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Research Article

AI-Powered Approaches for Sustainable Environmental Education in the Digital Age: A Study of Chongqing International Kindergarten

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Abstract

The integration of technology into education has garnered significant interest, particularly in its potential to support environmental sustainability. This exploratory research investigates the role of artificial intelligence (AI) in early childhood education, with a focus on its implementation at Chongqing International Kindergarten to teach sustainability concepts. Guided by Mezirow's Theory of Transformative Learning and Goleman's concept of Ecological Intelligence, the study explores how AI-powered tools—including virtual ecosystems, real-time feedback systems, and eco-conscious behavior tracking mechanisms—enhance critical reflection, foster ecological intelligence, and promote environmentally responsible behaviors among young learners. A qualitative case study approach was employed, incorporating classroom observations, educator interviews, and pre-and post-assessments to evaluate engagement, environmental awareness, and behavioral changes. The findings reveal that AI tools significantly enhance environmental literacy, helping children understand the consequences of their actions and encouraging them to adopt sustainable practices. Interactive and personalized learning experiences AI provides stimulate critical thinking, transform sustainability-related values, and foster a deeper understanding of ecological interconnections. Students demonstrated improved awareness of sustainability concepts, such as resource conservation and biodiversity, alongside increased engagement in eco-friendly behaviors, including recycling and energy conservation. This research highlights the transformative potential of AI in early education, demonstrating its capacity to influence children's attitudes and behaviors toward environmental responsibility. Integrating AI-driven educational tools into sustainability curricula is crucial for cultivating a generation capable of making informed environmental decisions. The study concludes by recommending further exploration of AI's role in early education to optimize its impact on fostering long-term ecological intelligence and transformative learning.

Keywords: Artificial intelligence (AI); Environmental Awareness; Ecological Intelligence; Transformative Learning; Virtual Environments.

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1. INTRODUCTION

In AI technologies, adaptive learning systems, virtual environments, and real-time feedback mechanisms present outstanding opportunities to fuel increased student engagement, knowledge retention, and problem-solving [1]–[3]. Due to the robustness of these advancements, they are particularly pertinent for environmental education, especially where AI can help spur sustainability practices through interactive and engaging learning experiences. With the help of AI tools, educators will use them to create lessons adjusted to the needs of individual students to provide them with special knowledge of complex sustainability problems and the ability to make educated choices regarding environmental protection [4]–[7].

The potential for AI in environmental education extends beyond the confines of traditional schoolrooms. With AI simulations, virtual ecosystems, and real-time data analysis, abstract concepts of the environment can be tactile by students engaging in hands-on learning whilst being informed of the planet's long-term consequences of their actions [8], [9]. As a result, AI can provide real-time feedback, driving more dynamic and experiential learning that involves students trying different solutions to sustainability problems [10].

Future generations will need handicrafts, which will now form an important part of environmental education in tackling the global challenges of climate change, resource depletion, and biodiversity loss [11]. As these issues become increasingly urgent, there is also a growing demand from the educational system to equip students with the knowledge, skills, and mindset necessary to live sustainably. The relation between education and the shaping of environmental attitudes and behavior is important in the environmental education literature and one important factor in promoting environmental sustainability globally [12], [13].

Environmental education provides young learners with an understanding of ecological systems, human impacts on the environment and the necessity for responsible resource management [14]. Introducing sustainability concepts to children early is important because this is a critical period in early childhood when children's fundamental beliefs and values are formed. Moreover, integrating sustainability into school curricula also imparts a sense of environmental responsibility among students while involving them in proactive behaviors, including waste reduction and energy conservation [15].

AI technologies are being integrated into educational environments to enhance environmental education through personalized learning experiences and various means for students to explore sustainability concepts. Virtual ecosystems, gamified learning platforms, and sustainability simulations are tools with AI power to build immersive and interactive environments in which students can experiment with multiple environmental scenarios and learn what they can do in each situation [16]. These tools provide students with tools to visualize complex environmental systems, provide real-time feedback, and encourage thinking and decision-making critically about sustainability [17].

In early childhood education, AI tools are used to make educational experiences about environmental sustainability more engaging for young children. For instance, children can play AI-based games and virtual simulations to interact with digital ecosystems and figure out how to manage resources, conserve, and pollute in a controlled yet dynamic virtual environment [18]. They deliver a personalized learning experience that matches every child's pace and style, keeping them interested and actively engaged with the content.

AI tools, such as digital assistants, are being utilized in Chongqing International Kindergarten to teach environmental education in innovative and engaging ways. For example, AI-driven virtual ecosystems enable children to understand the value of their actions, such as reducing waste, conserving water at the tap, or turning off lights when leaving a room. Children can experiment with varied actions and verify how those actions affect a virtual environment with these tools [19], [20]. Such AI tools are integrated into the kindergarten curriculum so that from an early age, the kindergarten helps to develop eco-conscious behaviors, teaches children the importance of sustainability, and gives them skills to make environmentally responsible decisions [21]–[24]. Integrating AI technologies with environmental education offers new and innovative ways to engage young learners with sustainability concepts in an intriguing and captivating manner. These AI-driven tools make learning more interactive and personalized, enabling children to gain a better understanding of how their actions impact the environment and, in turn, encourage sustainable practices.

1.1. Problem Statement & Research Questions

Although there is an increasing awareness of environmental education in addressing global sustainability challenges, the specific role of AI-powered tools in promoting sustainability education, especially at the early childhood level, has not received adequate research focus. However, AI has been successfully integrated into higher education and adult learning environments, and its application in early childhood education to promote sustainable behaviors has been underexplored [18]. Environmental values and attitudes are best cultivated during early childhood. Nonetheless, AI has the potential to contribute to this process via interactive and personalized learning tools, and the evidence for this in academic literature remains sparse.

In addition, with the growing number of education systems worldwide adopting digital tools for their buildings, the inclusion of AI in environmental education at such an early stage presents unique challenges and opportunities. There is very little research on how AI technologies can engage young learners in sustainability education (learning about resource conservation, biodiversity and waste management). This research gap is necessary to explore how AI can help build ecological intelligence and sustainable behaviors in young children, especially in early learning environments such as Chongqing International Kindergarten.

These inquiries aim to explore how AI tools can be effectively integrated into sustainability education to promote meaningful engagement, inspire proactive behaviors, and foster a deeper understanding of environmental issues. Specifically, this study aims to address the following key questions:

(1) How do AI tools contribute to transformative learning in sustainability education?
(2) What makes AI tools help build ecological intelligence in early learners?
(3) How does learning AI change students' environmental awareness and behaviors?

1.2. Significance of the Study

This paper aims to explore how AI can be applied to learning environments and activities related to environmental consciousness in early years education. Focusing on the presented case of Chongqing International Kindergarten, the

research analyses how these technologies can facilitate students' understanding of sustainable concepts and foster their sustainable behaviors. The study is significant in three key ways: First, it contributes to the development of AI-based interventions for the early years, which are understudied compared to secondary and tertiary education; second, it serves as an informative guideline for educators, administrators, and policymakers to design AI-enhanced early years learning for sustainability; third and finally, it supports how AI can positively influence young learners to practice sustainability while learning key content. Altogether, this research can be deemed as filling the gap between technology education and a valuable outcome, such as the development of generations who will be more conscious of the Earth's sustainable use.

2. LITERATURE REVIEW

2.1. AI in Education: Overview and Trends

2.1.1. Evolution of AI in Education

Over the last few decades, artificial intelligence (AI) has been enhancing education by evolving from basic automation of administrative tasks to complex applications that can truly transform teaching and learning. Initially, AI was applied to education through automated grading systems and administrative management applications [25]–[28]. The application has recently progressed to include other functions, such as personalized learning systems. With machine learning algorithms, machine learning algorithms, natural language processing (NLP) and adaptive learning platforms, it is possible to develop these systems that can personalize educational content according to individual learners' needs, strengths, and weaknesses [29]–[31].

Furthermore, AI-powered simulations and virtual environments facilitate students' engagement with topics that were either previously impossible or too complex to address with traditional methods. Using computers, these tools create immersive, interactive experiences that let students conduct experiments within virtual ecosystems in real-time to solve problems. There has been a surge of intelligent tutoring systems (ITS), which offer real-time feedback to students and, therefore, invite autonomous learning [32]–[35].

2.1.2. Emerging Trends in AI-Powered Environmental Education Tools for Sustainability

Artificial intelligence (AI) is becoming an indispensable tool in environmental education, promoting sustainability. Increasingly, AI-driven platforms and applications are being utilized to promote environmental awareness and encourage sustainable behavior. Students can experiment with ecological concepts, such as carbon footprints, water cycles, or energy usage, and tools like virtual simulations provide their application in a risk-free, interactive environment.

Moreover, AI-based applications such as smart educational games or eco-friendly virtual assistants can juggle the tasks of engaging students in sustainability issues through personalized and engaging learning [36]. These systems can adjust for the level of complexity as the learner progresses and offer real-time feedback on sustainable behaviors. Other emerging AI technologies include tools that monitor environmental data for energy use and waste management and present personalized options for reducing environmental impact. Moreover, with these tools, sustainability education is stimulated as much as creating a sense of belonging, responsibility, and action in response to issues at a young age [37], [38].

2.2. Theories Relevant to AI in Environmental Education

2.2.1. Mezirow's Theory of Transformative Learning

Based on the theory of transformative learning developed by Jack Mezirow [39], critical reflection, perspective transformation, and behavioral change are of major importance for adult learning. Applying this theory to sustainability education suggests that it can motivate learners to critically examine their assumptions and beliefs about the environment and their role within it.

The core principles of Transformative Learning provide a robust framework for advancing sustainability education. Critical reflection encourages learners to examine their beliefs about environmental impact, sustainability practices, and their relationship with ecological systems, prompting them to question and evaluate their assumptions. Through this process, learners transform their perspective, shifting from a narrow, individualistic view to a broader, ecocentric perspective that emphasizes interconnectedness and collective responsibility. Ultimately, this leads to behavioral change as learners translate their new understanding into informed actions that align with sustainable practices.

In sustainability education, these principles are put into practical application through AI-powered tools that create interactive and immersive learning experiences. These technologies challenge learners' existing views by employing AI-driven scenarios, real-time simulations, and personalized feedback, prompting them to think critically about their environmental behaviors. These tools enable students to explore sustainability from multiple angles, fostering a deeper understanding of ecological systems and equipping them with the skills and insights needed to contribute to a more sustainable future.

2.2.2. Ecological Intelligence Theory

According to the theory of ecological intelligence by Daniel Goleman [4] ecological intelligence is defined as the ability to comprehend the correlations between human activities and the ecological systems in which they are situated. It is about understanding how individual behavior, collective practice, and societal structures impact the environment and taking actions that support a healthy planet in the long run. Ecological intelligence refers to the ability to make well-informed decisions concerning resource use, energy consumption, waste management and environmental stewardship.

Embodied learning experiences made possible by AI technologies help expose students to real-world

environmental challenges, such as climate change, deforestation, and pollution, leading to the development of ecological intelligence. By being driven by AI platforms, it can also simulate and experiment with environmental systems to observe the consequences of students' actions or the results in a simulated and controlled space. These experiences lead to a more comprehensive understanding of the causes and effects of human activities on environmental outcomes.

2.2.3. Integration of Both Theories in an AI-Powered Education Model

Transformative Learning Theory and Ecological Intelligence Theory work together effectively in AI-powered sustainability education, each contributing unique strengths. Transformative Learning drives students to reflect critically and shift their perspectives, leading to meaningful behavioral changes. At the same time, Ecological Intelligence helps students understand the complex relationships between human actions and ecological systems. By integrating these approaches, AI tools actively engage students in understanding their environmental impact and adopting sustainable practices, fostering individual transformation and a heightened sense of ecological responsibility.

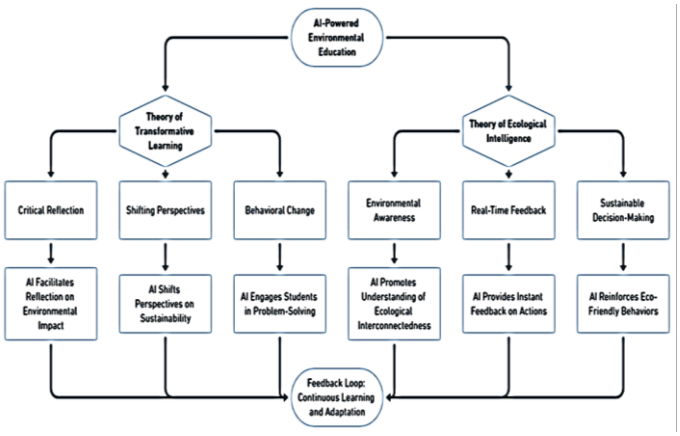

Figure 1. Conceptual Framework for AI-Powered Environmental Education

As shown in Figure 1, these theories create a comprehensive framework for AI-driven sustainability education. Transformative Learning can help students reflect on their environmental behaviors and shift their perspectives. At the same time, Ecological Intelligence provides the content and context for understanding the long-term consequences of those behaviors. By integrating both theories, AI tools can foster critical thinking, empathy, and actionable knowledge that empowers students to act sustainably.

2.3. Sustainability Education with AI

2.3.1. Current Applications of AI in Teaching Environmental Sustainability

AI is integrated into sustainability education to engage students with real-world environmental challenges. Students use AI-enabled tools to interact with environmental data to enhance their understanding of sustainability issues like climate change, conservation of resources, waste management and biodiversity preservation.

AI technologies in adaptive learning systems customize learning for individual learners, adjusting the content and difficulty level according to learners' progression and needs. They are implemented in the context of sustainability education. They can direct students through material on energy conservation, ecosystem services, or sustainable agriculture in a manner that is dynamic and tailored to them [40], [41].

Learners can experiment with environmental scenarios and observe the consequences of decisions using virtual ecosystems and environmental simulation software. For instance, AI software helps students model the effects of different farming techniques on biodiversity or different policies on climate change [42], [43].

Platforms based on AI systems were designed for students to make environmentally conscious decisions. Through real-time feedback and suggestions, these AI tools highlight the environmental impacts of choices. For example, AI-based apps can monitor individual water or energy consumption and provide tips to reduce it by leveraging the learner's habits [44].

AI tools can dramatically increase student engagement and learning outcomes in environmental sustainability studies. These tools enable teachers to deliver lessons in an interactive, immersive, and personalized manner, allowing learners to engage with content and practice real-world environmental problem-solving. AI-driven learning environments are more effective than traditional learning environments in fostering active participation, critical thinking, and long-term retention of knowledge (and change of behavior) in sustainability [45].

2.3.1. Case Studies of AI-powered Tools in Sustainability Education

Interest in using AI to teach sustainability to the young is growing. AI-powered applications are developing ideas for recycling, saving energy, and promoting environmental friendliness, teaching children through fun games, virtual characters, and eco-friendly simulations. For instance, certain programs feature chatbots that mimic scenarios that are relevant to the real world and provoke children to make environmentally sustainable decisions [46].

An illustration of how AI can help translate abstract sustainability concepts for young learners is provided by a case study on the implementation of AI in teaching environmental education at the Chongqing International Kindergarten. Virtual assistants powered by AI take children through environmental teaching, such as the water cycle or renewable energy sources. As children interact with these AI tools, they learn about sustainability while honing critical thinking and problem-solving skills vital for future environmental efforts.

Schools and universities are adopting AI-powered platforms to deliver sustainability education in more sophisticated ways. Take, for instance, the use of AI-powered simulations in environmental science classes at the University

of California to model climate change and resource management. Students can then use the simulations to test how different policies or actions affect global ecosystems. AI-based learning management systems tailor sustainable practice recommendations to students according to their interactions with course content [47].

AI applications in primary and secondary schools also cultivate a sense of sustainability by simulating environmental issues, such as pollution or deforestation. Besides promoting problem-solving for students, these tools encourage environmental stewardship by offering stakeholders actionable knowledge on reducing carbon footprints and waste production [48].

2.4. Gaps in the Literature

Although more research on AI in education is being published, several gaps still exist, including those related to the environmental education of young children using AI. These gaps suggest the need for further specialized studies and the incorporation of educational theories that can position AI for defensive teaching and sustainability.

2.4.1. Few Studies in AI for Environmental Education of Young Children.

Although considerable research has been conducted on AI in education for older students and adults, there is a notable lack of research on utilizing AI in early childhood environmental education. AI-driven education studies usually focus on mathematics, reading, and STEM (science, technology, engineering, and mathematics) [49], [50]. However, the latter is a relatively new and underdeveloped area of investigation in environmental education for young learners, particularly with the advent of AI technologies.

Additionally, the literature should investigate how AI tools can be designed for the developmental needs of young children (cognitive development, language acquisition, social learning) in an age-appropriate manner that promotes sustainability [51]. More research is needed to investigate how AI technologies can foster an emotional connection in early learners to environmental issues and promote lifelong behavioral changes toward environmental sustainability.

2.4.2. Need for Integrating Transformative Learning and Ecological Intelligence

Integrating established educational theories such as transformative learning and ecological intelligence is much needed to develop AI-driven environmental educational learning tools. Although AI offers the possibility to assist students' sustainability learning, the power of AI to promote perspective transformation Mezirow [39] and the development of ecological intelligence Goleman [4] have not yet been systematically researched.

Drawing on these theories, we propose that AI learning tools can be designed within a more comprehensive framework to promote sustainability. For example, transformative learning principles can serve as guidance for developing AI systems that foster critical reflection on personal environmental behaviors. AI systems, such as those that utilize ecological intelligence, can help indicate how interconnected individual behaviors are with the global ecological systems. The literature has not fully addressed how these theories can be applied to the development and implementation of AI tools for environmental education.

This current status of existing AI applications in environmental sustainability education. It discusses existing case studies from early childhood schools and universities where AI tools have proven effective and promising in teaching sustainability. Significant gaps in the literature have also been identified, and recommendations for future research on AI in early childhood education, as well as for developing transformative learning and ecological intelligence theories into AI-based environmental education frameworks, have been offered.

3. MATERIAL & METHODS

3.1. Research Design

The problem under investigation employs a qualitative case study research design to assess the use of AI-powered tools in sustainability education at Chongqing International Kindergarten. The case study approach is best suited for exploring complex educational phenomena in real-world settings. It enables a more in-depth examination of how AI technologies influence environmental education in this context. However, in this study, we focus on a single case, aiming to uncover rich, contextual insights that will aid future applications of AI in sustainability education, particularly for young learners.

The study examines how AI-based educational tools, such as virtual simulations, interactive games, and eco-conscious habit tracking, are utilized to educate children about sustainability. With this, we aim to assess the impact of these tools on students' environmental awareness, critical thinking, and sustainable behavior.

3.2. Location of Study

Located in Chongqing, China, Chongqing International Kindergarten has pioneered an educational environment that integrates AI-powered tools into its curriculum, specifically designed to help students learn about sustainability. Using AI in a kindergarten helps experiment with how it impacts early childhood education by presenting personalized learning experiences that nurture ecological intelligence during a child's early learning years.

Virtual simulations are one of the AI tools used in this class's educational setting. Students can interact with environmental issues such as resource conservation, pollution and energy use in a controlled virtual world. Using these simulations, students can gain experience interacting with environmental problems and witness the direct consequences of their actions. Interactive games are also designed to get children to practice sustainable behaviors like sorting trash, conserving water and decreasing energy consumption. Comprehensive information concerning eco-conscious

behavior tracking technologies is another approach. This technology monitors students' daily environmental actions and offers real-time feedback about the real-world implications of those actions. These AI-based tools will be integrated into the curriculum to foster a deep sense of environmental responsibility from kindergarten.

3.3. Participant Demographic

A detailed participant demographic table will be presented to provide a comprehensive understanding of the study's context. This table will include essential information such as age, gender, educational background, teaching experience (for teachers), and level of study (for students). By providing a clear representation of the participants' profiles, the table will enhance the interpretability of the findings and enable a more in-depth analysis of how various demographic factors may impact the study outcomes.

This demographic data will contribute to better transparency and replicability, enabling future researchers to understand the diversity and representativeness of the sample. This understanding is particularly critical in determining the applicability of the findings across different settings and populations. By including demographic details, the study ensures that readers can access valuable background information that supports nuanced discussions about the results and their implications [52].

Table 1. Participant Demographics and Role in the Study

Participant Group	Participants	Key Demographics	Role in Study
Students (Primary Focus)	3	Age: 4-6 years, mixed gender, diverse cultural backgrounds	Observed for engagement, learning outcomes, and behavioral change
Teachers	5	Experienced in environmental education, trained in using AI tools	Interviewed to gather insights on AI tool implementation and impact
AI Tools	-	AI-powered virtual simulations, interactive games, eco-behavior tracking systems	Used as a central part of the study's educational intervention

This study employed purposive sampling to ensure the selected participants possessed characteristics directly relevant to the research objectives. Children aged 4–6 years were chosen as the primary focus because they are at a critical stage of cognitive and social development. Their diverse cultural backgrounds were considered to explore the impact of technology on a heterogeneous group. Teachers were selected based on their expertise in environmental education and their training in utilizing artificial intelligence (AI) tools, enabling them to provide detailed insights into the implementation and effectiveness of these technologies.

AI-based tools, including interactive virtual simulations, educational games, and eco-friendly behavior tracking systems, were deliberately selected to maximize their impact on student engagement and to facilitate precise measurement of behavioral changes. This approach ensured the collection of highly relevant data, supporting the study's research objectives.

3.4. Data Collection

Various data collection methods were employed to comprehensively evaluate the impact of AI-powered tools on disseminating sustainability principles at Chongqing International Kindergarten. Various strategies were developed to collect data on dimensions of the learning experience, such as engagement, behavior change and educational outcomes. Classroom observations, Interviews with the educators and student assessment were among the methods adopted.

Classroom observations were conducted to document interactions between students and AI-powered tools. Using AI tools, observers focused on engagement, behaviors, and how students soaked sustainability concepts. One specific focus was on how AI tools promoted students' critical thinking or behavioral changes, such as students changing their behavior, for example, taking more sustainable actions like recycling, after receiving feedback from AI systems. The objective was to identify how AI tools promoted reflective learning experiences that prompted behavioral changes toward sustainability goals.

Educators were semi-structured to understand why AI tools were used in teaching sustainability. The interviews focused on the teachers' educational goals, the implementation strategies they employed, and the challenges they encountered when integrating AI tools into the curriculum. The interviews also examined students' perceptions of the impact of AI tools on their learning outcomes and, more broadly, offered context regarding how AI-supported methods enhanced sustainability education in early childhood classrooms.

Pre- and post-assessments were given to evaluate the impact of AI tools on students' environmental awareness and sustainable behaviors. The assessments aimed to measure changes in students' knowledge of key environmental concepts and their ability to apply this knowledge in solving real-world environmental problems. The pre-mental test assessed students' knowledge before the AI-powered sustainability education; the post-mental test measured any improvement students have gained in their understanding and behavior after AI intervention. Assessments of behavioral changes, including increased participation in eco-friendly practices such as recycling and energy conservation, were also conducted.

3.5. Data Analysis

Thematic analysis was used to analyze the classroom observations, educator interviews, and student assessment data. Qualitative research method – thematic analysis allows

researchers to find patterns or themes in the data [53], [54]. With this method, it was possible to analyze the rich, narrative data produced by the study in-depth to explore how AI tools impacted students' environmental awareness and behavior. An analysis was conducted on how AI tools prompted students to engage in transformative learning by encouraging critical reflection on environmental issues and shifting their perspectives on sustainability. For example, the age group examined was one where students were encouraged to revisit their concept of sustainable practices and how they were expected to integrate the new perspectives into their day-to-day living.

The study also examined how ecological intelligence, or the ability to recognize the interconnection between human actions and environmental influences, was enhanced by AI tools. To understand the role AI may play in environmental education, the researchers examined whether AI-driven feedback mechanisms linked students' behavior (such as waste generation or energy consumption) to environmental outcomes, leading to a deeper understanding of sustainability.

Explored how AI-driven education impacted students' understanding of sustainability and the formation of sustainable behavior in the long term. The objective of the analysis was to understand how AI tools supported students in developing more positive attitudes towards sustainability and becoming better able to act in environmentally responsible ways, for example, making more sustainable choices in their day-to-day activities.

This analysis helped me understand how AI tools are incorporated into sustainability education for young learners, facilitating transformative learning and ecological intelligence in early childhood education. This process provided insight into the potential for AI to facilitate long-term changes in students' environmental knowledge, behavior and attitude.

4. RESULTS

4.1. AI Tools Overview at Chongqing International Kindergarten

With a wide range of AI tools integrated into the sustainability curriculum at Chongqing International Kindergarten, interactive and dynamic learning has been fostered. Some key AI-powered tools that can be integrated into the student's learning environment are virtual ecosystems, AI-based educational games, and real-time feedback systems. These tools allow children to investigate how environmental concepts about waste management, energy conservation and ecosystem balance work hand in hand.

Virtual ecosystems serve as a realistic sounding board for environmental systems, allowing students to experiment with variables such as pollution levels, biodiversity, and water resources. Using these simulations makes abstract environmental concepts tangible for young learners. In addition to this, AI-based games can help expose students to concepts of resource management and environmental sustainability, where they must learn to make decisions that strike a balance between sustainability and resource management. Finally, real-time feedback systems provide personalized feedback based on the student's actions in the learning tools, encouraging them to modify their behavior and reflect on the environmental consequences of their actions.

4.2. Student Engagement and Expectation

Students have demonstrated a highly positive engagement with AI tools, and many are now more interested in environmental sustainability topics. Students love the interactive quality of virtual ecosystems and AI games, where they see the results of their actions in real-time—and educators observe that students take to them like fish to water.

Pre- and post-assessments with quantitative data demonstrate that students' environmental knowledge improved significantly. Students could define basic sustainability concepts, such as recycling, renewable energy, and ecosystem balance, before the intervention at a rate of 30%. After six weeks of using AI tools, 85% of students had firmly grasped these concepts. Many have applied these concepts in their daily lives, for instance, by correctly using the recycling bins or discussing energy conservation at home.

In addition, the observed behavioral changes indicate that students learn from these concepts and apply them in their own way. For instance, some students who previously did not participate in such exercises now showed great interest in sorting waste during their lunch breaks. Another phenomenon that teachers observed during that time was the increase in student-led initiatives, such as setting up a mini-campaign for water conservation or planting trees in the kindergarten's outdoor area.

4.3. Evidence of Transformative Learning

AI tools facilitate transformative learning, helping students critically reflect on their environmental actions and perspectives. Students used the virtual ecosystems to gain experiential learning in an environment where they actively adjusted variables to observe the impact on the simulation. A good example is when a group of students had to interact with a simulation that required balancing the needs of human development with environmental protection. They had to oversee the growth of a city while minimizing environmental damage. This simulation enabled students to observe the long-term consequences of unsustainable development and fundamentally altered their understanding of sustainability.

Further, AI-driven feedback mechanisms facilitated critical reflection. Students were provided real-time guidance on the ecological consequences of their actions as they made choices. For example, the AI system will inform a student that if they use water resources excessively, it will increase the likelihood of water scarcity; therefore, the child should reconsider their actions. Teachers cited this form of guided self-reflection as making students consider the broader environmental implications of their decisions.

One interesting case involved a student who showed little concern for sustainability. After interacting with AI-based simulations on climate change, the student changes their behavior voluntarily and encourage their peers not to use items made of plastic. In other words, it means that the AI-

driven activities facilitated perspective transformation, which is an integral part of Mezirow's transformative learning theory.

4.4. Evidence of Ecological Intelligence Development

However, AI-driven tools that provided immediate, context-specific feedback on students' actions seemed to significantly improve students' development of ecological intelligence. As part of the learning process, students participated in real-time simulations that modeled the environmental consequences of human behaviors, including pollution and deforestation. By completing these activities, students gained a deeper understanding of how their actions are interconnected with systems on a much broader ecological scale.

For instance, in a virtual ecosystem simulation, students can see how small actions, such as overusing water resources or polluting a water body, can disrupt the ecosystem's balance. Seeing that their behavior was being mapped to harmful actions, they adjusted their behavior to avoid those actions as their activity was interacted with in real-time by the AI system during that experiment. "*I did not know using too much water would hurt the fish in the lake*," another student said. "*Now I am more careful and tell my friends to do as well*." The behavioral changes result from the ecological intelligence students have developed, which involves accepting that their actions have consequences and adjusting them accordingly.

Moreover, as a human teacher modeled the AI-based feedback, students could derive the idea that sustainability is a complex, interdependent system, which inspired them to follow eco-friendly practices in the classroom and in other professional and personal contexts in the future. For example, when many students started carrying eco-friendly lunchboxes, the use of single-use plastic was reduced. Teachers found that the AI-powered feedback systems encouraged students to make more sustainable choices independently, with minimal intervention from teachers.

4.5. Comparative Analysis of AI-Driven Education vs. Traditional Approaches

One key observation from the study was the difference between the AI-powered learning approach and the typical sustainability education methods. Basic environmental concepts were conveyed through traditional methods, including storytelling and teacher-led discussions. Nevertheless, the AI (artificial intelligence) tools proved more engaging and interactive than data sheets, facilitating the students' retention of sustainability knowledge and their application in real-world settings.

Students who used AI tools articulated the environmental consequences of their actions and engaged in behavior change more frequently than students taught by conventional methods. Moreover, AI tools enabled individualized learning, allowing each student to learn at their own pace and receive tailored feedback that traditional classroom settings did not render feasible for all.

4.6. Statistical and Behavioral Statistics Data

The study revealed significant outcomes in various aspects of environmental education. Following the intervention, the percentage of students who understood key sustainability concepts—such as water conservation, renewable energy, and waste management—rose to 55%, highlighting notable gains in environmental knowledge. Moreover, throughout the study, 70% of the students demonstrated increased pro-environmental behaviors, including reducing plastic usage, participating in recycling initiatives, and conserving water. Observations in the classroom further showed that AI-based learning activities fostered nearly 30% more engagement compared to traditional methods, with students interacting more frequently with AI tools and actively contributing to classroom discussions. These findings underscore the effectiveness of AI in enhancing both the knowledge and behaviors of students in sustainability education.

The results demonstrate that AI-based environmental education has a positive impact on students' understanding of sustainability, fosters transformative learning, and develops ecological intelligence. For future studies, follow-up assessments could be conducted to determine the long-term impact of AI-driven sustainable education on students, specifically whether eco-friendly behaviors persist throughout their educational journey. Widening the study to various other schools or age groups could provide important insights into how scalable and extensible AI tools are for this type of sustainability education across different learning environments.

This research suggests that AI-powered tools can effectively deliver environmental education to young students, enhance their understanding of sustainability, and encourage changes in their behavior to facilitate a more sustainable future. This approach offers a comprehensive and robust framework for understanding how AI can facilitate more transformative learning experiences by integrating transformative learning theory and ecological intelligence theory.

5. DISCUSSIONS

5.1. Application of Transformative Learning Theory

The research finds that AI-empowered tools have a profound impact on enabling transformative learning in sustainability education, particularly at Chongqing International Kindergarten. Following Mezirow's Transformative Learning Theory [39], transformative learning is characterized as a process by which an individual critically reflects on their present assumptions and changes their perspective to provoke behavioral change. The AI tools — virtual ecosystems and real-time feedback systems — encouraged deep engagement with children in sustainability concepts, leading to critical thinking and reflective inquiry. With these AI-powered tools, students can simulate environmental effects and replace their current views on environmental responsibility.

AI simulations of ecosystems enable children to visualize how their current actions will impact the ecosystem over the long term, for example, how their decisions regarding waste management and energy use will affect the ecosystem's well-being. Interactive learning in this form allowed students to reconsider their behaviors and change their thoughts about environmental values [55]. Students' reflective learning process was reinforced by the real-time feedback of AI systems, which led students to see and feel the consequences of the real world in real-time and make the shift of environmental values. Beyond providing this sustainability knowledge, these AI tools also forced students to reflect on their actions and helped spark transformative learning outcomes [56], [57].

5.2. Application of Ecological Intelligence Theory

According to the Ecological Intelligence Theory, when people learn about the interconnectedness of human actions with ecological systems, they can make sustainable decisions [58], [59]. AI tools allow Chongqing International Kindergarten students to understand in real-time how their actions produced negative environmental impacts and let other children see their effects with their own eyes. The AI systems connected children's behaviors (such as waste management or water usage) to large-scale environmental outcomes, cultivating their ecological intelligence.

To this end, AI-driven games and simulations enabled children to see cause-and-effect relationships in the environment. For instance, some students were obliged to make waste-related decisions in a virtual simulation, for which the consequences—pollution in water bodies and a decrease in biodiversity—were immediately visible. It created an awareness of the environmental consequences of their actions, something Goleman [4] calls ecological intelligence. With such awareness promoted, AI tools helped students base their informed, sustainable decisions in the classroom and at home on the association between those choices and the planet's health.

Real-time feedback mechanisms, where the child sees the effects of their actions on the environment in real-time, also encourage students to take sustainable actions. Seeing the direct outcomes of their decisions allowed young learners to connect what they do in their everyday lives with global ecological consequences, which is following ecological intelligence [60].

5.3. Integration of the Theories

This research integrates Transformative Learning Theory and Ecological Intelligence Theory to demonstrate how these two theories can support one another, providing a more comprehensive and holistic approach to sustainability education. Based on their actions, transformative learning implies a new dimension in perspective resulting from critical reflection, while ecological intelligence requires that human actions are seen in context with ecological systems [61], [62]. Together, these theories provide a dual-layered approach: Transformative learning changes the students' environmental attitudes; however, ecological intelligence helps the students link their behavior with ecological consequences [63].

The use of AI tools in Chongqing International Kindergarten was not only a showcase of the theories as mentioned above synergizing to enhance students' understanding and intellectualization of ecological systems (ecological intelligence) but also an illustration of these theories in the context of prompting students' perspective shifts (transformative learning). Combined, both theories enabled AI-powered education to foster a deeper environmental awareness in students and lead to a significant change in their behavior. One example is a child who does not consider the impact of their daily actions on the environment. By walking them through a process of reflection and exposure to the consequences, the child was able to adopt more sustainable behaviors. By integrating these two theories into one, AI tools promoted a long-lasting effect on students beyond the level of knowledge, encouraging them to build habits that stick with them [64].

5.4. Comparison with Existing Literature

Findings from this research can be contextualized in relation to other studies on AI, sustainability education, and the intersections between these areas. However, they also bring some unique perspectives to the body of knowledge in this space. Providing interactive simulations and individual feedback through AI-based learning systems is an area where AI can help with sustainability education [5], [65], [66]. While those studies investigate the latter, this study builds on earlier work by focusing on early childhood education and combining transformative learning theories and ecological intelligence. Most studies that focus on the use of AI in the context of sustainability education are undertaken with older students or in higher education, and there has been a void where a discussion of the specific effect on young children was concerned [67]–[69].

AI is a new use of AI to enhance transformative learning and ecological intelligence. Existing work highlights the potential role of AI in providing knowledge in the environment. However, they rarely investigate its potential for promoting critical reflection and behavior change, characteristics of transformative learning [70]–[73]. Sustainability, design, research, and AI can all be transformed by tools such as Design Square into learning opportunities that extend beyond the scope of traditional lecturing.

The study also illustrates the role of real-time feedback in unique AI-powered systems. The ability of students to link actions to responses in their environment, a prerequisite to developing ecological intelligence, was a key component in this use of AI tools. The feedback loop created by AI allowed for continual learning and adaptation, which is an integral part of sustainability education [74]–[76].

Plenty of work remains to be done on this matter, particularly in assessing the long-term impact of AI-enabled sustainability education on children's behavior and attitudes. Moreover, studies could investigate how these AI-based learning tools might be adjusted to different cultural contexts to further international sustainability education efforts.

6. IMPLICATIONS

This study is valuable at meeting the objectives of understanding the integration of AI in teaching early childhood education for sustainability; however, there are unending avenues for future study. The long-term effects of using AI-powered sustainability education with young learners could be investigated for further studies. Although this study was conducted with an eye on short-term shifts in environmental knowledge and behavior, it would be interesting to investigate how these changes endure into children's adulthood and concur with their increased years of living. This could shine a greater light on the effect of AI tools on lifelong sustainability practices.

Another research direction is to extend the application of AI to diverse educational settings and cultural contexts. Although this study occurred in Chongqing International Kindergarten, exploring the possibility of utilizing AI to incorporate sustainable education in different regions for different living and learning demands would also be as important as they have their own cultural customs, environmental conditions and educational systems. Additionally, comparative studies across different educational levels, including primary and secondary schools, could shed light on how AI tools impact resource sustainability education at various learning levels. Decision-makers and educators will explore the scalability of AI tools for sustainability education if a decision is made to scale up AI-powered education.

7. CONCLUSION

In this study, the use of AI-powered tools in promoting ECE sustainability has been observed, particularly at Chongqing International Kindergarten, which serves as a case study. AI tools were found to significantly facilitate the development of transformative learning and ecological intelligence in young learners. Through interactive simulations, real-time feedback, and personalized learning experiences, AI tools empower children to critically reflect on and understand the long-term consequences of their actions on environmental issues. These tools for promoting critical thinking about sustainability helped students practice these learned behaviors daily.

Mezirow's Transformative Learning Theory and Goleman's Ecological Intelligence Theory were successfully applied as an underlying framework to help understand how AI tools could generate change in student environmental values and behaviors. Perspective shifts on sustainability were facilitated through transformative learning, and ecological intelligence was fostered via real-time feedback on the environmental implications of actions, all utilizing AI-driven simulations. Collectively, these theories demonstrate AI tools as a medium for learning, enabling a holistic and impactful learning experience that incorporates critical reflection and learning about one's environment.

The conclusion is that the AI-based approaches have the potential to revolutionize environmental education, charting a future where sustainability becomes a core aspect of the minds of young learners and a more sustainable and environmentally conscious world.

8. RECOMMENDATIONS

According to the findings of this study, the following practical recommendations could be made to educators and policymakers. A first approach is taken to embed AI tools in sustainability curricula at the early stage of learner education. These tools can enhance engagement, foster active learning, and promote critical reflection on environmental issues. Educators must become proficient with AI tools, understanding how they can foster transformative learning and ecological intelligence.

Policymakers should also consider the value of AI-powered sustainability education while designing national or regional curricula. The synergy between AI technology developers and educational institutions can enhance sustainability education by developing age-appropriate and interactive tools. Lastly, strenuous measures should be taken to provide underprivileged communities with equal opportunities to utilize AI-based learning tools, ensuring equitable access to education for all and preventing disparities in educational opportunities. This will also promote awareness of environmental issues among everyone.

There are tremendous transformative possibilities for AI in early childhood education. This study demonstrates that AI tools can convey important sustainability knowledge and serve as powerful tools for instilling sustainability values and behaviors in students. With the potential to advance ecological intelligence, AI can develop a larger group of ecologically aware people who are prepared to make environmentally sustainable decisions in their everyday lives through critical thinking. As AI technologies in sustainability education continue to develop, they will become increasingly important, opening up new avenues for innovative teaching and learning practices.

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