A preschool Eco-STEM teaching model focusing on environmental awareness: Grounded in embodied cognition theory

Peng Zhang[1] ✉ (iD)
Nurfaradilla Mohamad Nasri[2] (iD)
Suziyani Mohamed[3] (iD)

(✉ Corresponding Author)

[1,2,3]*Faculty of Education, Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia.*
[1]*Email: P113164@siswa.ukm.edu.my*
[2]*Email: nurfaradilla@ukm.edu.my*
[3]*Email: suziyani@ukm.edu.my*

Abstract

It is noteworthy that current eco-STEM practices pay limited attention to the cognitive relationship between learners and the environment, with the preschool stage being almost entirely absent from the discussion. However, this absence could hinder the earliest development of environmental awareness. Therefore, in this study, a preschool Eco-STEM teaching model focusing on environmental awareness was developed. Given the complexity of model development, a sequential mixed-methods approach was employed, beginning with semi-structured interviews that identified four themes regarding the needs of eco-STEM teaching practices: Systematic Requirements for Teaching Models, Required Competencies, Exploration and Practice Needs, and Emotional Connection Needs. Based on these needs, focus group discussions with seven senior preschool teachers identified fifteen initial elements for the model. Finally, the Fuzzy Delphi Method (FDM) was used with a panel of eleven experts to refine and validate the model, achieving consensus on thirteen of the fifteen elements. The retained elements emphasized the cognitive relationship between learners and the environment, including meaningful scientific experiences and dissection and reconstruction, while the excluded elements, such as micro-innovation abilities, reflected experts' prioritization of cognitive aspects. After modifications, a practical teaching model comprising fifteen elements was ultimately developed. This study highlights the contribution to the field of eco-STEM by developing an innovative preschool eco-STEM teaching model tailored to preschool specificities, with the potential to reshape the field.

Contribution of this paper to the literature
This study is distinctive in its focus on preschool Eco-STEM education, with environmental awareness identified as a central learning focus. Methodologically, this study moves beyond single-method approaches by employing a systematic methodology of needs-driven (interview) and consensus-developing (Fuzzy Delphi Method), resulting in a clear flowchart for educators and researchers.

1. Introduction

Eco-STEM is the expansion of the environmental discipline into the rooted STEM structure (Candan-Helvacı, 2022). The reason for the initial expansion was that integrating "engineer" into STEM curricula is very challenging, so the environment was only considered as one of the ideal alternatives to the traditional "E" in STEM (Blackley & Sheffield, 2015). When environmental issues arise, international agreements, sanctions, or individual efforts often produce results that fall short of expectations. Consequently, people are increasingly turning their hope to eco-STEM education (Caldwell, Garcia, & Cagle, 2018). Similar to traditional STEM education, eco-STEM education primarily aims to address real-world environmental problems, fostering a willingness among individuals to engage in practical solutions (Struyf, De Loof, Boeve-de Pauw, & Van Petegem, 2019).

There are three fixes to solve environmental problems (Heberlein, 2012). In the context of eco-STEM education, it clearly emphasizes cognitive fixes. Specifically, environmental awareness, which is a pillar of eco-STEM (Candan-Helvacı, 2022), is also a long-term solution proposal for addressing environmental problems. The reason for this is that it continuously stimulates young children's cognitive and thinking structures. This will not only lead to a shift in environmental awareness at a critical level but also has the potential to promote the development of problem-solving skills and the ability to reflect on environmental issues (Díaz Encinas & Fuentes, 2018; Duncan, 2013).

However, while environmental awareness is important for eco-STEM education, little attention has been paid to revealing the cognitive relationship between learners and the environment in eco-STEM practices. Particularly, young children in the preschool stage are completely absent from current discussions on eco-STEM. Evidently, developing environmental awareness in children at a young age is crucial (Gülay, Koçer, & Önder, 2023). Because it is an important determinant of positive attitudes toward the environment (Yang, Wu, Tong, & Sun, 2022) and one of the key steps to achieve sustainability (Mahmood & Ali, 2024), environmental experiences should be gained at foundational ages (Gokceli & Kandir, 2015). However, it is observed that environmental awareness in the preschool period is not at the desired level (Borg, Winberg, & Vinterek, 2019). Although everyone is born with a certain degree of naturalist intelligence, if the human environment does not provide social-emotional and intellectually supportive enrichment during early childhood, serious concerns may arise, negatively affecting development (Gunnar, 1996). This deficiency makes it more difficult for students to enhance their environmental awareness after entering middle school (Arı & Yılmaz, 2017).

The lack of environmental awareness among young students may be attributed to the teaching methods employed by educators responsible for relevant subjects. Most teachers tend to emphasize critical thinking skills aimed at solving environmental problems, but often overlook the fundamental concept that eco-STEM education fosters the development of multidimensional understanding. Additionally, teachers appear to focus more on environmental problem-solving skills as a primary teaching objective. This approach may stem from the urgent societal need to address environmental issues; when teachers recognize that enhancing environmental awareness can significantly promote environmental problem-solving skills, they tend to implement eco-STEM practices more from a consciousness-raising perspective. Although limited research has addressed this issue, as noted by Candan-Helvacı (2021), Rahmawati, Taylor, Taylor, Ridwan, & Mardiah (2022), there remain substantial gaps in this field that warrant further attention.

Hence, this study aimed to develop an eco-STEM teaching model to foster environmental awareness. The model, developed with consensus among a panel of experts, is designed for teaching young children in kindergarten. This model will be significant in assisting preschool teachers in developing environmental awareness among young children. Likewise, environmental awareness will eventually translate into problem-solving abilities in the face of environmental issues.

2. Literature Review

2.1. Eco-STEM Education

Emerging as a strategic U.S. governmental initiative to preserve global economic leadership, STEM education was fundamentally designed to develop advanced workforce capacities in scientific and technological domains (Jeong, Park, & Lee, 2019). However, this economic imperative has paradoxically engendered pedagogical distortions, with educators disproportionately emphasizing industrial applications at the expense of ecological considerations (Bajuri, Maat, & Halim, 2020). This pedagogical imbalance risks cultivating what Fitzpatrick (2017) critically terms "technologically capable savages" – professionals possessing technical expertise but lacking environmental conscientiousness. Responding to these epistemological limitations, scholars have initiated a paradigm shift toward eco-STEM education – an integrative framework systematically incorporating environmental literacy into traditional STEM disciplines (Fraser, Gupta, Flinner, Rank, & Ardalan, 2013).

Scholars have increasingly reimagined STEM education frameworks by positioning environmental integration as a promising alternative to conventional engineering paradigms (Blackley & Sheffield, 2015). Such alternative eco-STEM education emphasizes encouraging individual engagement with the environment and exploring traditional STEM scientific concepts motivated by caring for the environment (Fraser et al., 2013). Learning activities are primarily centered on carefully planned outdoor environments (Dohn, 2011; Storksdieck, Ellenbogen, & Heimlich, 2005) including outdoor audiovisual camps (Ghadiri, Liu, Gottesman, Shepardson, & Pijanowski, 2018) urban outdoors (Paulsen & Andrews, 2019) museums (Başaran & Erol, 2023) homes (Almeida, 2021) tea gardens

(Wahyuni, Arrohman, Wilujeng, Widowati, & Suyanta, 2022) gardens (Turner, Logan, & Wilks, 2022) school forests (Sweeney, 2020) outdoor math trails (Livers, 2022).

With the continuous development of global industrialization and the deterioration of environmental problems, finding solutions to environmental issues has become crucial. The Makki, Abd-El-Khalick, & Boujaoude (2003) emphasize the importance of addressing these challenges. The North American Association for Environmental Education (2018) advocates that there is a need to shift from viewing the environment merely as a focus for considering science concepts to seeing STEM education as one that helps learners understand various environmental problems within the context of their lives, and their lives within the context of environmental issues. Consequently, research has increasingly focused on learners' understanding of and solutions to air pollution caused by fine dust, highlighting the importance of integrating environmental awareness into educational practices (Kim & Hyun, 2020), soil pollution from heavy metals (Zheng, 2020) the water cycle (Tadena & Salic-Hairulla, 2021), and marine ecological litter (Zhang, 2022). Moreover, the learning environment is primarily focused indoors, with only a few schools engaging in STEM teaching practices that utilize local resources, such as the conservation of rare white cranes in South Korea (Birney, Kong, Evans, Persuad, & Danker, 2018; Lee, 2017) and the oyster restoration project at Portside School in the United States (Birney et al., 2018).

In synthesizing current eco-STEM scholarship, two critical epistemological gaps emerge. Firstly, extant paradigms demonstrate limited engagement with the cognitive reciprocity between learners and pedagogical environments, irrespective of spatial configurations (outdoor vs. indoor modalities). Secondly, methodological constraints persist as predominant research trajectories remain confined to exploratory case developments and descriptive outcome analyses (Sweeney, 2020) while systematically neglecting processual investigations into implementation mechanisms. This dual deficiency aligns with (Sweeney, 2020)'s critical observation that eco-STEM constitutes an emergent field requiring substantive epistemological scaffolding. These identified limitations necessitate the development of a comprehensive eco-STEM framework that theorizes the dynamic cognition-environment interface through bidirectional adaptation models and that establishes methodological protocols for examining pedagogical enactment processes.

2.2. Eco-STEM Teaching Model

From time to time, environmental problems become increasingly complex, while the human capacity to overcome these issues does not increase significantly in proportion to the growing complexity of environmental challenges (Yeh, Tran, Hung, & Huang, 2022). In this context, many eco-STEM teaching models based on inquiry-centered approaches have been applied to address environmental problems.

It is undoubtedly true that not all environmental problems can be solved. For this reason, Çorlu and Çallı (2017) emphasize "constraints" in the eco-STEM teaching model based on Knowledge-Based Life Problems (BTHP). These constraints that need to be considered when solving problems and designing solutions may include the availability of resources, time restrictions, technological feasibility, environmental impacts, and economic costs, which encourage students to propose genuinely feasible and practical solutions.

In addition, some other scholars are considering what the actual "environmental problem" is Ua-Umakul and Chaiwatchatuphon, 2018). In their application of the eco-STEM teaching model, they respond by defining the problem to clarify the complexities of environmental issues. The unique aspect of this teaching model lies in its focus on real and specific environmental problems within the community, enabling students to better understand and address the environmental challenges they face in their immediate surroundings. Arndt and Tweed (2014) and Zubair, Khan, and Alam (2023) also provided driving answers to real environmental problems to stimulate learners' intrinsic motivation to participate in eco-STEM activities. The detailed learning activities include enriching the problems with driving forces, identifying a local environmental problem, and providing options for students.

Obviously, exploratory thinking is essentially rational, primarily viewing how to solve environmental problems from a methodological or technical perspective, without considering the transmission of values. Therefore, value-transmitting ecological thinking is applied in the eco-STEM teaching model. In the research conducted by Rahmawati et al. (2022), the concept of "dilemma stories" is applied to the eco-STEM teaching model. The uniqueness of this teaching model lies in the ethical and value considerations that learners engage in while discussing and addressing these dilemmas. While Candan-Helvacı (2021) integrated environmental awareness throughout the entire teaching model, emphasizing that the generated prototypes must be created "consciously".

All in all, the majority of scholars primarily apply the eco-STEM teaching model with a problem-solving mindset. While problem-solving thinking has significant advantages in cultivating students' logical thinking and innovative abilities, the core essence of eco-STEM goes far beyond merely addressing environmental issues. Although two scholars have already acknowledged the importance of the awareness aspect within the eco-STEM teaching model, it is unfortunate that there still exist notable deficiencies in this field.

2.3. Embodied Cognition Theory

Embodied cognition theory asserts that our knowledge of the world is not an "objective image" of the world but is formed through the unique channels of the body's structure and sensory-motor system. The learner's construction is not purely cognitive but also a physical construction (Ye, 2015). It is greatly influenced by the interaction between the body and the environment. In other words, the mind is rooted in the body, and the body is rooted in the environment. When the learning process undergoes these embodied stages, cognitive abilities are enhanced because embodied cognition is a coupling process, and instruction should fully satisfy the conditions for this coupling.

Previous research has examined the influence of bodily involvement on final learning outcomes and learning efficiency. The results show that the positive role of physical involvement in learners' mastery of knowledge, learning motivation, emotional experiences, abilities, and skills in various contexts, such as early literacy education (Roessingh & Bence, 2018) mathematics education (Drodge & Reid, 2000; Nemirovsky & Ferrara, 2009) physical Education (McClelland, Pitt, & Stein, 2015) and English vocabulary acquisition (Schmidt et al., 2019). Although the characteristics of instructional design vary across different teaching models, all emphasize the importance of

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environmental design as well as the contextual and dynamic aspects of learning, suggesting that the learning process should be dynamically generated through the interaction between the body and the environment.

However, none of the existing eco-STEM practices focus on revealing the cognitive relationship between learners and the teaching environment, whether outdoors or indoors. Environmental educator David Sobel believes that if young children study only global problems, they may begin to dissociate themselves from the natural world. A sense of place helps promote environmental behavior, associated moods, attitudes, and behavioral intentions (Brehm, Eisenhauer, & Stedman, 2013). Therefore, in this study, embodied cognitive theory (ECT) was conceptualized as the anticipated framework for developing the eco-STEM teaching model. Specifically, it includes three key elements: mind, body, and environment.

3. Methodology

To develop an innovative preschool eco-STEM teaching model tailored to preschool teachers' needs and validate its effectiveness, this study employs a mixed methods approach. The research was conducted through an exploratory sequential design, in which both qualitative and quantitative data were collected consecutively to fulfill the research questions (Creswell, 2014). The study collected qualitative data mainly through interviews, starting with semi-structured interviews with preschool teachers to explore their needs for implementing eco-STEM teaching practices. Based on this, focus group interviews were used to obtain the elements of the preschool eco-STEM teaching model. Regarding the quantitative research paradigm, the Fuzzy Delphi Method (FDM) was employed as an analytical tool for the decision-making process to achieve consensus on the elements of the preschool eco-STEM teaching model among a panel of experts.

3.1. Participants

The first group of participants in this study consists of 26 in-service preschool teachers, all from Fuyang Town Central Kindergarten in Chaozhou. The purpose of the interview is to explore preschool teachers' needs for implementing eco-STEM teaching practices. Therefore, the respondents were selected as in-service preschool teachers who have implemented eco-STEM for over one year. The specific information about the respondents is shown in Table 1.

Table 1. Profile of interview respondents.

Item	Category	Frequency	Percentage
Gender	Male	1	3.8%
	Female	25	96.2%
Title	Primary	8	30.8%
	Middle	15	57.7%
	High	3	11.5%
Work Experience	Less than 5 years	8	30.8%
	6-14 years	13	50%
	More than 15 years	5	19.2%
Academic qualification	Technical secondary	3	11.6%
	Junior college	14	53.8%
	Undergraduate college	8	30.8%
	Postgraduate	1	3.8%

The second group consisted of 7 senior preschool teachers. To introduce diverse practical experiences and perspectives, four were selected from Chaozhou Fuyang Town Central Kindergarten, the same kindergarten as the first group, while the other three were from two different institutions: Miande Kindergarten and Chaozhou Central Kindergarten. Since the purpose of the focus group discussions in this study was to explore the elements of the preschool eco-STEM teaching model, the have been identified as senior preschool teachers with at least 10 years of teaching experience. In detail, Table 2 presents the profiles of the 7 respondents in the focus group discussions.

Table 2. Profile of focus group respondents.

Code	Gender	Position	Years of experience	Expertise	Title
R1YW	Female	Research and development director	20	Nature-based education	Senior teacher
R2DT	Female	Research group leader	15	STEM education	First-level teacher
R3SL	Female	Deputy research group leader	18	Outdoor and Nature-based science	Senior teacher
R4JH	Female	Curriculum specialist	15	Science Assessment and Evaluation	Second-level teacher
R5XM	Female	Curriculum specialist	10	STEM education	First-level teacher
R6QM	Female	Curriculum specialist	12	STEM education	First-level teacher
R7MZ	Female	Curriculum specialist	11	STEM education	First-level teacher

As for the third group of participants, they are experts from various fields. Based on the criteria set for experts in the study, 30 experts were shortlisted for Principal of a public kindergarten, preschool education, and educational technology college, teachers specializing in STEM and the Nature field. Ultimately, 15 out of 30 experts responded positively, but four experts decided to withdraw. The experts were from Chaozhou Central Kindergarten, Chaozhou Miande Kindergarten, Zhejiang University, Chaozhou Normal Branch of Hanshan Normal University, and Anshan Normal University. Eleven experts participated in the online survey, comprising

three professors, six associate professors, and two PhD holders in their respective fields. The specific profiles are shown in Table 3.

Table 3. Expert Panels for the Delphi Technique.

Experts	Number	Code	Expertise
Professor Dr	3	E1PG	Early Childhood Nature-Based Education
		E2YG	Early Childhood STEM Education
		E3XJ	STEM Education
Associate Professor Dr	6	E4XH	Early Childhood Science Education
		E5JW	Outdoor and Nature-based science
		E6ZH	Early Childhood Science Education
		E7SY	STEM Education
		E8SL	Outdoor and Nature-based science
		E9SL	STEM Education
Dr	2	E10LY	Early Childhood Nature-Based Education
		E11CP	STEM Education
Total	11		

3.2. Instruments

The instruments in this study were an interview protocol for a semi-structured interview and focus group discussion among preschool teachers, and an FDM questionnaire developed from the themes that emerged from the analysis of the interviews with preschool teachers. The semi-structured interview focused on the challenges of implementing eco-STEM in preschool education. Additionally, the value of eco-STEM education for children was highlighted, with a total of four main questions. The interview protocol was reviewed by four preschool teachers with similar backgrounds to enhance the content reliability of the questions. The duration of each meeting was approximately 90 minutes. Another interview involved a focus group discussion, which, based on the semi-structured interview results, centered on a core theme: "What are the elements of the preschool eco-STEM teaching model?"

To ensure the effectiveness of the interviews, we individually selected 5 preschool teachers and 2 senior preschool teachers with similar characteristics for the pilot discussion. After the preliminary interviews, we invited the participants to provide feedback and suggest improvements for the interview process. During the entire interview process, the real names of all participants will not be revealed; instead, letters (A, B, C…L) will be used to refer to their responses.

The structure of the Delphi questionnaire in this study was determined based on focus group discussions regarding the preliminary prototype of the preschool eco-STEM teaching model. A 5-point Likert scale (5=strongly agree, 4=agree, 3=neutral, 2=disagree, and 1=strongly disagree) was used to measure responses. The purpose of the Delphi questionnaire is to evaluate the degree of importance of the preschool eco-STEM teaching model elements, which consist of four parts: Teaching Objectives, Learning Activities, Teaching Strategies, and Teaching Assessment. Before the formal study, two experts participated in a pre-test to provide feedback for improvement.

3.3. Data Analysis

After the discussion, the researcher meticulously transcribed the audio recordings from the 26 in-service preschool teachers and 7 senior preschool teachers, and organized detailed written documents in conjunction with on-site notes. Subsequently, these documents were transcribed and analyzed thematically to form the items of the FDM questionnaire.

The collected data in the FDM questionnaire on the consistency of each element of the model were analyzed using triangular fuzzy numbers and a defuzzification process. In the context of this research study, the linguistic Likert scale was converted to a fuzzy scale using triangular fuzzy numbers (Table 4). An accepted item should meet the following conditions in the fuzzy Delphi technique: triangular fuzzy numbers 1) Threshold value (d) $\leq$ 0.2; 2) Percentage of experts' consensus > 75%; 3) Fuzzy score (A) $\geq$ α – cut value = 0.5. The findings for each part are described in the following sections.

Table 4. Fuzzy scale used for this study.

Strongly disagree	1	(0.0,0.1,0.2)
Disagree	2	(0.0,0.2,0.4)
Partially agree	3	(0.2,0.4,0.6)
Agree	4	(0.4,0.6,0.8)
Strongly agree	5	(0.6,0.8,1.0)

4. Results

4.1. Results of Qualitative Analysis for the Elements of Preschool Eco-STEM Teaching Model

After analyzing the interview results, four themes were summarized regarding the need for eco-STEM teaching practice for preschool teachers: systematic requirements for teaching models, required competencies, exploration and practice needs, and exploration and practice needs. In fact, the majority of categories under the main themes are consistent with the previous literature (Çinar & Terzİ, 2021; Lee, 2017). Nevertheless, new findings include theme 1: 'Think outside the box of STEM pedagogy,' theme 2: 'Micro-innovation abilities,' theme 3: 'The need to interact with life systems in the natural environment,' and theme 4: 'The need to eliminate children's negative impressions of the environment.' Figure 1 presents the overall findings of this study regarding preschool teachers' needs for eco-STEM teaching practices.
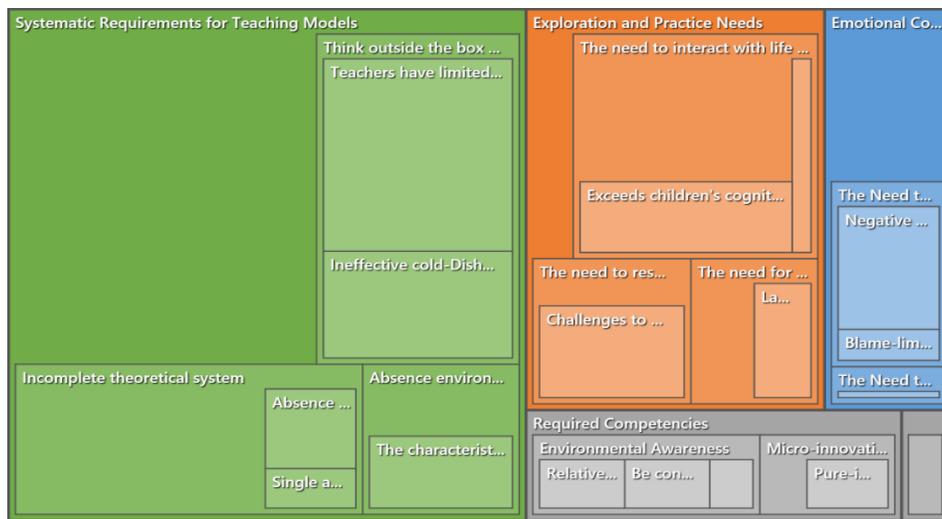
Figure 1. Rectangular tree structure diagram-nodes compared by quantity.

4.1.1. Teaching Objective

The interview results revealed preferences regarding teaching objectives. As a novel educational approach, eco-STEM education pursues two main objectives: one is to use STEM education as a means to understand environmental problems and, where feasible, to take action to mitigate these problems. Senior preschool teachers, based on the need findings regarding the required competencies, explicitly pointed out that "solving environmental problems obviously exceeds young children's cognitive capacity" (n=7), indicating that eco-STEM teaching objectives should be set in accordance with the cognitive levels of young children. In fact, addressing environmental problems not only involves providing technological fixes (Heberlein, 2012) but also emphasizes learning in the context of eco-STEM education, thereby aligning more closely with cognitive fixes that foster environmental behaviors and attitudes. Therefore, environmental awareness has been established as one of the teaching objectives of the preschool eco-STEM teaching model.

Another pursuit of eco-STEM teaching objectives is to utilize environmental education as a method to enhance STEM knowledge and skills. When determining teaching objectives, it is essential not only to consider the cultivation of environmental awareness at an ideological level but also to emphasize vital skills in STEM, with a particular focus on creative thinking (Sırakaya, Alsancak Sırakaya, & Korkmaz, 2020). According to other findings related to the required competencies, senior teachers reached a consensus that micro-innovation abilities should be established as another teaching objective for the preschool eco-STEM teaching model (n=6). In fact, it is difficult to create disruptive innovations and products for young children.

It is worth mentioning that during the discussion process, the respondents expressed the idea of incorporating the enhancement of STEM learning attitudes as a teaching objective for the preschool eco-STEM teaching model. Essentially, eco-STEM is merely an extension of STEM (Candan-Helvacı, 2022), yet it still falls under the umbrella of STEM education. The respondents (n=5) believed that for young children, STEM learning attitudes not only influence the quality of STEM education but also have a profound impact on their future career trajectories in STEM fields. Therefore, there was a consensus to identify STEM learning attitudes as another teaching objective for the preschool eco-STEM teaching model.

4.1.2. Learning Activities

According to the findings regarding exploration and practical needs, the majority of senior teachers (n=6) agree that perceptual trial experiences can fulfill the need for a close connection to children's daily lives. If young children are provided with more sensory experiences, they are more likely to be motivated to actively engage in eco-STEM learning. In fact, for young children, scientific knowledge possesses a "pre-scientific" nature, and their early STEM experiences should be hands-on (Andersson & Gullberg, 2014), as they require direct experiences to gain an understanding of the world around them, which in turn stimulates their motivation for active learning.

Furthermore, to support the needs of young children in understanding eco-STEM scientific concepts, the majority of senior teachers (n=5) suggested exploring and practicing through the dissection and reconstruction of finished products. They asserted that if young children do not break down completed products into simpler components, they may not fully grasp the components and functions of these concepts. It has been demonstrated that decomposition and reconstruction are the beginnings of children's engineering design thinking and are inherent to children's nature, particularly evident in their "destructive" dismantling of toys (Kewalramani, Palaiologou, & Dardanou, 2020).

To meet the exploratory and practical needs of young children in interacting with life systems in the natural environment, the majority of senior teachers (n=5) agreed that meaningful scientific experiences can facilitate this interaction in a nature-friendly manner. In fact, the natural environment offers tremendous learning potential (Utami, Rohman, & Islamiyah, 2020), particularly in developing their sensory skills. For young children, perception guides thought, and this perception is based on the experiences they acquire through their senses.

Additionally, participants (n=7) pointed out that meaningful scientific experiences can also fulfill the emotional connection needs of young children. Furthermore, such experiences can help eliminate any negative impressions children may have about the environment. They asserted that if children's exploration of nature is restricted throughout their childhood, it implies that they are not provided with a socially and emotionally enriched, as well as intellectually congruent, support system. This could lead to serious consequences regarding nature preservation, which would negatively affect all young children (Gunnar, 1996).

In addition to the interview findings regarding meaningful scientific experiences addressing the need for emotional connection, nearly all participants (n=6) believed that young children should engage in biomimicry to stimulate their motivation for environmental protection. They asserted that providing children with more

opportunities for biomimicry is likely to help them establish a deeper connection with the natural environment, particularly on an emotional level. In fact, when students are frequently exposed to natural environments and further use the natural world as a subject of learning, they are more likely to enhance and develop their awareness of environmental protection.

It is important to note that during the discussion, respondents supplemented the idea of "comparison and sharing" to enhance preschool eco-STEM learning activities. Respondents (n=6) believed that, essentially, eco-STEM is merely an extension of traditional STEM (Candan-Helvacı, 2022) and that it still needs to adhere to the fundamental principles of conventional STEM learning activities to promote continuous growth in a dynamic learning environment. Therefore, nearly all senior teachers agreed that integrating comparison and sharing into preschool eco-STEM learning activities is essential.

4.1.3. Teaching Strategies

The term "learning activities" merely defines the behaviors or tasks of young children during the learning process, and in order to ensure that learning activities can be carried out smoothly, teaching strategies are also needed to provide support within the instruction. Therefore, the results from the interviews indicate that the use of teaching strategies always aligns with the established teaching objectives. Senior teachers, based on the need findings regarding the required competencies, explicitly pointed out that storytelling should be utilized as a method to achieve the goal of fostering environmental awareness (n=6). In fact, storytelling can be considered an effective strategy across the curriculum, especially when raising young students' environmental awareness is an educational goal (Yannis & Gillian, 2017).

Another pursuit of the eco-STEM teaching objectives is the 'STEM learning attitude.' Game-based learning has a unique role in the implementation of STEM practice in kindergartens (Laranjeiro, 2021), and it is regarded as the foundation of STEM experiences during a child's learning process. As a result, senior preschool teachers have reached a consensus to incorporate gamified teaching as an instructional strategy within the preschool eco-STEM teaching model (n=6).

In addition to traditional teaching strategies, such as storytelling and game-based learning, reverse engineering pedagogy is also identified as an important theme. Senior teachers (n=5) emphasized, based on the need findings regarding the necessary competencies for "micro-innovation capabilities," that relying solely on traditional STEM teaching methods is insufficient. Instead, it is essential to think outside the box to achieve the expected effectiveness.

4.1.4. Teaching Assessment

The interview results showed that nearly all respondents (n=6) agreed that teaching assessments should closely align with existing teaching objectives, particularly in the area of the environment. Clearly, this is consistent with the findings regarding the needs of preschool teachers for implementing eco-STEM teaching practices. Teaching assessment serves as an effective means of evaluating the achievement of teaching goals. Therefore, this study will incorporate environmental awareness, micro-innovation abilities, and STEM learning attitudes as the key evaluation criteria.

Additionally, senior teachers pointed out that the content-level assessment focuses on specific implementation steps, and for the model, it is more important to apply various methodological approaches to meet this demand. Consequently, there is a consensus on the use of pre-assessment, formative assessment, and post-assessment as part of the teaching evaluation for the preschool eco-STEM teaching model. In fact, these three assessments will be integrated throughout the entire teaching activity to achieve a holistic evaluation of the students (Dong et al., 2023).

4.2. Results of Quantitative Analysis for the Elements of Preschool Eco-STEM Teaching Model

In this subsection, to present the experts' consensus on the elements of the teaching model more intuitively, this study has systematically organized these elements by coding and numbering them according to their sequence in the Expert Review Questionnaire. The Preliminary preschool eco-STEM teaching model includes: Teaching Objectives (TO), TO01: Environmental Awareness, TO02: Micro-innovation Abilities, TO03: STEM Learning Attitudes; Learning Activities (LA), LA01: Perceptual Trials, LA02: Dissection and Reconstruction, LA03: Meaningful Scientific Experiences, LA04: Determining Biomimetic Objects and Analysis, LA05: Design and Remanufacturing, LA06: Comparison and Sharing; Teaching Strategies (TS), TS01: Reverse Engineering Pedagogy, TS02: Narrative Storytelling Method, TS03: Game-Based Learning; and Teaching Assessment (TA), TA01: Pre-assessment, TA02: Formative Assessment, TA03: Post-assessment.

4.2.1. Expert Consensus on Teaching Objectives

The results from the first round, presented in Table 5, show that two out of the three items have reached an acceptable expert consensus above 75%, with a threshold value of less than 0.2. This indicates a strong agreement among the expert panel. The "Micro-innovation Abilities" item has a Fuzzy Score of 0.4545, which is less than 0.5, and the percentage for expert consensus is 72.73%, slightly below the 75% threshold. This suggests divergence among the experts regarding TO02. Therefore, this item should be rejected, while the other two items can be accepted for the teaching objectives.

Although TO02 was rejected, the scores are close to the levels of those that were accepted. In addition, the experts provided reasons for rejecting them and specific suggestions for modifications. Experts E2YG noted that even lowering the difficulty of teaching goals about creativity to micro-innovation skills would still put excessive pressure on young children. The final product created by the young children isn't as crucial as their specific performance in tasks. In other words, the teaching objectives should be positioned as performance objectives. Consequently, experts E2YG rejected TO02 but simultaneously suggested adjusting it to creativity self-efficacy. Then, a second round of the Delphi method was conducted; the results show that the fuzzy score for TO02 is 0.6727, which is greater than 0.5, and the proportion of expert consensus is 100.00%, significantly higher than 75%.

This indicates that the experts reached a consensus on the importance of the item. Therefore, this item should be accepted as a teaching objective.

4.2.2. Expert Consensus on Learning Activities

The learning activity elements are listed in Table 5. The results from the first round show that all six items have reached acceptable expert consensus above 75%, but TA04 has a Fuzzy score smaller than 0.5. In terms of effect size, the result does not demonstrate a solid consensus. Consequently, TA04, "Determining biomimetic objects and analysis," should be rejected, while the remaining five items can be accepted for the learning activities. In addition, the different rankings for each phase reveal that the researchers should prioritize the items that are ranked first. The ranking indicates that the learning activities that should be prioritized are "Meaningful scientific experiences." Only positive environmental experiences can enhance interest in engaging in eco-STEM activities (Haslip & Gullo, 2018).

Another rejected element, LA04, faced refusal due to two reasons. Experts E5JW highlighted the lengthy duration of the entire project-based activity cycle, considering the limited memory retention of young children. She suggested timely recording of their feelings through representation after meaningful scientific experience. In addition, experts E7SY stressed the varying difficulty for different young children in identifying biomimetic objects and analyzing. Teachers need to comprehend young children's thoughts through their representations to guide them in different levels of biomimetic creativity.

Although the experts did not explicitly articulate their specific suggestions for modifications, their feedback nonetheless prompts researchers to engage in further reflection. For young children, representation serves as a crucial intermediary step in the transition from perception to cognition (Anzieu-Premmereur, 2018), helping to establish a clearer observational point, thereby providing a foundation for their thinking. Consequently, in this study, LA04 "Determining biomimetic objects and analysis" has been revised to "Representation and Biomimicry." The results from the second round of the Delphi method show that the fuzzy score for LA04 is 0.5636, which is greater than 0.5, and the proportion of expert consensus is 90.91%, significantly higher than 75%. This indicates a strong consensus on this item among the expert panel. Therefore, "Representation and Biomimicry" should be accepted as a component for learning activities.

Table 5. Result of the consensus on model learning activities.

Indicator	Threshold value (d)	Percentage of experts' consensus, %	Fuzzy score (A)	Ranking	Expert consensus, %
LA01(Round1)	0.0893	90.91%	0.6364	10	Accepted
LA02(Round1)	0.0992	81.82%	0.6182	12	Accepted
LA03(Round1)	0.0926	100.00%	0.6727	4	Accepted
LA04(Round1)	0.0926	100.00%	0.4727	14	Rejected
LA05(Round1)	0.0661	90.91%	0.6182	13	Accepted
LA06(Round1)	0.0893	90.91%	0.6364	9	Accepted
LA04(Round2)	0.0893	90.91%	0.5636	15	Accepted

4.2.3. Expert consensus on Teaching Strategies

The next step is to develop teaching strategies for the model. The results of the expert consensus are shown in Table 6. It is clear from the table that all three items were accepted with a high percentage of experts' consensus. All content has a threshold value less than 0.2, and the fuzzy score value (A) is all more than 0.5. The ranking indicates that the most prioritized element is reverse engineering pedagogy; therefore, it is essential to move away from forward-looking project-based pedagogy and to think beyond the conventional boundaries of STEM pedagogy.

The next step is to develop teaching strategies for the model. As shown in Table 6, all three items have reached acceptable expert consensus above 75%. All three items achieved a high level of expert consensus, ranging from 90.91% to 100%. This reflects a high level of agreement among the experts. This strong consensus is further evidenced by low threshold values (all < 0.2) and high fuzzy scores (all > 0.5), which together indicate a high level of agreement from the experts. Among these, the ranking identifies reverse engineering pedagogy as the most prioritized element. Therefore, it is essential to move away from forward-looking project-based pedagogy and to think beyond the conventional boundaries of STEM pedagogy.

Table 6. Result of the consensus on model teaching strategies.

Indicator	Threshold value (d)	Percentage of experts' consensus, %	Fuzzy score (A)	Ranking	Expert consensus, %
TS01	0.1157	90.91%	0.6727	5	Accepted
TS02	0.119	90.91%	0.6909	2	Accepted
TS03	0.0331	100.00%	0.7818	1	Accepted

4.2.4. Expert consensus on Teaching Assessment

The teaching assessment for the preschool eco-STEM teaching model in the questionnaire consists of three items. The results in Table 7 show that all three items have met the conditions for expert consensus in the fuzzy Delphi method. Therefore, all the evaluations for the preschool eco-STEM teaching model can be accepted. Although TA03 ranks higher than TA01 and TA02, the fact that the expert consensus for all three items is 100% indicates that all three assessment methods are equally important, as they collectively form a comprehensive evaluation system, with each method playing an indispensable role.

Table 7. Result of the consensus on model teaching assessment.

Indicator	Threshold value (d)	Percentage of experts' consensus, %	Fuzzy score (A)	Ranking	Expert consensus, %
TA01	0.0926	100.00%	0.6727	6	Accepted
TA02	0.0793	100.00%	0.6545	7	Accepted
TA03	0.0992	100.00%	0.6909	3	Accepted

5. Discussion

5.1. Discussion on the Elements of Preschool Eco-STEM Teaching Model

5.1.1. Discussion on the Teaching Objectives of Preschool Eco-STEM Teaching Model

Based on the results of the focus group discussion regarding the teaching objectives of the preschool eco-STEM teaching model, all participants agreed that the primary objective should be environmental awareness. This finding aligns with Candan-Helvacı (2022), who emphasizes that their eco-STEM teaching practices incorporate behaviors that promote environmental awareness as key objectives. They argue that developing environmental awareness is fundamental to the eco-STEM approach, serving as a core pillar of its educational philosophy.

In the discussion regarding another teaching objective, "micro-innovation abilities," in this study, this objective is similar to that of eco-STEM applied activities, such as the conservation of the White Crane (Lee, 2017), soil heavy metal pollution remediation (Zheng, 2020), and air pollution fine dust. Creativity is considered a key teaching objective and an essential process of eco-STEM (Sánchez, Torres, & Díaz, 2022). For the age limitations of young children, positioning innovation ability at the micro-innovation level aligns more closely with the developmental patterns of younger learners (Zhang, Fu, & Xing, 2024). As Vygotsky (2004) stated, these are also small creative endeavors.

However, the experts disagreed with the 'micro-innovation ability' of the teaching objectives. The reasonable justification for the deletion was age restrictions, as there is a certain gap between the potential creative abilities of young children and their actual performance (Haase, Hoff, Hanel, & Innes-Ker, 2018). Studies with young children as participants have shown a positive correlation between belief in oneself (self-efficacy) and creativity (Haase et al., 2018; Jaussi & Randel, 2014). Therefore, experts suggest measuring the other side of creativity by observing what young children attempt to accomplish, how they attempt it, and how much energy they spend on the process. Additionally, considering that the development of the teaching model in this study is framed by the concept of embodied cognitive theory (ECT), creative self-efficacy, as a form of awareness, can respond more concretely to embodied cognitive theory. This truly demonstrates the significant characteristics of the preschool eco-STEM teaching model.

Based on the consensus among senior preschool teachers regarding the previously mentioned environmental awareness and micro-innovation abilities, the participants further discussed and supplemented the inclusion of STEM learning attitudes as a teaching objective within the model of this study. Moreover, this result is consistent with the research conducted by Birney et al. (2018) on eco-STEM practices. In fact, it has been shown that a positive STEM learning attitude can drive students to engage in STEM learning (Sun, Hu, Yang, Zhou, & Wang, 2021).

5.1.2. Discussion on the Learning Activities of Preschool Eco-STEM Teaching Model

The results of the focus group discussion with senior preschool teachers highlighted the elements of the preschool eco-STEM teaching model. They all agreed that the learning activities should be set as "Perceptual Trials" and "Dissection and Reconstruction." This finding is consistent with the nature of children (Alotaibi, 2023) Children generate intuitive concepts during trials and disassembly, and then gradually transfer scientific concepts, which reduces their cognitive load to a certain extent (Zhong & Liu, 2021). What's more, product disassembly also provided a wealth of ideas for product redesign (Rohmer & Rodriguez, 2017). In the environmental water clock eco-STEM activity, the children's dialogue demonstrated their understanding of the principles of simple energy conversion: "Child A: Look, it's turning! Child B: That's right! We need to keep the water flowing so the water clock keeps turning. Child A: If we add more water, will the time turn faster? Child B: It should! I think the more water flows, the faster the water wheel turns." From this dialogue, it is clear that the environmental changes (fast rotation) caused by the physical action (adding water) prompted them to grasp the causal relationship between water and kinetic energy, which confirms the core idea of embodied cognition.

In addition, the focus group discussions also mentioned two other important learning activities: meaningful scientific experiences and biomimetics. These findings align with the essence of eco-STEM education (Koculu & Girgin, 2022), which involves integrating the natural world into young children's self-awareness in a meaningful way through scientific experiences and biomimetics. It has been demonstrated that when the natural world is described as an extension of self-awareness, environmental damage can be avoided, as it would be perceived as self-destruction (Roszak, 2001). In the energy-saving fans eco-STEM activity, a child said: "The weather is too hot, the elephant needs to play in the water here, or it will get sick." From this dialogue, it is clear that through physical action (drawing), the children internalized the environmental information they observed (elephant playing in water), thereby transforming the abstract concept of "animal protection" into a tangible understanding of animals' specific needs.

However, experts suggested adjusting the phrase "determine bionic objects and analyze" to "representation and bionics." The rationale for this adjustment is that, to respond to the "Mind" element in ECT theory and achieve teaching objectives, young children's natural experiences cannot remain solely at the level of perception but need to be internalized through thought. In fact, representation is the link from perception to thinking (Alston, 2005). In other words, young children can only generate thought and form cognition through representational activities based on perception.

Apart from this, after the stimulation of natural exploration stops, the images that young children retain in their brains are the main basis for their memories. Given the unique nature of the participants in this study, young children's memory capacity is limited, and the accuracy of their memories is also relatively low (Reynolds,

Nileksela, Gignac, & Sevillano, 2022). Taking this into account, it is necessary to use representation to stimulate the visualization memory in the minds of young children from the natural world. This is also another important reason why experts recommended adding 'representation' to 'determining and analyzing bionic objects'.

As for the supplemented learning activities of this research model, "Comparison and Sharing," this finding aligns with several teaching models, including the "Four-Stage Six-Step Model" (Xu, 2020), and the preschool STEM teaching model based on intelligent toys (Yang, 2021), the STEAM Maker course (SML) teaching model (Bertrand & Namukasa, 2023), and the Knowledge-Based Life Problem Model (BTHP) (Çorlu & Çallı, 2017). Caldwell et al. (2018) who noted that a project is generally regarded as successful when students recognize what they have accomplished and share it with others. It has been demonstrated that this step may be the most effective aspect of eco-STEM projects.

5.1.3. Discussion on the Teaching Strategies of the Preschool Eco-STEM Teaching Model

The findings from the focus group discussions on teaching strategies are consistent with the existing eco-STEM applied activities. In creating eco-villages from recyclable materials, Lee (2017) incorporates the Narrative Storytelling Method and Game-Based Learning as key teaching strategies in eco-STEM practice. It has been proven that conducting STEM activities in the form of stories and games can enhance young learners' creativity (Morris, 2015), environmental awareness (Yannis & Gillian, 2017), and STEM comprehension (Asrifan & Darwis, 2024). More importantly, storytelling and games have a unique role in early childhood STEM (Laranjeiro, 2021).

In addition, the supplemented teaching strategies "Reverse Engineering Pedagogy" align with the robotics education practices research conducted by Zhong, Li, and Wang (2020). Previous studies have confirmed the teaching advantages of reverse engineering pedagogy in engineering education disciplines, and the applicability of this method in STEM education, as a typical engineering education curriculum, is undoubtedly warranted (Kang & Zhong, 2020).

5.1.4. Discussion on the Teaching Assessment of Preschool Eco-STEM Teaching Model

The model elements for teaching assessment highlighted in the focus group discussion, such as "Pre-assessment, Formative Assessment, Post-assessment," are crucial components in educational evaluation. Our findings are consistent with existing energy (Meiliasari et al., 2024) and natural fence tea gardens (Wahyuni et al., 2022), with a particular emphasis on assessing students' changes in values, attitudes, skills, and knowledge throughout the entire learning process. In fact, it appears that eco-STEM has made significant progress in terms of teaching strategies and assessment methods. In alignment with this, the model for the identity recognition process must keep pace (Reigeluth & An, 2020).

Based on the above discussion, we have developed an integrated preschool eco-STEM teaching model (see Figure 2). This model effectively responds to the integration of the embodied cognition framework. Specifically, "Representation and Bionics" and "Comparison and Sharing" serve as higher-order "mind" processes that do not occur in a vacuum but are stimulated by the "body's" deep interaction with the "environment." Young children explore the material environment through the body, such as "Perceptual Experimentation," "Dissection and Reconstruction," and "Design and Remanufacturing." All these bodily actions are precisely embedded within the meticulously designed "environment" of "Meaningful Scientific Experience." Thus, this model clearly demonstrates that learners' cognition is ultimately an emergent result of the interaction between mind, body, and environment.
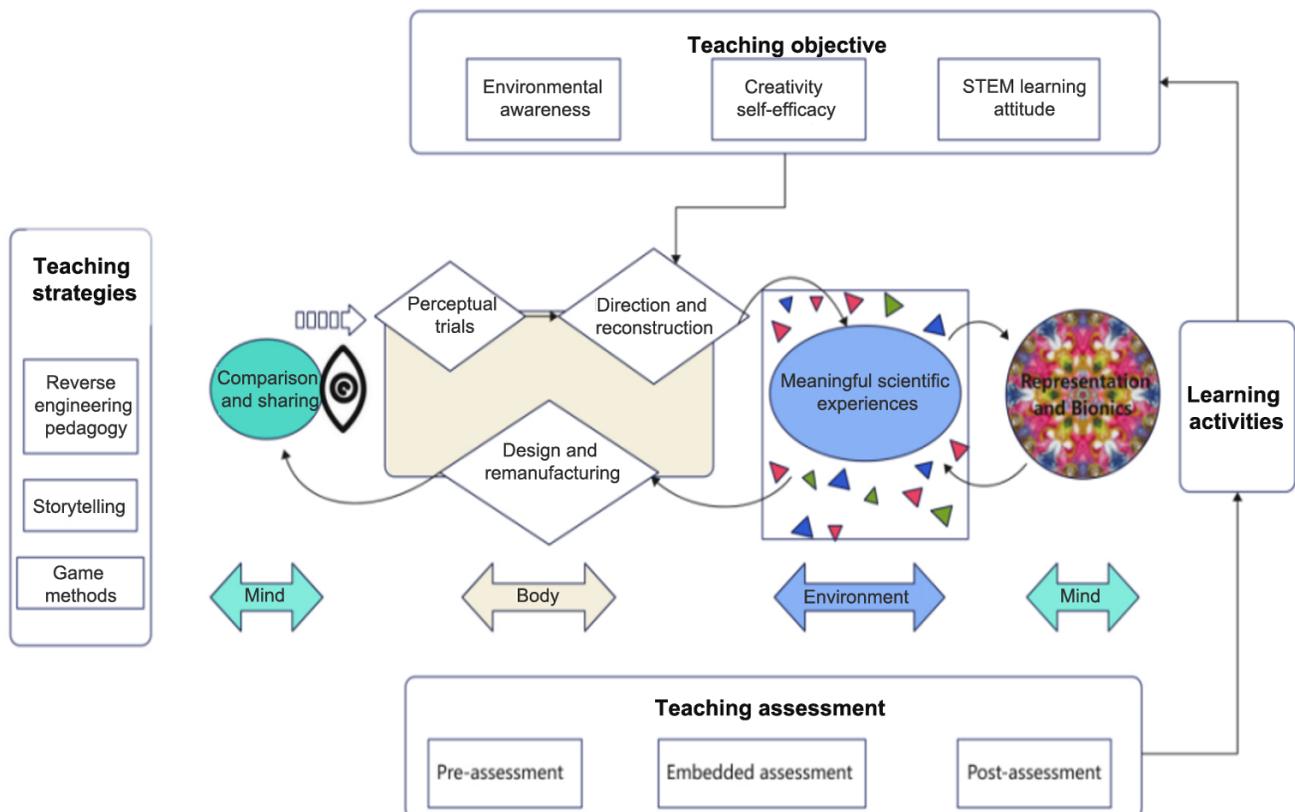

Figure 2. The preschool Eco-STEM teaching model based on embodied cognition theory.

6. Implication

We advance eco-STEM pedagogy through several contributions. First, the innovative preschool eco-STEM teaching model is based on the theoretical framework of embodied cognition, clarifies the direction in cultivating

young children's environmental awareness, and fills the research gap regarding the unique characteristics of preschool eco-STEM education.

Second, this study breaks away from the limitation of most previous eco-STEM studies, which only focus on the learning activities. In the process of model development, we started with the needs of preschool teachers for implementing eco-STEM teaching practices. After forming a preliminary model, experts reached a consensus on the newly developed model. This study always adhered to a systematic approach of inductive modeling. This approach, which is more in line with the multicultural background, has made an important contribution to promoting the localization of eco-STEM in China.

Third, this study breaks away from the existing eco-STEM practices that concentrate solely on technological fixes to solve environmental problems. Instead, it encourages young children to reconnect with natural environment living systems and conduct bionic creative design. This new perspective through cognitive fix provides rich theoretical and practical references for teachers and curriculum designers in eco-STEM education.

Although the findings of the study offer many benefits for educational research, this research has some inherent limitations, most notably in model validation, which is currently limited to Chinese educational experts due to regional and resource constraints. While the model is theoretically aligned with embodied cognition, additional neurocognitive evidence is required to clarify how specific body-environment interactions influence STEM learning effectiveness. Beyond multisite validation, the model's theoretical alignment with embodied cognition, though conceptually coherent, requires further neurocognitive substantiation to elucidate how specific bodily-environmental interactions mediate STEM learning outcomes. Future research should prioritize multisite trials across diverse cultural contexts, coupled with mixed-methods analyses of both cognitive-behavioral outcomes and embodied learning mechanisms.

7. Conclusion

This study aimed to develop a preschool eco-STEM teaching model centered on environmental awareness. The results showed that the model includes 15 elements that reveal the cognitive relationship between learners and the environment. The analysis revealed two major findings: First, the needs of eco-STEM teaching practices include four themes: Systematic Requirements for Teaching Models, Required Competencies, Exploration and Practice Needs, and Emotional Connection Needs. Second, the preschool ecological STEM teaching model includes teaching objectives such as Environmental Awareness, Creativity Self-Efficacy, and STEM learning attitudes; learning activities such as Perceptual Trials, Dissection and Reconstruction, Meaningful Scientific Experiences, Design and Remanufacturing, Comparison and Sharing; teaching strategies such as Reverse Engineering Pedagogy, Narrative Storytelling Method, and Game-Based Learning; and teaching assessments such as Pre-assessment, Formative Assessment, and Post-assessment.

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