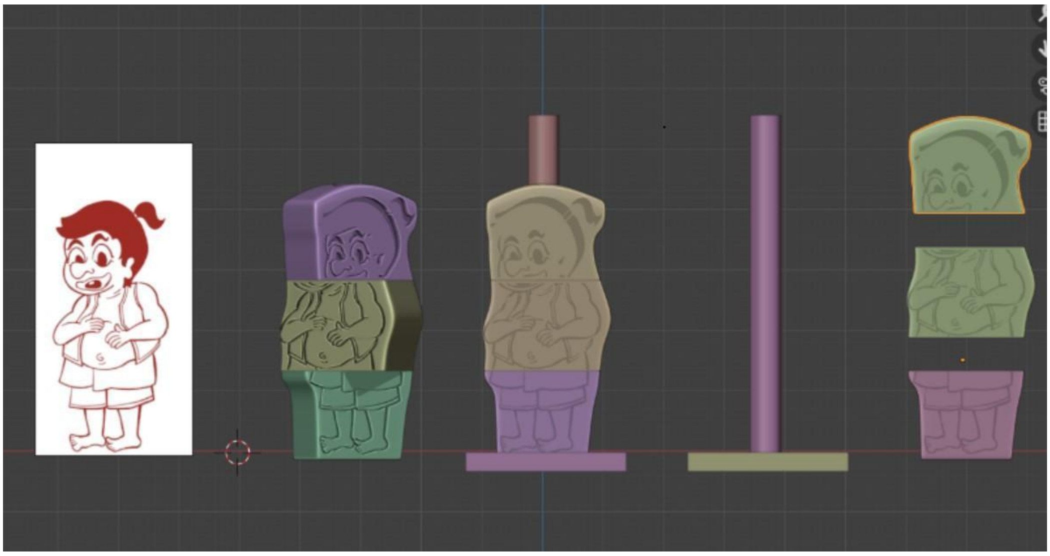

Figure 4. 3D Modelling Proccess

The resulting 3D models were not intended for mass production but functioned as preliminary prototypes to visualize and refine the design concept. These digital models can subsequently be exported in STL format, making them compatible with 3D printing processes that utilize PLA filament. The primary objective of this phase was to assess the conceptual viability of the design in terms of form, proportion, and interactive play value. PLA was selected as the material because of its environmentally sustainable, plant-derived composition and its high printability, both of which align with the ecological and design sustainability principles that form the foundation of this research.

https://doi.org/10.37134/kupasseni.vol14.sp.9.2026

Figure 5. Final Puzzle Conceptualization

Accordingly, this study proposes a conceptual model of Educational Play Tools (EPT) that synthesizes three core dimensions: educational enrichment through play-based learning, cultural contextualization through the incorporation of Punokawan characters, and environmental sustainability through the utilization of PLA material. The outcomes of this research are confined to the conceptualization and prototyping stages, without extending to empirical field testing or mass production. Nonetheless, the findings provide a foundational framework for subsequent studies aimed at further refinement, practical implementation, and validation of culturally integrated, eco-sustainable educational tools.

DISCUSSION

The developed Educational Play Tool (EPT) prototype functions not merely as an instrument for play but as an interactive medium for cultural transmission and learning. By incorporating Punokawan characters, figures that embody Javanese philosophical values such as wisdom, humility, and humor, the design establishes a meaningful link between tradition and modern educational practices. This integration aligns with the framework of culturally responsive pedagogy, which emphasizes connecting learning experiences to students' cultural backgrounds to enhance engagement and contextual relevance (Abdalla & Moussa, 2024). Empirical findings by Güven et al. (2025) further demonstrate that culture-based toys can foster creativity, symbolic thinking, and deeper cultural awareness among children. In the Indonesian context, where cultural plurality is vast but often underrepresented in educational media, this design approach contributes to revitalizing a sense of cultural identity that is increasingly threatened by globalization.

From an environmental standpoint, the adoption of polylactic acid (PLA) as the primary material reflects a tangible commitment to sustainable design principles. PLA, synthesized from renewable resources such as corn starch and cassava, possesses a lower carbon footprint and biodegrades under controlled industrial conditions (Trivedi et al., 2023). Compared to petroleum-derived plastics such as acrylonitrile butadiene styrene (ABS) and polyvinyl chloride (PVC), PLA can reduce greenhouse gas emissions by approximately 40 percent and does not emit toxic substances during production (Yadou et al., 2025). However, its large-scale application still encounters obstacles, including high production costs, limited thermal and humidity resistance, and dependence on imported filament supplies within Indonesia (Trivedi et al., 2023). Overcoming these challenges necessitates coordinated efforts between research institutions and local manufacturers to develop domestically produced PLA and explore bio-composites reinforced with natural fibers, which could enhance durability while maintaining ecological integrity. Therefore, although PLA represents a significantly more sustainable alternative to conventional plastics, its widespread integration in the educational toy industry requires strategic interventions addressing technical, economic, and logistical barriers at the local level.

https://doi.org/10.37134/kupasseni.vol14.sp.9.2026

The implementation of 3D printing technology as the main production method in this project further strengthens the adaptability and sustainability of the design. Additive manufacturing allows for precise, material-efficient, and customizable production processes. In the context of culturally rooted EPT, 3D printing enables the realization of intricate local motifs and character details that would be difficult to replicate through conventional fabrication methods (Fokides & Lagopati, 2024). Moreover, this technology supports iterative prototyping, allowing rapid design modifications based on feedback from educators or users without incurring substantial production costs. Such flexibility is particularly beneficial for educational contexts that demand continuous adaptation to curricular goals and cultural content (Fokides & Lagopati, 2024). Consequently, 3D printing serves not only as a means of production but also as a driver of pedagogical and cultural innovation.

Fundamentally, this EPT design aligns with the theoretical foundations of constructivism and play-based learning. Constructivist pedagogy asserts that knowledge is actively constructed through experiential interaction with the environment (Shah, 2022). When assembling the Punokawan puzzle, children engage in activities that develop fine motor coordination, spatial reasoning, and problem-solving, while simultaneously immersing themselves in cultural narratives that encourage reflection and critical thought. In parallel, the play-based learning approach positions play as a central mode of learning that enhances intrinsic motivation, curiosity, and emotional engagement (Dean & Wenner, 2025). By integrating cultural context, sustainable materials, and digital fabrication technologies, this study establishes a holistic educational ecosystem in which children learn not only about culture but also through culture, within an environment that is pedagogically meaningful, environmentally conscious, and socially inclusive.

IMPLICATIONS OF THE STUDIES

Theoretically, this study contributes to the growing body of educational design literature by illustrating how constructivist and play-based learning principles can be operationalized through culturally grounded and environmentally sustainable media. This approach is consistent with the framework of culturally responsive pedagogy, which underscores the importance of identity formation, active participation, and learner engagement (Shih, 2022). From a practical standpoint, the proposed conceptual prototype has potential applications in kindergartens and elementary schools as a customizable and curriculum-aligned educational tool. Its feasibility is further supported by the use of 3D printing technology, which promotes creativity, learner engagement, and the development of adaptable learning materials (Fokides & Lagopati, 2024). Nonetheless, several limitations merit critical consideration.

While offering both theoretical insights and practical implications, the present study remains at the conceptual development stage and lacks empirical validation. The use of PLA as the primary material introduces technical constraints, including limited resistance to heat and humidity relative to materials such as ABS or PETG, alongside challenges of cost and local accessibility (Trivedi et al., 2023). Therefore, future investigations should incorporate prototype testing with children and educators, detailed ergonomic assessments, and experimental exploration of PLA-based biocomposites (for instance, those reinforced with natural fibers) to enhance material durability without compromising environmental performance (Trivedi et al., 2023).

In the broader perspective, this research model holds promise as a framework for developing sustainable educational tools in Indonesia by combining cultural heritage preservation with eco-conscious material innovation. Such an approach aligns with current educational and environmental initiatives that envision schools as ecosystems fostering sustainability-oriented behavior and agency from early childhood (Abanoz & Yabaş, 2025; Mukhlis et al., 2024). Consequently, this design transcends the limitations of conventional EPT, offering a forward-looking paradigm for educational media that are pedagogically meaningful, culturally embedded, and environmentally responsible.

https://doi.org/10.37134/kupasseni.vol14.sp.9.2026

CONCLUSIONS

This study underscores the significance of developing Educational Play Tools (EPT) that holistically nurture children's cognitive, motoric, social, and emotional growth while simultaneously embedding local cultural values and utilizing sustainable materials. Employing a Qualitative Conceptual Design Research approach, the research successfully generated a conceptual prototype of a Punokawan-themed puzzle that merges Javanese philosophical insights with constructivist and play-based learning principles. The resulting prototype demonstrates the potential to serve as a playful, contextually meaningful, and value-enriched medium that promotes cultural appreciation and identity formation from early childhood.

From a sustainability standpoint, the choice of polylactic acid (PLA) as the primary production material provides an environmentally responsible alternative to conventional plastics. However, challenges remain concerning its production cost, mechanical strength, and accessibility within the local market. Concurrently, the adoption of 3D printing technology introduces new opportunities for creating flexible, efficient, and customizable EPT designs that can be adapted to diverse educational settings and cultural contexts.

Although the research is limited to the conceptual and prototyping stages without field implementation, it contributes substantially to the discourse on cultural integration and sustainability within educational design. Future research directions should include empirical testing with children and educators, ergonomic performance evaluation, and experimental exploration of PLA-based biocomposites aimed at enhancing material durability.

In the long term, this research offers a promising framework for developing sustainable educational tools in Indonesia by integrating local cultural heritage, technological innovation, and environmentally conscious materials. Ultimately, the study not only addresses the shortcomings of conventional EPT but also introduces a forward-looking paradigm for designing educational media that are pedagogically relevant, culturally grounded, and sustainability oriented.

ACKNOWLEDGEMENT

This study was not supported by any grants from funding bodies in the public, private, or not-for-profit sectors. The authors would like to express their sincere gratitude to Universitas Sebelas Maret, Faculty of Fine Arts and Design, for the institutional support and facilities provided throughout the completion of this research. Special thanks are extended to all respondents and peers who contributed constructive feedback during the conceptual development phase of this study.

CONFLICT OF INTEREST

The authors declare no conflicts of interest regarding the publication of this article.

Author Contributions

Author 1.: Conceptualization, Methodology, Writing Review. **Author 2.**: Data Curation, Writing Review, Visualization. **Author 3.**: Writing- Review and Editing.**Author 4.**: Writing- Review and Editing. **Author 5.**: Supervision.

AVAILABILITY OF DATA AND MATERIALS

Data available on request from the authors. The 3D model files, conceptual sketches, and visual renderings supporting this study are available upon reasonable request.

https://doi.org/10.37134/kupasseni.vol14.sp.9.2026

DECLARATION OF GENERATIVE AI USE

During the preparation of this work, the authors used ChatGPT (OpenAI, GPT-5) to enhance the clarity and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the final version of the publication.

ETHICAL STATEMENTS

This research did not involve human participants or animal subjects requiring ethical approval. Not applicable.

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