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Fostering Early Numeracy through Natural Loose Parts: A Nature-Based Pedagogical Approach in Early Childhood Classrooms

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ABSTRACT

Early numeracy lays a critical foundation for abstract mathematical reasoning; however, conventional early childhood instruction frequently relies on abstract, worksheet-driven tasks that hinder active cognitive engagement. Framed by embodied cognition and constructivist theories, this practitioner action research evaluated the impact of a nature-based loose parts pedagogy, utilizing twigs, leaves, seeds, and stones, on early numeracy acquisition among 15 preschool children aged 4 to 5 years across two action cycles. Data were collected using validated observation rubrics, performance assessments, and video documentation. Results demonstrated substantial gains in developmental mastery, expanding from a baseline of 20.00% to 40.00% in Cycle I, and reaching 80.00% in Cycle II. Inferential verification confirmed that these gains were statistically significant ($p < 0.001$) with an exceptionally large effect size ($r = 0.89$). Granular analysis revealed that one-to-one correspondence achieved the highest growth trajectory, surging by +1.80 points on a 4-point scale (a 107.78% relative increase). Parallel improvements were recorded in teacher instructional facilitation (69.44% to 86.11%) and student active engagement (68.05% to 83.33%). Natural loose parts provided tactile-sensory scaffolding that mediated the cognitive transition from concrete physical manipulation to spatial-numerical mapping and symbolic abstraction. This research establishes nature-based loose parts pedagogy as an equitable, scalable, and low-cost early STEM intervention that bridges concrete tactile exploration with abstract mathematical reasoning.

Keywords: Early Numeracy, Natural Loose Parts, Embodied Cognition, Early Childhood STEM, Practitioner Action Research

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1. INTRODUCTION

Early numeracy development plays a foundational role in children's subsequent mathematical learning and problem-solving, while numerical and spatial skills are closely associated with the development of mathematical competencies during early childhood (Devlin et al., 2022; Harris et al., 2026; Ouyang et al., 2022; Vessonen et al., 2024). During the preschool years, young learners undergo important conceptual changes as they develop basic number sense, understand quantities, and acquire symbolic representations of numbers (C. Chen et al., 2024; Jordan et al., 2022; Scalise & Ramani, 2021). However, early childhood mathematics instruction continues to face challenges in moving from teacher-directed and conventional practices toward more child-centered and play-based approaches, particularly when teachers must respond to competing expectations from parents, society, and educational demands (Zhang et al., 2024; Zhu et al., 2021). Overly didactic and drill-oriented approaches may be misaligned with young children's developmental needs by placing greater emphasis on procedural efficiency and repetitive practice than on mathematical reasoning, interaction, and engagement. Such practices may constrain children's motivation and opportunities to develop deeper conceptual understanding of foundational mathematical ideas (Cheung & Kwan, 2021; Clements et al., 2023; B. Y. Hu et al., 2021; Yang et al., 2022).

To support learners' understanding of abstract concepts, recent educational research has highlighted the potential of concrete manipulatives and hands-on learning activities, particularly when learners are guided to connect concrete representations with abstract symbols (Byrne et al., 2023; Donovan & Fyfe, 2022; Ebner et al., 2025). While commercially manufactured and highly structured manipulatives can support specific, task-oriented learning activities, their limited functions and affordances may constrain the range of actions and representations available to children, potentially reducing opportunities for open-ended exploration, flexible problem solving, and cognitive flexibility (Cankaya et al., 2025; Zeng & Ng, 2025). In contrast, natural loose parts, including materials such as sticks, leaves, branches, seeds, and stones, provide diverse affordances for child-led exploration, imaginative play, and hands-on interaction with the environment (Ellis et al., 2021; H. Hu, 2025; Loebach & Cox, 2022). According to Loose Parts Theory, unscripted materials enable children to rearrange, combine, and transform objects according to their own ideas and intentions, providing opportunities for exploration, problem-solving, reasoning, and divergent thinking (Cankaya et al., 2023; Pereira et al., 2023; Tay & Kaveri, 2026). Despite the growing interest in nature-based pedagogy, the pedagogical mechanisms through which natural materials may support children's mathematical learning remain insufficiently articulated. In particular, while nature play has been associated with opportunities for developing mathematical thinking, research has paid less attention to how children's physical engagement with concrete materials is intentionally scaffolded toward abstract mathematical representations and symbolic numeracy (Byrne et al., 2023; Donovan & Fyfe, 2022; Gilligan-Lee et al., 2023; Speldewinde & Campbell, 2022).

From an embodied cognition perspective, early mathematical thinking is closely connected to children's physical actions, sensory experiences, and interactions with objects and their environment (Gashaj et al., 2025; Roesch et al., 2026; Way & Ginns, 2024). When young children physically manipulate, group, and arrange objects, sensorimotor engagement can provide embodied experiences that support the development of spatial and numerical representations, linking action-based experiences with emerging mathematical knowledge (Anobile et al., 2026; Gilligan-Lee et al., 2023; Prabhu et al., 2026). Unlike uniform, commercially manufactured counters, natural loose parts offer greater variability in physical properties and affordances, requiring children to attend to and respond to differences in shape, size, texture, and material behaviour as they manipulate objects during play (Ellis et al., 2021; Loebach & Cox, 2022). Grounding early mathematics instruction in natural materials can integrate nature-based learning with children's active engagement in mathematical experiences, creating meaningful opportunities to develop mathematical understanding through exploration and educator-supported play (Donovan & Fyfe, 2022; Mart & Campbell-Barr, 2026; Speldewinde & Campbell, 2022).

In classroom practice, bridging concrete object manipulation and abstract symbolic representation remains a pedagogical challenge, as children do not necessarily transfer knowledge from manipulatives to symbolic representations without explicit connections and appropriately sequenced instructional support (Cheung et al., 2023; Donovan & Fyfe, 2022; Ebner et al., 2025). Preschoolers continue to develop the ability to connect concrete or non-symbolic quantities with abstract numerical symbols, suggesting that early numeracy instruction should provide explicit and meaningful opportunities for children to coordinate physical or non-symbolic quantities with symbolic representations (Hung et al., 2024; Orrantia et al., 2024; Tobia et al., 2021). Practitioner action research offers a systematic and reflective approach to addressing instructional challenges within authentic classroom contexts, enabling educators to investigate their practice and generate context-specific knowledge for pedagogical improvement (Marsh & Deacon, 2025; Matsui, 2021). Through iterative cycles of planning, action, observation, and reflection, educators can examine how children respond to instructional practices, critically evaluate their pedagogical decisions, and make informed adjustments to improve the quality and responsiveness of the learning environment (J. J. Chen, 2023; Ruming & McFarland, 2022).

To address these theoretical and empirical gaps, this study investigates the implementation of a nature-based loose parts pedagogical approach designed to support early numeracy development among preschool children aged 4 to 5 years. Specifically, the study examines how iterative cycles of engagement with natural loose parts may support children's ability to recognize number symbols, recite number sequences, and understand quantity–symbol correspondences. Furthermore, the study explores the broader effects of the intervention on children's active classroom participation and teachers' facilitation strategies. By examining the cognitive and pedagogical processes underlying children's engagement with natural loose parts, this study aims to contribute theoretical insights and practical guidance for educators seeking to implement contextualized, play-based STEM learning in early childhood education.

2. METHOD

This study employed a Practitioner Action Research (PAR) design to systematically investigate and refine classroom pedagogical practices through iterative cycles of inquiry, action, observation, and reflection (Bjørke et al., 2023; Lundie et al., 2022). The action research framework was structured into two iterative cycles, each comprising four integrated stages: planning, acting, observing, and reflecting. PAR was selected because it enables educators to investigate context-specific instructional challenges within authentic classroom settings and to use evidence from practice to inform ongoing pedagogical improvement (Hennessy et al., 2021; Newman et al., 2024). Rather than relying solely on qualitative observations, the study incorporated quantitative pre- and post-intervention assessments within the action cycles to quantify changes in children's numeracy performance. This integration of qualitative practitioner inquiry and quantitative assessment enabled the study to examine both changes in children's numeracy outcomes and the pedagogical processes underlying those changes.

The research was conducted at an early childhood education center in West Java, Indonesia, during the 2025/2026 academic year. Participants comprised 15 preschool children aged 4 to 5 years, consisting of 8 females and 7 males with a mean age of 4.4 years, enrolled in Group A. Participants were selected using purposive sampling based on initial diagnostic assessments indicating substantial difficulties in recognizing number symbols, reciting sequence orders, and establishing quantity-to-symbol correspondences. To protect participant anonymity in compliance with international ethical standards, all children were assigned standardized identification codes from C01 to C15.

To address these learning difficulties, the pedagogical intervention replaced conventional worksheet-based instruction with structured, nature-based loose parts learning activities. Loose parts materials consisted of unscripted, natural objects collected from the surrounding environment, including tree twigs, dried leaves, organic seeds, stones, and wooden cups. The intervention was executed across two distinct cycles spanning four weeks, with each cycle consisting of three 45-minute instructional sessions per week. In Cycle I, the intervention focused on foundational tactile exploration and guided group activities, such as arranging twigs to form number symbols and grouping seeds inside wooden cups to match specified quantities. Based on reflection outcomes from Cycle I, Cycle II introduced advanced, self-directed learning challenges, including spatial number sequencing using leaf cards, independent quantity matching, and collaborative mathematical problem-solving games.

To evaluate the effectiveness of these pedagogical activities, data were collected using a multi-method approach combining structured behavioral observations, performance assessments, and video-recorded classroom interactions. Early numeracy skills were evaluated across four core developmental indicators adapted from standardized early childhood mathematics frameworks. These indicators assessed number sequence recitation from 1 to 10 in correct order, quantity-concept recognition through object grouping, symbolic sequence ordering using number cards, and one-to-one correspondence by matching numerical symbols with physical object counts. Children's performances were evaluated using a four-point rubric ranging from 1 for Not Yet Developed to 4 for Developed Very Well. Teacher instructional facilitation and active child engagement were recorded simultaneously using structured observation schedules during every learning session.

To ensure methodological rigor and data reliability, the assessment rubric underwent content validation by three independent experts in early childhood education and mathematics pedagogy. The Content Validity Index yielded a score of 0.92, indicating high instrument validity. Furthermore, to eliminate researcher bias during observation, two independent observers, consisting of the lead researcher and a certified early childhood teacher, evaluated student performance simultaneously. Inter-rater reliability was calculated using Cohen's Kappa coefficient, yielding a value of 0.86, which demonstrates strong agreement between observers.

Data gathered from these observations were analyzed using both descriptive and inferential statistical techniques. Descriptive statistics, including mean scores and percentages, were calculated to summarize developmental mastery levels across baseline, Cycle I, and Cycle II. Success criteria were established when at least 80% of participating children achieved the expected developmental threshold. To evaluate whether improvements across cycles were statistically significant despite the small sample size of 15 participants, a non-parametric Wilcoxon Signed-Rank Test was performed. Furthermore, the magnitude of the pedagogical intervention was measured by calculating the Effect Size using the standard test statistic divided by the square root of total observations.

Throughout the data collection process, this study adhered strictly to ethical guidelines regarding research involving young children. Institutional approval was granted by the school administrative board prior to data collection. Written informed consent was obtained from the parents or legal guardians of all 15 participating children, authorizing their child's participation and the use of anonymized data for publication purposes. Additionally, verbal assent was obtained from each child before every session, ensuring that participation remained completely voluntary throughout the research process.

3. RESULTS

3.1. Overview of Early Numeracy Skill Trajectory

The implementation of nature-based loose parts media produced a consistent upward trajectory in early numeracy skill acquisition among preschool children ($N = 15$). Diagnostic baseline assessments indicated that a large majority of participants struggled with core numerical tasks, with only 3 children

(20.00%) achieving the benchmark criteria for developmental mastery. Following the introduction of tactile loose parts interventions in Cycle I, developmental mastery doubled to 6 children (40.00%). By the conclusion of Cycle II, instructional refinements and expanded self-directed manipulation enabled 12 children (80.00%) to attain expected or advanced levels of developmental mastery, thereby fulfilling the pre-established 80.00% success threshold.

To evaluate progression beyond binary mastery categories, children's performances were tracked using a four-point rubric scale ranging from 1 for Not Yet Developed, 2 for Starting to Develop, 3 for Developed as Expected, to 4 for Developed Very Well. The overall mean score across all four numeracy indicators expanded systematically across the action research iterations. At baseline, the sample recorded a mean score of 1.87 (SD = 0.43), corresponding to the Starting to Develop category. Following Cycle I, the mean score rose to 2.53 (SD = 0.51). Upon completion of Cycle II, the overall mean score reached 3.40 (SD = 0.49), indicating that average cohort performance shifted firmly into the Developed as Expected and Developed Very Well categories. Table 1 summarizes the consolidated trajectory of early numeracy development across the three assessment phases.

Table 1. Consolidated Trajectory of Early Numeracy Skill Mastery Across Intervention Phases

Mastery Category	Rubric Scale	Baseline Phase	Cycle I Phase	Cycle II Phase
Mastery Criteria Met Developed as Expected or Very Well	Scale 3.00 to 4.00	3 (20.00%)	6 (40.00%)	12 (80.00%)
Mastery Criteria Not Met Not Yet Developed or Starting to Develop	Scale 1.00 to 2.99	12 (80.00%)	9 (60.00%)	3 (20.00%)
Cohort Performance Metrics				
Total Cohort Participants		15 (100.00%)	15 (100.00%)	15 (100.00%)
Overall Mean Score (M±SD)	Scale 1.00 to 4.00	1.87 ± 0.43	2.53 ± 0.51	3.40 ± 0.49

3.2. Granular Indicator-Level Numeracy Performance

A granular analysis of student performance across the four evaluated developmental indicators provides deeper insight into how nature-based loose parts scaffolded specific numerical competencies. Each indicator was assessed on a scale of 1.00 to 4.00 across the baseline, Cycle I, and Cycle II evaluation phases. The empirical data revealed progressive score improvements across all four indicators, with the overall cohort progressing from foundational skill deficits toward advanced developmental competence. Table 2 outlines the mean scores, standard deviations, and net score gains for each indicator across the intervention cycles.

Table 2. Distribution of Mean Scores and Standard Deviations Across Numeracy Skill Indicators

Numeracy Skill Indicator	Baseline Phase (M±SD)	Cycle I Phase (M±SD)	Cycle II Phase (M±SD)	Net Gain (ΔM)	Growth Rate (%)
Indicator 1: Number Sequence Recitation	2.13 ± 0.52	2.73 ± 0.46	3.53 ± 0.52	+1.40	65.73%
Indicator 2: Quantity Concept Recognition	1.87 ± 0.52	2.53 ± 0.52	3.40 ± 0.51	+1.53	81.82%
Indicator 3: Symbolic Sequence Ordering	1.73 ± 0.46	2.40 ± 0.51	3.27 ± 0.46	+1.54	89.02%
Indicator 4: One-to-One Correspondence	1.67 ± 0.49	2.47 ± 0.52	3.47 ± 0.52	+1.80	107.78%

At the baseline phase, children demonstrated the highest initial capability in Indicator 1, which measured verbal number sequence recitation from 1 to 10 (M = 2.13, SD = 0.52). This initial advantage occurred because verbal counting is frequently practiced through rote memorization in conventional instruction. Conversely, tasks requiring conceptual depth and symbolic mapping registered low initial scores, particularly Indicator 3 (M = 1.73, SD = 0.46) and Indicator 4 (M = 1.67, SD = 0.49). Following the introduction of tactile loose parts in Cycle I, all indicators demonstrated positive score gains, with mean scores rising above the 2.40 threshold. By Cycle II, instructional adaptations allowed children to consolidate their learning, pushing all four indicator averages well above 3.20.

Among all evaluated indicators, Indicator 4 (One-to-One Correspondence) exhibited the most dramatic growth trajectory, recording a net score gain of +1.80 points and an overall growth rate of

107.78%. During the baseline phase, children frequently experienced confusion when matching abstract numerical symbols with corresponding object quantities. The physical manipulation of natural loose parts provided the tactile-sensory bridging necessary to solve this instructional barrier. By physically placing individual seeds into wooden cups or arranging specific counts of twigs next to leaf number cards, children transformed abstract numerical values into tangible physical quantities. This substantial surge in one-to-one correspondence confirms that unscripted natural materials serve as highly effective concrete scaffolding for grounding abstract mathematical concepts in young learners.

3.3. Inferential Statistical Verification and Effect Size

To confirm whether the observed improvements across the intervention cycles were statistically significant or merely attributable to sample variance, a non-parametric Wilcoxon Signed-Rank Test was conducted. A non-parametric test was selected due to the small sample size ($N = 15$) and the ordinal nature of the rubric-based evaluation data. Paired comparisons were executed across three experimental intervals: Baseline versus Cycle I, Cycle I versus Cycle II, and Baseline versus Cycle II.

The inferential analysis revealed statistically significant improvements in children's early numeracy scores across all paired comparisons ($p < 0.001$). The transition from Baseline to Cycle I yielded a significant increase in numeracy performance ($Z = -3.42$, $p < 0.001$). Similarly, the instructional refinements introduced between Cycle I and Cycle II generated further significant score gains ($Z = -3.43$, $p < 0.001$). Comparing the baseline condition directly to the final post-intervention state in Cycle II demonstrated a highly significant overall transformation in cohort numeracy performance ($Z = -3.44$, $p < 0.001$).

To measure the practical magnitude of the pedagogical intervention beyond statistical significance, the Effect Size (r) was calculated using the standardized formula: $r = \frac{|Z|}{\sqrt{N}}$; where $|Z|$ represents the absolute value of the Wilcoxon test statistic and N represents the total number of paired observations ($N = 15$). According to Cohen's criteria for behavioral sciences, an effect size value (r) of 0.10 indicates a small effect, 0.30 indicates a medium effect, and values of 0.50 or greater represent a large effect. Table 3 presents the summary of the Wilcoxon Signed-Rank Test results and calculated effect sizes across all evaluation phases.

Table 3. Wilcoxon Signed-Rank Test Results and Effect Size Calculations Across Intervention Phases

Paired Comparison Phase	Mean Rank (Positive Ranks)	Test Statistic (Z)	Asymptotic Sig. (2-tailed p)	Calculated Effect Size (r)	Magnitude Interpretation
Phase 1: Baseline vs. Cycle I	8.00	-3.42	< 0.001	0.88	Extremely Large Effect
Phase 2: Cycle I vs. Cycle II	8.00	-3.43	< 0.001	0.89	Extremely Large Effect
Phase 3: Baseline vs. Cycle II	8.00	-3.44	< 0.001	0.89	Extremely Large Effect

As detailed in Table 3, the calculated effect sizes across all phase comparisons ranged between $r = 0.88$ and $r = 0.89$. These values far exceed the standard threshold of 0.50 for a large effect size. The high magnitude of $r = 0.89$ for the overall intervention (Baseline to Cycle II) confirms that the implementation of nature-based loose parts media exerted a profound and substantial positive influence on children's early numeracy development. This inferential statistical verification provides robust evidence that the observed developmental gains were directly driven by the tactile-sensory pedagogical intervention rather than developmental maturation or random chance.

3.4. Classroom Pedagogical Dynamics: Teacher Facilitation and Student Engagement

Evaluating the pedagogical dynamics of the intervention revealed parallel, mutually reinforcing improvements across both teacher instructional facilitation and student engagement throughout the action research cycles. Teacher facilitation advanced significantly from an adequate score of 69.44% in Cycle I to 86.11% in Cycle II following key instructional adaptations, including small-group clustering, deliberate demonstration pacing, and open-ended scaffolding. Concurrently, student active engagement expanded from 68.05% to 83.33%, progressing from initial enthusiasm hindered by short attention spans toward sustained, self-directed exploration and collaborative problem-solving. To provide a clear and integrated view of these classroom dynamics, Table 4 presents a consolidated summary of teacher facilitation performance and student active engagement metrics across both action cycles.

The simultaneous progression of teacher facilitation from 69.44% to 86.11% and student engagement from 68.05% to 83.33% highlights the reciprocal nature of the pedagogical environment. Enhanced teacher facilitation provided the necessary structure and emotional safety for preschoolers to explore natural loose parts deeply. In turn, elevated student engagement provided teachers with positive feedback, reinforcing child-centered instructional strategies. This dynamic shift created a vibrant, interactive learning ecosystem that directly fueled the cognitive numeracy gains recorded throughout this study.

Table 4. Consolidated Performance Metrics of Teacher Facilitation and Student Active Engagement Across Action Cycles

Pedagogical Dynamic Dimension	Cycle I Score (%)	Cycle I Category	Cycle II Score (%)	Cycle II Category	Net Score Increase (% Points)
Teacher Instructional Facilitation	69.44%	Adequate	86.11%	Very Good	+16.67%
Student Active Engagement	68.05%	Adequate	83.33%	Very Good	+15.28%

4. DISCUSSION

4.1. Theoretical Integration: Embodied Cognition and Loose Parts Affordances

The empirical findings of this study demonstrate that integrating nature-based loose parts into preschool instruction was associated with substantial improvement in early numeracy acquisition. The proportion of children achieving developmental mastery increased from a baseline of 20.00% to 40.00% in Cycle I and ultimately reached 80.00% at the conclusion of Cycle II. Inferential analysis further indicated that this progression was accompanied by a very large effect size ($r = 0.89$, $p < 0.001$), suggesting a strong association between the pedagogical intervention and improvement in children's mathematical performance. Rather than representing only incremental gains in discrete skills, the observed progression may indicate that sustained engagement with natural loose parts supported children's developing capacity to coordinate perceptual, motor, and numerical representations. This interpretation is consistent with contemporary research on embodied cognition, which emphasizes the dynamic relationship between bodily action, perception, material objects, and mathematical activity (Gordon & Ramani, 2021; Shvarts et al., 2021).

Understanding why this intervention produced such substantial developmental gains requires examining the findings through the lens of embodied cognition. Contemporary embodied perspectives propose that mathematical learning is not solely a disembodied mental process but can emerge through dynamic interactions among bodily movement, perception, and the physical environment (Gordon & Ramani, 2021; Shvarts et al., 2021). When preschoolers physically grasp twigs, count organic seeds, align dried leaves, and group smooth stones, these activities engage children in direct perceptual and motor interactions with quantities, spatial relations, and object groupings. From an embodied perspective, such perception–action interactions can contribute to the development of mathematical meaning by linking physical manipulation with emerging numerical representations (Shvarts et al., 2021). Recent research on loose parts further suggests that open-ended materials can encourage children to explore, manipulate, transform, and reorganize objects in ways that support spontaneous STEM-related behaviours (Cankaya et al., 2025). Thus, natural loose parts may function not merely as concrete instructional materials but as embodied learning resources that provide children with opportunities to ground emerging numerical concepts in meaningful sensory-motor experiences.

Furthermore, the distinctive material affordances of natural loose parts may provide learning opportunities that differ from those offered by commercially manufactured manipulatives. Natural materials such as twigs, leaves, seeds, bark, and branches possess diverse physical characteristics and can be incorporated into children's play in multiple ways, thereby providing varied opportunities for manipulation, transformation, and symbolic use (Trina & Monsur, 2025). In contrast, commercially manufactured manipulatives are generally designed with predetermined forms and functions, which can provide useful structure for specific mathematical tasks but may offer fewer opportunities for children to redefine or repurpose the materials during open-ended exploration (Cheung et al., 2023). When children manipulate natural objects, variations in texture, shape, size, and physical properties can encourage direct sensory exploration and sustained engagement with the materials (Zeng & Ng, 2025). Such open-ended material conditions may also encourage children to experiment with different possibilities, construct solutions, and engage in problem-solving rather than simply reproduce predetermined actions (Tay & Kaveri, 2026). Consequently, the material diversity of nature-based loose parts can transform routine mathematical activities into exploratory learning experiences in which children actively investigate relationships among objects, quantities, and spatial arrangements.

4.2. Cognitive Mechanisms of Abstraction in Early Numeracy

A granular examination of individual skill indicators reveals that Indicator 4, measuring One-to-One Correspondence, experienced the most pronounced growth trajectory, increasing from a baseline mean of 1.67 to 3.47 in Cycle II, representing an extraordinary 107.78% growth rate. One-to-one correspondence represents a fundamental component of early counting and numerical development because it involves coordinating each object in a collection with a distinct counting word or numerical referent (Orrantia et al., 2022). In conventional instruction, preschoolers may experience difficulty coordinating the counting sequence with the objects being counted, particularly when numerical information is presented through less interactive representational formats. Contemporary research indicates that children's understanding of counting-based cardinal concepts develops progressively and that mastery of count-cardinal knowledge is closely related to the development of more advanced cardinality concepts (Baroody & Lai, 2022). By transitioning to physical natural loose parts, children were provided with discrete, three-dimensional objects that could be physically moved and reorganized as each item was counted. Such physical manipulation may help children maintain correspondence between individual objects and successive counting acts by making the object–number relationship perceptually salient. This interpretation is consistent with recent evidence showing that one-to-one correspondence develops prior to full understanding of cardinality, highlighting its foundational role in children's construction of numerical meaning (Thevenot & Krenger, 2024). Although three-dimensional manipulatives do not necessarily produce superior performance in every assessment context, their physical properties can provide an alternative representational format through which preschool children engage with counting and cardinality concepts (O'Rear et al., 2023).

This dramatic surge in skill acquisition illustrates a potentially important cognitive transition from concrete physical manipulation toward spatially organized numerical understanding and, ultimately, more abstract symbolic representation. Contemporary research on embodied learning in early mathematics suggests that children's mathematical understanding can develop through interactions among bodily action, perception, physical materials, and increasingly conventional mathematical representations (Way & Ginns, 2024). When preschoolers physically deposit individual seeds into wooden cups or align twigs alongside leaf cards displaying written digits, they can coordinate quantities, spatial arrangements, and numerical symbols within a shared perceptual context. Such activities may support the development of number–quantity mappings by making numerical relationships physically observable and manipulable (Orrantia et al., 2022). Evidence from preschool mathematics interventions further indicates that combining symbolic number knowledge with mapping processes and spatial reasoning can contribute to gains in children's numerical and geometric knowledge (Taborda-Osorio & Otálora, 2023). Similarly, research on embodied numerical learning has shown that physical actions, such as finger-based numerical strategies, can support subsequent arithmetic learning, providing further evidence that bodily experiences can contribute to the development of abstract numerical knowledge (Frey et al., 2024). Thus, repeated coordination of physical quantities with corresponding number symbols may help children gradually shift from relying primarily on object-based actions toward recognizing and interpreting numerical symbols as representations of quantity.

Furthermore, the open-ended nature of natural loose parts may influence the cognitive conditions under which young children engage in mathematical problem-solving. Contemporary cognitive load research distinguishes among intrinsic, extraneous, and germane load, emphasizing that the design and presentation of instructional tasks can influence the amount of cognitive resources available for learning and schema construction (Wang et al., 2022). In contrast to highly structured activities with predetermined procedures, loose parts provide children with flexible materials that can be explored, combined, reorganized, and repurposed according to their emerging ideas and developmental capabilities (Cankaya et al., 2023). Rather than requiring children to follow a single predetermined sequence of actions, such materials can create opportunities for children to explore mathematical relationships through direct manipulation and self-initiated experimentation. Recent research further indicates that loose-parts play can support young children's problem-solving by creating open-ended situations in which children encounter problems, consider alternatives, test possibilities, and develop solutions through interaction with materials (Tay & Kaveri, 2026). Similarly, loose-parts construction activities have been associated with opportunities to develop decomposition and algorithmic thinking, suggesting that open-ended material environments can support children's active engagement in higher-order thinking processes (Lim et al., 2024). Consequently, natural loose parts may function as flexible learning resources that shift children from primarily following predetermined procedures toward more active exploration, experimentation, and self-directed problem-solving.

4.3. Pedagogical Synergy and Dynamic Scaffolding

The quantitative findings of this study highlight a positive relationship between teacher instructional facilitation and children's active engagement across the action research cycles. Teacher facilitation performance improved from 69.44% in Cycle I to 86.11% in Cycle II, while student active engagement concurrently increased from 68.05% to 83.33%. Rather than functioning as entirely independent dimensions, the concurrent improvement in these two indicators suggests that teacher facilitation and children's engagement may develop in relation to one another within classroom interactions. Research on early childhood classroom quality indicates that children's learning experiences are shaped by the quality of instructional and emotional support provided by teachers (Paschall et al., 2023). In the initial cycle, teacher-centered habits and relatively rapid instructional pacing may have restricted opportunities for autonomous exploration, resulting in moderate levels of student engagement. As the teacher refined the instructional approach in Cycle II by organizing small-group activities and providing extended opportunities for tactile manipulation, children demonstrated greater opportunities for sustained participation and exploration. Evidence from preschool classrooms further indicates that responsive teaching and cognitive facilitation are positively associated with children's engagement, highlighting the importance of teachers' interactional practices in supporting active participation (Taylor et al., 2023). Within loose-parts learning, teacher facilitation can be particularly important because open-ended materials require responsive questioning and guidance to extend children's thinking and problem-solving rather than simply directing them toward predetermined outcomes (Tay & Kaveri, 2026). Thus, the concurrent improvement observed across the two action research cycles suggests that responsive teacher facilitation and active child engagement may operate as mutually supportive components of an increasingly child-centered learning environment.

This pedagogical transformation offers a contemporary interpretation of Vygotsky's Zone of Proximal Development in nature-based early childhood STEM education. Rather than relying exclusively on direct instruction, teachers can use responsive questioning to scaffold children's thinking and extend their exploration during play-based learning (Zeng & Ng, 2025). In Cycle II, the teacher reduced immediate answer-giving when children encountered difficulties with number sequences or quantity matching and instead used questions that encouraged them to examine quantities, compare alternatives, and explain their reasoning. Recent research on loose-parts play similarly indicates that open-ended questioning can promote persistent problem-solving, although teacher modelling and more focused questioning may initially be necessary to guide children toward productive exploration (Tay & Kaveri, 2026). Thus, the use of natural loose parts combined with responsive questioning created opportunities for children to work beyond what they could accomplish independently while gradually assuming greater responsibility for mathematical problem-solving.

Within this nature-based STEM framework, physical loose parts function as material resources that mediate teacher–child interactions and foster exploratory learning. Their open-ended characteristics allow children to manipulate, combine, and transform materials in multiple ways, creating opportunities for spontaneous STEM exploration, experimentation, and independent problem-solving (Cankaya et al., 2025). Rather than prescribing a single correct procedure, these flexible materials enable children to test ideas and revise their actions while teachers observe, question, and extend their emerging mathematical thinking, fully consistent with the principles of the Zone of Proximal Development (Zeng & Ng, 2025). Recent evidence further indicates that purposeful teacher questioning during loose-parts play strengthens children's persistence and problem-solving capacity while gradually encouraging greater autonomy in learning (Tay & Kaveri, 2026). Thus, the dynamic alignment of flexible natural materials and responsive teacher scaffolding creates an optimal learning environment in which young children develop foundational numeracy through active, guided discovery.

4.4. Global Scientific Contribution, Novelty, and Practical Implications

The empirical outcomes of this study contribute to contemporary research on early childhood mathematics and nature-based STEM education. Recent evidence confirms that the effectiveness of concrete manipulatives depends not only on their physical concreteness but also on how materials and mathematical language are integrated during instruction (Cheung et al., 2023). Extending this literature, the present study demonstrates that natural loose parts can provide an alternative material context for developing foundational numeracy, with developmental mastery increasing to 80.00% and a large observed effect size ($r = 0.89$, $p < 0.001$). Recent research with preschool children further demonstrates that natural playscapes and loose materials can elicit engineering thinking, experimentation, problem-solving, and other STEM-related behaviours through child-directed exploration (Yuan et al., 2025). Similarly, experimental evidence indicates that loose-parts play can generate significantly greater STEM engagement and mathematical exploration than play with materials offering more limited affordances (Cankaya et al., 2025).

The principal contribution of this study lies in extending the application of loose parts from general play and STEM exploration toward the intentional development of foundational numeracy skills. Rather than positioning natural materials as substitutes that are necessarily superior to commercial manipulatives, the findings suggest that locally available materials can provide a flexible and accessible context for children to practise one-to-one correspondence, number sequencing, and quantity–symbol relationships. This extends current nature-based STEM research by connecting open-ended material affordances with specific early mathematical learning outcomes.

From a practical perspective, these findings suggest that early childhood curricula can incorporate locally available natural materials alongside existing mathematical resources. Teacher professional development should emphasize how educators can organize such materials around clear numeracy objectives while using open-ended questioning, observation, and responsive scaffolding to extend children's mathematical thinking. Such an approach may provide an economically accessible and contextually adaptable pathway for integrating play-based, nature-oriented STEM experiences into early childhood classrooms.

5. CONCLUSION

This study investigated the effectiveness of a nature-based pedagogical intervention utilizing natural loose parts to foster foundational numeracy skills among preschool children aged 4 to 5 years. The empirical results confirm that the intervention successfully addressed early numeracy deficits, driving developmental mastery from a baseline of 20.00% to 40.00% in Cycle I, and ultimately reaching 80.00% in Cycle II. Inferential verification via the Wilcoxon Signed-Rank Test proved that these gains were statistically significant ($p < 0.001$) with an exceptionally large effect size ($r = 0.89$). These cognitive gains were accompanied by parallel enhancements in classroom dynamics, as teacher instructional facilitation improved from 69.44% to 86.11% and student active engagement increased from 68.05% to 83.33%. Among the evaluated skill indicators, one-to-one correspondence achieved the highest relative growth rate of 107.78% (representing a net gain of +1.80 points on a 4-point scale), confirming that physical object manipulation provides essential scaffolding for abstract symbolic mapping.

Theoretically, this research advances early childhood mathematics education by demonstrating that unscripted natural materials, such as twigs, leaves, seeds, and stones, function as powerful cognitive anchors within an embodied cognition framework. Unlike uniform plastic manipulatives, natural loose parts offer rich sensory affordances that sustain children's perceptual focus and lower extrinsic cognitive load during mathematical problem-solving. By replacing abstract worksheet drills with open-ended tactile exploration, this pedagogical approach transforms early numeracy learning into an active, child-centered discovery process. Furthermore, natural loose parts pedagogy democratizes early STEM education by offering a low-cost, sustainable, and highly accessible instructional model that can be easily adapted across diverse educational settings globally.

Despite these positive outcomes, several limitations should be acknowledged. The research was conducted using a practitioner action research design with a relatively small sample size of 15 children within a single educational center, which restricts the direct statistical generalizability of the findings. Additionally, the intervention focused primary attention on early number sense and counting competencies over a four-week period. Future studies should employ quasi-experimental or longitudinal designs with larger, more diverse cohorts to examine the long-term retention of mathematical skills. Further research is also recommended to explore the application of natural loose parts across other developmental domains, including early spatial geometry, scientific inquiry, language acquisition, and socio-emotional development.

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