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Construction of an AI-empowered Triple Helix Model for the Ecologicalization of Primary and Secondary Science Curriculum and Exploration of Practical Pathways

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Global technological competition and the sustainable development agenda urgently demand a systemic reshaping of science education.This paper diagnoses a profound ecological crisis in primary and secondary science education in China: the fragmentation of knowledge structures leads to a rupture in the Knowledge Ecological Chain, the singularization of cognitive pathways causes the atrophy of the Cognitive Ecological Web, and the lack of value concern results in the desertification of the Meaning Ecological Field. Based on holistic ecological views and complexity theory, and integrating the concepts of the US NGSS standards and China's new curriculum standards, this study constructs an AI-empowered Triple Helix model for the ecologicalization of the science curriculum. This model focuses on the core framework of Knowledge Ecological Chain-Cognitive Ecological Web-Meaning Ecological Field, driven by an AI-enhanced learning ecological cycle of Perception-Interaction-Reflection-Creation. Through the practical pathways of Ecological Content Restructuring, Immersive Teaching Practice, and Intelligent Evaluation Guidance, it aims to propel science education from mechanical indoctrination towards organic generation, and from instrumental rationality back to value rationality. This paper provides a systematic theoretical framework and practical plan for addressing the ecological imbalance in science education, aiming to cultivate an innovative generation with scientific literacy, humanistic spirit, and ecological wisdom.

Keywords: primary and secondary science curriculum, curriculum ecology, triple helix model, AI empowerment

Introduction

Science education bears the sacred mission of cultivating future citizens' scientific literacy, innovative spirit, and ecological awareness. However, while significant progress has been made in primary and secondary science education in China, its internal ecosystem is in a concerning state of imbalance. The transmission of knowledge is disconnected from the construction of meaning, the exploration of scientific practice is detached from the needs of social reality, and technical rationality confronts the cultivation of humanistic spirit. These deep-seated contradictions collectively constitute a systemic ecological crisis in science education.

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The author's investigation into the current state of Chinese primary and secondary science education shows that 79% of students can proficiently memorize scientific formulas, but only 29% can reasonably explain the scientific principles behind these formulas; over 85% of teachers admit that experimental teaching primarily verifies known conclusions, with inquiry-based experiments accounting for less than 30%; only 36% of students express strong interest in science classes, a proportion that significantly decreases as grade levels increase. Hu (2020) found that the internal drive for research and practice in China's primary and secondary science education is insufficient, manifested as: the understanding of scientific literacy's connotation is based on policy frameworks rather than scientific substance, the absorption of globalized science curriculum increases, while localized curriculum development and practical research are in their infancy, research perspectives are shifting towards interdisciplinary domains but lack in-depth analysis, and theoretical study is disconnected from practice. Tian et al. (2021) pointed out that science education at the compulsory education stage faces four key issues: difficulty in realizing the educational value of the discipline, deviation in the execution of policy goals, challenges in the supply and allocation of high-quality teachers, and insufficient conditional support and internal drive for the implementation of inquiry-based experimental teaching. Li (2022) found that high school science experiments are continuously being weakened, with low rates of experiment implementation, short hands-on operation time for per student, and the replacement of students' experiments with teacher demonstrations or watching experiment videos has become a common phenomenon. Behind this evidence lies the structural imbalance of the science education ecology: the rupture of the Knowledge Ecological Chain, the singularization of the Cognitive Ecological Web, and the desertification of the Meaning Ecological Field.

The rapid development of artificial intelligence technology provides a historic opportunity to rebuild this imbalanced ecosystem. However, if AI is merely used as an efficient booster for drill-and-practice or an intelligent pipeline for knowledge indoctrination, it will not only fail to cure the ecological maladies but may exacerbate the technological alienation of education, making the learning experience more fragmented and dehumanized. Therefore, we must adhere to the holistic view of ecological philosophy and the systems thinking of complexity science, repositioning AI as an ecological regulator and cognitive catalyst to reconstruct a science curriculum ecosystem characterized by self-organization, dynamic balance, and co-evolution.

Based on this proposition of our time, this study attempts to transcend superficial curriculum integration and technological add-ons, constructing an AI-empowered Triple Helix model for the ecologicalization of the science curriculum from the philosophical height of ecological reconstruction. We will diagnose ecological pathologies through critical reflection, draw an ecological blueprint through theoretical construction, and open up practical pathways through exploration, ultimately promoting the return of science education to its authentic mission—not only imparting knowledge to conquer nature but also cultivating the wisdom to understand life, the warmth to care for the world, and the responsibility to protect the planet.

Literature Review: Paradigm Shift From Curriculum Integration to Educational Ecologicalization

The educational ecology perspective views the curriculum as a complex adaptive system with life characteristics. American educator Lawrence Cremin in 1976 first systematically expounded the concept of ecology of education in his *Public Education*, emphasizing the interrelationships and dynamic balance among various elements in the educational context. This perspective redefines education from isolated knowledge transmission to complex interactions between living organisms and their environment, providing a more profound framework for understanding issues in science education.

In the international science education community, the trend of curriculum integration has evolved from STS (Science-Technology-Society) to STEM (Science, Technology, Engineering, and Mathematics), and further to NGSS (Next Generation Science Standards). The NGSS standards, released in 2013, constructed a three-dimensional integration framework of Disciplinary Core Ideas (DCIs), Science and Engineering Practices (SEPs), and Crosscutting Concepts (CCCs), already bearing the rudiments of ecological thinking. Particularly, its organization of K-12 science content into a coherent system through Learning Progressions reflects attention to the continuity of the knowledge ecology. However, the NGSS framework still pays insufficient attention to local knowledge, cultural diversity, and ethical dimensions of science and technology, making its ecology incomplete. Phenomenon-Based Learning (PhBL) originating from Finland organizes teaching around real-world phenomena (e.g., immigration, energy systems) rather than disciplines, emphasizing embodied cognition and situational authenticity (Symeonidis & Schwarz, 2016).

Domestic research, while responding to international trends, also shows localized exploration. The 2022 edition of the Compulsory Education Curriculum Standards explicitly requires strengthening interdisciplinarity, promoting practical exploration of curriculum integration. Cui and Guo (2023) elaborated on four key characteristics of interdisciplinary thematic learning, emphasizing the integration goal of aiming at cultivating competencies. Fan and Wei (2023) pointed out that research on the view of the nature of science in science education should return to the original purpose of cultivating scientific literacy. Therefore, according to the new requirements of China's compulsory education science curriculum, a core-competency-oriented view of the nature of science and an interdisciplinary HPS (History, Philosophy, and Sociology of Science) teaching practice approach should be constructed based on the concept of broad science education. Chen and Xu (2022) analyzed the progression path for implementing ecological civilization education in primary school science and secondary school biology teaching based on the content related to ecosystems in primary school science and secondary school biology textbooks. Liu Yuan (2021) and Zheng et al. (2025) conducted useful explorations from the perspectives of integrated construction of science curriculum and AI-empowered science education, respectively.

However, most existing studies focus on the technical pathways of how to integrate, with few systematically diagnosing the structural imbalances of science education across cognitive, affective, and value dimensions from an overall ecosystem perspective.

Research on artificial intelligence provides new possibilities for this. Sun (2025) proposed five innovative pathway conceptions for AIGC-empowered science education by integrating multi-dimensional scenarios such as maker spaces, interdisciplinary courses, and off-campus practical resources to achieve potential connections, analyzing its theoretical value in dimensions such as personalized learning support, virtual laboratory construction, interdisciplinary collaboration mechanisms, competency assessment innovation, and output, cultural inheritance and integrated innovation. The application of AI in science education spans various fields, from machine-assisted experiments to adaptive learning systems.

However, most of these studies treat AI as a tool rather than an organic component of the ecosystem. The breakthrough development of generative AI, particularly its powerful semantic understanding, content generation, and dialog capabilities, enables it to play the roles of cognitive partner, thinking mirror, creativity catalyst, and empathic partner, while also focusing on educational equity, strengthening resource sharing, and promoting low-cost experiments, thereby providing a technical foundation for building a wiser, more dynamic, supportive, and humanistic learning ecosystem.

It is within this theoretical context and technological background that this study attempts to promote the transformation of science education research from an integration paradigm to an ecological paradigm, deeply embedding AI into the reconstruction process of the educational ecology, and exploring a path towards the revival of scientific humanistic education that returns to life, wholeness, and meaning.

Pathological Diagnosis of the Science Education Ecology

To rebuild a healthy ecology for science education, it is first necessary to accurately diagnose its current pathological imbalances. The current science education ecosystem exhibits severe functional disorders in three core dimensions: knowledge transmission, cognitive development, and meaning generation.

Fragmentation and Rupture of the Knowledge Ecological Chain

A healthy ecosystem relies on the cyclic flow of matter and energy; similarly, a sound knowledge system relies on organic connections and logical progression between concepts. However, the current science curriculum exhibits a severe rupture of the Knowledge Ecological Chain. The Law of Conservation of Energy in physics, the Mass-Energy Relationship in chemistry, the Energy Flow in biology, and the Carbon Cycle in geography should constitute a grand narrative chain for understanding energy transformation and conservation in the universe. Yet, within the rigid framework of subject-based teaching, they are mechanically fragmented into unrelated pieces of knowledge, scattered across different textbooks, class hours, and test questions.

Content analysis of current mainstream science textbooks reveals significant differences in the expression of cross-cutting big ideas like system across different subject textbooks, lacking a unified conceptual map and consistent expression. For instance, physics focuses on ideal models of isolated systems and open systems, while biology emphasizes the material cycles of ecosystems. This artificial conceptual fragmentation makes it difficult for students to form a holistic, interdisciplinary understanding of system. The rupture of the Knowledge Ecological Chain directly leads to the fragmentation and superficial understanding of students' cognitive structures. They might proficiently recite each law but fail to perceive the unified natural philosophy behind these laws, akin to recognizing every tree but seeing no life network of the entire forest.

Singularization and Homogenization of the Cognitive Ecological Web

A thriving ecosystem is characterized by its biodiversity; a healthy educational ecosystem should be based on the diversity of cognitive pathways. However, strongly shaped by standardized testing and efficiency-oriented teaching culture, the Cognitive Ecological Web of science education is becoming increasingly singularized and homogenized.

The inquiry process is simplified into a fixed procedure of posing questions-forming hypotheses-experimental verification-drawing conclusions; scientific thinking is narrowed down to formula derivation and calculation skills; problem-solving is templated into the mechanical process of identifying question types and applying methods. The 2024 physics grading report for a certain province's college entrance examination showed that over 70% of candidates scored very low on an innovative design question, with their answers revealing astonishing homogeneity of thought—the vast majority attempted to apply conventional mechanics formulas rather than creatively modeling from basic principles. This exposes that our education is producing cognitive clones who possess similar thinking paths and problem-solving strategies but severely lack the cognitive flexibility and innovative tension to deal with the uncertainty and complexity of the real world. The atrophy of the Cognitive Ecological Web is the greatest obstacle to cultivating innovative talent.

Desertification and Emotional Alienation of the Meaning Ecological Field

Science is not only a system of knowledge and a way of thinking but also a cultural tradition and source of meaning full of human brilliance. However, current science education almost ignores the cultivation of the Meaning Ecological Field, reducing the learning process to mere technical exercise, devoid of emotion and suspended values.

Those thrilling intellectual leaps in the history of science—from Copernicus's heliocentric theory to Darwin's theory of evolution, from Wegener's continental drift to Einstein's theory of relativity—along with the struggles, courage, intuition, and perseverance of the scientists behind them, are generally absent from classroom narratives. The profound ethical challenges brought by technological development—such as the boundaries of gene editing, the autonomy of artificial intelligence, the dual nature of nuclear technology—also rarely become themes for students' deep reflection. Questionnaire surveys show that over 60% of students believe that science class is about mastering definitions, principles, and being able to solve problems and pass exams smoothly, while less than 20% can meaningfully connect the science knowledge they learn with their personal lives, social issues, or future ideals.

This desertification of the Meaning Ecological Field is the root cause of the decline in students' interest in science as grade levels increase and the low identification with science careers. When learning loses its intrinsic connection to life experience, value exploration, and meaning construction, it becomes an external, compulsory, and tedious burden. This is the oringination of the students' dilemma of having knowledge without wisdom, having skills without sentiment.

Construction of the Triple Helix Model for Science Curriculum Ecologicalization

In response to the aforementioned ecological pathologies, we have constructed an AI-empowered Triple Helix model for the ecologicalization of the science curriculum. This model reconceptualizes the science curriculum as a complex ecosystem composed of the Knowledge Ecological Chain, Cognitive Ecological Web, and Meaning Ecological Field, which are interdependent and mutually nourishing. An AI-Enhanced Learning Ecological Cycle serves as the driving core for maintaining the system's dynamic balance and continuous evolution, as shown in Figure 1.

Knowledge Ecological Chain: A Network Structure With Vertical Coherence and Horizontal Integration

The Knowledge Ecological Chain aims to repair the rupture of knowledge, constructing an organic network of concept-proposition-theory-paradigm that progresses through four levels and interweaves vertically and horizontally (Wang, 2017).

Vertical Coherence (Learning Progressions): Based on learning progression theory and utilizing AI knowledge graph technology, design spiral ascending cognitive paths for core concepts (e.g., structure of matter, energy, heredity) across the K-12 stages. Taking structure of matter as an example, its progression path can be designed as: perceiving macroscopic diversity of matter through observation at the elementary stage; introducing the molecular-atomic model to explain changes of state and chemical reactions at the junior high stage; delving into the internal structure of atoms and start to learn quantum mechanics models to understand frontiers in materials science at the senior high stage. The AI system can dynamically track students' positions on this chain and provide appropriate learning resource scaffolding.

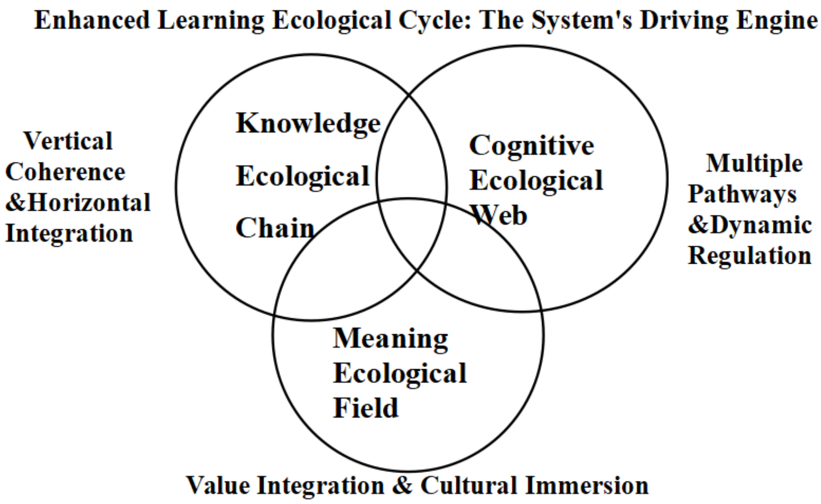

Figure 1. The Triple Helix Model for science curriculum ecologicalization.

Horizontal Integration (Crosscutting Concepts): Weave an interdisciplinary knowledge network using Big Ideas as the link. For example, the big idea Systems and Models can connect physical force systems, biological ecosystems, geographical Earth systems, and mathematical function models. AI, as a cognitive engine, can automatically identify and visualize the specific manifestations and intrinsic connections of these concepts across different disciplines, generating interdisciplinary question chains such as re-examining the calculation of reaction heat in chemistry using the principle of energy conservation in physics, thereby driving deep integration and transfer of knowledge.

Cognitive Ecological Web: A Cluster of Thinking With Multiple Pathways and Dynamic Regulation

The Cognitive Ecological Web respects and cultivates the diversity of individual cognition, constructing a community of thinking that includes multiple pathways such as Empirical Investigation-Modeling-Computational Thinking-Critical Thinking-Creation.

Pathway Diversification: Acknowledge and encourage students to adopt different cognitive styles to solve problems. Some students excel at collecting data through precise experiments (Empirical Investigation), some are adept at constructing mathematical models for prediction (Modeling), some prefer exploring patterns through computer simulation (Computational Thinking), while others are skilled at critical examination from logical and ethical perspectives (Critical Thinking). AI virtual laboratories and modeling tools (e.g., NetLogo, Python) provide a low-threshold, high-support technical environment for this.

Dynamic Regulation and Scaffolding: The AI learning analytics system describes students' cognitive trajectories and thinking characteristics in real-time by analyzing their operation logs, dialogue records, and outcome products. When the system detects that a student is stuck in a certain thinking set (e.g., over-reliance on formula application), it can proactively provide cognitive scaffolding, such as providing counter examples, suggesting alternative solutions, or guiding group collaboration, to expand their cognitive boundaries and maintain the richness and adaptability of the cognitive ecology.

Meaning Ecological Field: A Spiritual Home With Value Integration and Cultural Immersion

The Meaning Ecological Field aims to cure emotional alienation and value desertification, elevating science learning into a process of meaning construction through cultural immersion and value dialogue.

Science History Narratives and HPS Integration: Integrate the History, Philosophy, and Sociology of Science (HPS) organically into the curriculum. For example, when learning Newtonian mechanics, not only learn $F = ma$ but also review the priority dispute between Newton and Hooke over universal gravitation, discussing the social construction of scientific discovery; when learning the theory of evolution, discuss the impact of Darwin's ideas on religious and ethical views.

Science-Technology Ethics Debates and Socioscientific Issues (SSI): Introduce Socioscientific Issues such as Will AI replace human creativity? and Where are the ethical boundaries of gene editing technology? Organizing role-playing, debates, and value ranking activities. Generative AI can here play the role of a Socratic questioner or experts holding different stances to stimulate students' deep thinking and value clarification.

Ecological Awareness and Scientific Humanism: Integrate universal values such as environmental protection, sustainable development, and scientific humanism into science education. In the Ecosystem unit, not only learn about food chains and energy pyramids but also discuss the impact of human activities on biodiversity, reflect on the ecological costs of modern technological civilization, and cultivate students' planetary citizenship awareness and concern for the fate of humanity.

AI-enhanced Learning Ecological Cycle: The System's Driving Engine

The effective operation and synergy of the above three dimensions rely on an AI-enhanced learning ecological cycle named Perception-Interaction-Reflection-Creation.

Perception: Use IoT sensors, AR/VR devices, wearable technology, etc., to comprehensively collect learning environment data and student physiological/behavioral data, achieving real-time perception of the ecological state.

Interaction: Based on perception data, the AI system engages in multimodal, contextualized intelligent interaction with students, providing personalized resources, tasks, and conversational support.

Reflection: AI guides students to review and reflect on their learning processes, thinking strategies, and value judgments, promoting metacognitive development through methods like generating mind maps and analyzing learning journals.

Creation: With AI assistance, students externalize internalized knowledge, developed abilities, and realized values into creative solutions, artistic works, or social practices, completing the creative output of learning outcomes and initiating a new round of the ecological cycle.

Exploration of Ecologicalized Practical Pathways

The theoretical model needs to be translated into concrete practical actions.We propose the following three mutually supportive ecologicalized practical pathways to promote the substantive transformation of the science education ecosystem.

Ecologicalized Content Restructuring: From Rigid Textbooks to Flexible Curriculum Ecology

Break the rigid structure of traditional textbooks and build a flexible curriculum system of Basic Modules-Extension Modules-Innovation Modules.

Basic Modules (approx. 60%): Ensure all students master the core concepts and competencies of each discipline, consolidating the foundation of the Knowledge Ecological Chain. Content organization emphasizes the structuring of knowledge within disciplines.

Extension Modules (approx. 30%): Design interdisciplinary thematic units to promote the horizontal integration of the Knowledge Ecological Chain. For example, the thematic unit The Science and Society of Carbon Neutrality could integrate chemical carbon emissions, physical photovoltaic power generation, biological carbon sinks, geographical climate patterns, and political-economic policy analysis.

Innovation Modules (approx. 10%): Focus on cutting-edge technologies and complex social issues, such as AI Ethics Design and Synthetic Biology and Biosecurity, encouraging students to engage in frontier exploration and innovative practice, nourishing the Meaning Ecological Field.

Immersive Teaching Practice: From Knowledge Transmission to Situational Immersion

Adopt an ecologicalized teaching model of Situational Immersion-Problem-Driven-Collaborative Inquiry-Outcome Creation, allowing learning to occur naturally in authentic or simulated situations.

Situational Immersion: Use VR/AR/MR technologies to create immersive learning environments. For example, students can enter a virtual cell interior to observe protein synthesis or travel to London during the Industrial Revolution to explore the origins of air pollution.

Problem-Driven: Use complex, ill-structured real-world problems (e.g., How to design a sustainable water recycling system for our community?) as the starting point for learning, stimulating students' inquiry desire.

Deep Integration of Engineering Design Processes: In projects such as Designing an Assistive Device for People with Disabilities, students need to comprehensively apply knowledge of ergonomics (Biology), materials science (Chemistry/Physics), structural mechanics (Physics/Mathematics), and programming control (Information Technology), experiencing the complete engineering cycle of defining the problem-background research-conceptualizing solutions-prototype building-testing and iteration. AI can provide material databases, simulation, and design optimization suggestions during this process.

Language Empowerment through Reading+Writing+Expression: Adopt graded reading strategies to match students with quality science readings like theAmerican Science Reader, combining science vocabulary learning with logical analysis skills training. Encourage students to write research reports, scientific essays, and even popular science articles, and express them through presentations, debates, exhibitions, etc., realizing the externalization and refinement of thinking.

Intelligent Evaluation Guidance: From Score Orientation to Growth Navigation

Establish an Intelligent Evaluation Guidance System aimed at promoting ecosystem health rather than simple ranking.

Construct an Ecologicalized Evaluation Indicator System: Go beyond the mastery of single knowledge points to construct evaluation indicators covering multiple dimensions such as Depth of Conceptual Understanding, Quality of Inquiry Process, Complexity of Cognitive Strategies, Effectiveness of Collaboration and Communication, and Scientific Attitudes and Values.

Establish Process-Oriented Growth Portfolios: Use AI to record the whoel process and analyze students' behavioral data in virtual experiments, group discussions, and project progression, automatically generating Learning Ecological Diagnostic Reports containing textual descriptions and data visualizations. The report not only points out problems but also reveals students' cognitive strengths, growth trajectories, and developmental potential.

Outcome Exhibition and Value Recognition: Widely adopt forms such as science festivals, project defense sessions, and solution hearings, inviting teachers, parents, community representatives, and even relevant field experts to participate in evaluation. Evaluation criteria highlight the scientificity, innovation, practicality, and social value of the outcomes. Allowing students' excellent work to receive feedback and recognition from the real world greatly increases their sense of value and achievement in learning.

Comprehensive Assessment of Interdisciplinary Competencies: Design comprehensive assessment tasks, such as Propose a comprehensive plan to reduce the urban heat island effect and demonstrate its feasibility, to assess students' ability to integrate and apply knowledge, methods, and values from multiple disciplines like mathematics, physics, chemistry, and biology to solve complex problems. Use an integration of student self-assessment, peer assessment, teacher assessment, and AI data analysis to ensure the comprehensiveness and fairness of the evaluation.

Conclusion: Towards an Ecologicalized Future for Science Education

The ecological transformation of science education is an inevitable choice for addressing the complex challenges of the 21st century and cultivating a responsible, innovative generation. The AI-empowered triple helix ecological model constructed in this study is not only a systematic response to current educational maladies but also a prospective vision for the future of education. It redefines the science curriculum from a cold knowledge transmission system to a warm, vibrant learning ecosystem: constructing an ecologicalized curriculum system that reflects the characteristics of continuity, integration, and generativity, aligns with the principles of cognitive neuroscience and knowledge ecology, features clear point-line-2D-3D-network structures, is easy to learn and apply, correlates with core competencies and evaluation indicator systems, and allows for controllable and visible goal achievement; promoting the brain-heart-hand in tandem, integrating science-technology and humanities education, achieving two-way integration of practice and theory, and building a support system from multiple dimensions such as school management, teacher development, policy support, and home-school-community cooperation.

In this ecosystem, knowledge flows and connects like living water, cognition coexists diversely like a forest, and meaning nourishes universally like sunlight. Artificial intelligence is no longer a cold technology external to education but an intelligent regulator embedded within the ecology, empowering each individual life to thrive according to its unique rhythm and forming a more powerful collective wisdom through interconnection.

The road ahead remains challenging. It requires teachers to transform from knowledge authorities to ecological mentors, schools from educational factories to learning communities, and evaluation from selection sieves to growth navigators. This requires the co-evolution of policy, culture, technology, and practice. But we have reason to believe that, upholding ecological wisdom and leveraging technological power, we will ultimately be able to rebuild a balanced, healthy, and vibrant science education ecosystem where every young mind can not only harvest knowledge to conquer exams but also nurture the wisdom to understand the world, the courage to explore the unknown, and the warmth to care for life—this is the most authentic mission and glory of science education.

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