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Mars Base Ecological Chamber: A STEM Course Focusing on Advanced Thinking Development

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ABSTRACT

This paper focuses on the design of STEM courses aimed at cultivating advanced scientific thinking skills, using a Mars base ecological cabin as the backdrop to construct an innovative STEM teaching case study centered on science and engineering practice. Chinese students currently lag behind their peers in developed countries in terms of advanced scientific thinking abilities, necessitating urgent efforts to strengthen their cultivation. The distinctive features of the course design include an emphasis on interdisciplinary integration, task-driven deep learning, and the cultivation of systems thinking. The instructional design encompasses learning content analysis, learner analysis, competency goal setting, and instructional process design, aiming to cultivate students' abilities in scientific reasoning, scientific argumentation, and scientific modeling. Implementation strategies include establishing an interdisciplinary integration framework centered on scientific higher-order thinking, designing science and engineering practice task chains, and establishing a diversified formative assessment system.

1. Introduction

In 2024, the China Education Development Strategy Association released the STEM (Science, Technology, Engineering, and Mathematics) Education 2035 Action Plan, which clearly proposes the construction of a high-quality STEM curriculum and project system to lead the transformation of learning methods and strengthen the educational value of STEM education. China's STEM education has its own unique educational context, and it must undergo localization to fully realize its educational value and truly become a hallmark of China's school education. STEM education should cultivate students' critical thinking, problem-solving, and innovative practical skills, while also enhancing their scientific reasoning, scientific argumentation, and scientific modeling abilities—all aspects of higher-order scientific thinking. Although Chinese primary and secondary school students demonstrate strong performance in foundational scientific knowledge, there remains a significant gap in advanced scientific thinking abilities compared to developed countries. This disparity underscores that cultivating students' advanced scientific thinking is an urgent issue in current educational reform. The essence of scientific higher-order thinking lies in the cognitive process of students creatively solving scientific problems, with scientific reasoning, scientific argumentation, and scientific modeling as its domain attributes, and operational and executional functions. Metacognition and critical thinking regulate and judge, while scientific attitudes, learning motivation, and self-efficacy regulate and influence the operation of the scientific thinking system.

This case study addresses this context by promoting the advancement of students' thinking through a science and engineering practice-oriented STEM course that integrates scientific higher-order thinking.

2. Key Concepts of Instructional Design

This case study focuses on the development of students' higher-order scientific thinking skills. It relies on science and engineering practices to construct a closed-loop learning path from scientific inquiry to engineering design to system optimization, focusing on the construction of a recycling system for inedible parts of plants. By simulating the closed-loop resource recycling requirements of a Mars base ecological cabin, students are guided to transfer their thinking from environmental protection issues on Earth to engineering challenges in the extreme environment of space, thereby promoting the systematic advancement of their higher-order scientific thinking skills. First, based on the science and engineering practice framework, the case emphasizes interdisciplinary integration and focuses on cultivating students' higher-order scientific thinking, particularly in scientific reasoning, scientific argumentation, and scientific modeling. By deeply integrating scientific inquiry (such as strain selection and condition optimization), engineering design (such as device prototype iteration), and mathematical modeling (such as decomposition efficiency data modeling), the case drives students' transition from single-discipline knowledge to multidisciplinary collaborative application. Students strengthen their data-driven decision-making abilities through the cognitive

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chain of identifying patterns, constructing models, and arguing explanations, thereby cultivating their scientific reasoning and scientific argumentation abilities. This helps students apply scientific reasoning to real-world problems and also encourages them to optimize engineering design through scientific modeling, driving technological progress (Brassler & Dettmers, 2017).

Second, task chains drive deep learning, particularly in balancing the complex challenges of designing temperature control modules in Mars' low-gravity environment. This sparks students' autonomous learning and exploratory spirit, enabling group collaboration and iterative optimization through data sharing and joint testing between scientific and engineering teams. Students continuously refine functional modules based on reflections on anomalous phenomena, thereby constructing a comprehensive knowledge network. The theory of cultivating systems thinking draws on system dynamics models to establish a closed-loop logic from monitoring to regulation to iteration, helping students understand the dynamic feedback between microbial decomposition efficiency and device environmental parameters, especially the nonlinear relationships among variables such as temperature, pH, and oxygen concentration, thereby deepening students' understanding of complex systems (Daneshpour & Kwegyir-Afful, 2022).

Third, the project focuses on cultivating higher-order cognitive abilities such as multi-condition coupled regulation strategies through performance-based assessment. Through engineering log visualization (e.g., sensor layout optimization records), cross-group peer reviews, and Earth-space scenario comparisons and reflections, the project comprehensively evaluates students' scientific reasoning, scientific argumentation, and scientific modeling abilities when solving real-world problems. The project also has a unique logic in terms of interdisciplinary integration. By addressing the closed ecological requirements of a Mars base, it integrates biology (microbial metabolism), physics (simulation of closed-space environments), engineering (modular design), and mathematics (thermal mapping modeling) into an organic system, reflecting the interdisciplinary nature of science serving engineering and engineering informing science (Fan et al., 2021).

Fourth, the course also incorporates education on social responsibility, helping students reflect on the environmental value of sustainable development on Earth through comparisons of common issues in Earth's food waste management and Mars' resource recycling, thereby deepening their understanding of technological ethics and social responsibility. In terms of the integration of theory and practice, the project employs an anomaly-driven approach, closely linking the scientific group's experimental verification with the engineering group's prototype iteration, embodying the "learning by doing" philosophy and helping students develop the ability to solve complex problems through hands-on practice (Geng & Su, 2024).

3. STEM Teaching Design Based on Scientific Higher-Order Thinking

3.1. Analysis of Learning Content

In terms of learning content, this course must consider students' existing knowledge and potential gaps. In terms of subject knowledge, students typically already understand basic microbial classification (e.g., bacteria, fungi) and fundamental concepts of ecosystem material cycles. However, their understanding of microbial metabolic mechanisms (e.g., the principles of cellulase action) is superficial, and they lack deep knowledge of the Martian environment and complex systems. In terms of experimental and engineering skills, students can perform basic microbial culture experiments but lack systematic engineering design experience, such as modular design and requirements analysis. In terms of interdisciplinary integration capabilities, students are familiar with the superficial integration of biology and geography but have weak abilities to convert scientific data into engineering parameters, potentially struggling to seamlessly integrate microbial activity with temperature control module design. Specific domains, existing foundations, potential shortcomings, and teaching strategies are outlined in Table 1.

Table 1. Learning Content Analysis Framework

Domain	Existing Foundation	Potential Weaknesses and Teaching Strategies
Subject Knowledge	Biology: Basic understanding of microbial classification (e.g., bacteria, fungi) and decomposition concepts (middle school curriculum content)	Lack of depth: No systematic learning of microbial metabolism mechanisms (e.g., principles of cellulase action); Strategy: Visualize enzyme activity principles through Strain Function Cards to reduce cognitive load.
	Geography: Understanding of basic ecosystem material cycle model (producer-consumer-decomposer)	
	Physics: Familiarity with properties of gases in closed spaces (e.g., oxygen concentration measurement)	
	Mathematics: Basic data processing skills (averages, line graph plotting)	
Experimental and Engineering Skills	Experimental operations: Able to perform basic microbial cultivation (e.g., culture medium preparation, sterile operations)	Lack of engineering experience: Insufficient systematic engineering design experience (e.g., needs analysis, modular design) Strategy: Provide engineering templates (e.g., device function list framework) to break down the design process step by step
	Simple modeling: Use tables to record data, plot variable relationship graphs (e.g., temperature-decomposition rate curves)	
Interdisciplinary Integration Ability	Participated in comprehensive practical activities (e.g., campus composting projects), exposed to shallow integration of biology and geography	Weak integration skills: Difficulty in independently connecting scientific data with engineering parameters (e.g., optimal temperature for strains → temperature control module threshold) Strategy: Design data transformation worksheets (e.g., science team → engineering team requirement interface table)
	Initial application of mathematical tools in physics and chemistry experiments (e.g., calculating reaction rates)	

3.2. Learner Analysis

Learners are currently in the preparatory phase of transitioning from junior high school to high school, necessitating the prediction of learning difficulties and the design of supportive measures to enhance overall teaching effectiveness. First, gaps in engineering thinking often lead students to focus narrowly on achieving single functional objectives, such as overly emphasizing airtightness while neglecting the system's overall energy efficiency and maintenance costs (Giffney & Lane, 2025). To address this issue, a Mars resource constraint table can be introduced to enforce designs that balance multiple conditions. Additionally, inefficient cross-group collaboration is widespread, with communication between science and engineering groups often remaining superficial, such as merely exchanging final data

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without effective process coordination. To address this, mid-term data exchange meetings can be established to enforce the sharing of interim data, such as the correlation between initial measurements of microbial activity and adjustments to device dimensions. On the other hand, students often lack intuitive understanding when grasping abstract concepts, especially nonlinear relationships (such as the threshold effect of pH on enzyme activity) (Guzey et al., 2016). This can be addressed by using simulation software to dynamically demonstrate the impact of variables, supplemented with extreme value cases (such as microbial death at pH=2) to aid understanding. In terms of interest stimulation and role division, interest anchors can be established by linking to science fiction themes, such as the ecological cabin scenes in The Martian, and introducing tasks through film clips, while designing engineer badge incentive mechanisms (e.g., Best Module Design Award, Efficient Collaboration Award). In terms of role matching, the science group is suitable for students who excel at experimental operations and are data-sensitive, while the engineering group attracts students who enjoy hands-on creation and have strong spatial imagination.

3.3. Clarification of Competency Goals

Competency objectives focus on core disciplinary concepts, advanced scientific thinking, scientific and engineering practices, and emotional attitudes and values. First, in terms of core disciplinary concepts, students need to master core biological and chemical concepts such as the principles of cellulase action and the metabolic differences between aerobic and anaerobic bacteria to understand the role and mechanisms of microorganisms in the decomposition process. Additionally, students need to understand the design principles of closed fermentation systems, including modular structures, energy efficiency balance, and feedback mechanisms. By considering the unique conditions of the Martian environment (such as low gravity and energy constraints), students can evaluate and justify the rationality of the system's design. Second, in terms of higher-order scientific thinking, the focus is on cultivating students' advanced scientific thinking skills, including scientific reasoning, scientific argumentation, and scientific modeling abilities. Students must design and conduct comparative experiments to identify efficient decomposing bacterial strains and investigate factors influencing decomposition efficiency (such as temperature and pH variables). Students need to establish quantitative relationship models and scientifically argue the experimental results. Additionally, students should reason about abnormal phenomena that occur in the experiment (such as bacterial inactivation), infer defects in the experimental conditions, and propose optimization schemes to cultivate their critical reflection abilities, helping them not only obtain data through scientific exploration but also conduct in-depth analysis and reflection on the data (Han et al., 2023). Third, in terms of scientific and engineering practice, the focus is on developing and using models, requiring students to convert scientific data into specific engineering parameters and validate the effectiveness of engineering solutions through model design and simulation testing. Students need to design temperature control modules based on the optimal temperature range of the bacterial strains and validate their stability through simulation testing. Additionally, in resource-constrained environments (such as energy limitations in a Mars base), students must optimize the design of fermentation equipment to balance decomposition efficiency, energy consumption, and maintenance costs. This not only requires students to possess solid engineering design capabilities but also to apply multidisciplinary knowledge (such as physics, chemistry, and biology) to solve practical problems, thereby demonstrating the close integration of science and engineering. Fourth, in terms of emotional attitudes and values, the program emphasizes students' emotional attitudes and values, particularly their concern for sustainability and social responsibility. Students need to assess the long-term impact of microbial decomposition systems on the ecological balance of the Mars base and propose improvements to Earth's ecosystems from the perspectives of resource recycling and environmental protection (Jiang et al., 2025). Through technology transfer proposals, students should convey the value of "technology for good." When presenting their findings, students should demonstrate a sense of social responsibility, express concern about Earth's resource waste issues, and reflect their moral and social responsibility in practical applications.

3.4. Teaching Process and Evaluation Design

The core objective of this teaching process design is to cultivate students' higher-order scientific thinking through interdisciplinary integration. The overall task is to design a microbial fermentation system suitable for a Mars ecological cabin, achieving efficient decomposition of non-edible plant parts and closed-loop resource utilization. The driving question is how to design a fermentation device that can provide stable fermentation conditions for target microorganisms.

3.4.1. Problem Analysis and Requirement Definition

In Phase 1, "Problem Analysis and Requirement Definition," students will analyze the environmental conditions of Mars and the constraints of the ecological cabin. By combining Mars environmental parameters from geography and the characteristics of enclosed spaces from physics, students will engage in scientific inquiry, developing scientific reasoning and systems thinking skills. Through this task, students will understand the harshness of the Martian environment and learn how to apply theoretical knowledge to real-world problems, laying the foundation for subsequent tasks. Additionally, the comparative study of Earth and Mars resource cycles will allow students to explore biology and sociology, discussing decomposition technology and environmental significance, fostering a sense of social responsibility, and promoting interdisciplinary thinking. The learning outcomes will be demonstrated through the "Mars Ecological Chamber Environmental Constraints Report" and the "Earth Food Waste Processing and Mars Decomposition Requirements Comparison Table."

3.4.2. Science Group Task (Microbial Decomposition System)

In Phase Two, "Science Group Task (Microbial Decomposition System)," students focus on the design and optimization of microbial decomposition systems, beginning with microbial strain selection and cultivation experiments. This task integrates biology and chemistry knowledge, enabling students to deepen their understanding of experimental design through microbial metabolism research and medium preparation, while cultivating scientific reasoning and investigative skills. Through the "High-Efficiency Decomposition Strain Selection Report," students can present their experimental results and develop a profound understanding of microbial decomposition technology. Simultaneously, the optimization of decomposition conditions (such as temperature, pH, oxygen concentration, etc.) constitutes the second part of the task. Students must combine data modeling techniques from mathematics and environmental simulation methods from physics to analyze decomposition efficiency under different conditions, thereby cultivating their data analysis and model-

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building abilities. Through the completion of the "Decomposition Efficiency Heat Map" and the "Optimal Parameter Model," students can demonstrate their technical achievements in optimizing decomposition conditions.

3.4.3. Engineering Group Task (Fermentation Device Design)

In Phase Three, "Engineering Group Task (Fermentation Device Design)," students will participate in the design of device prototypes and functional module planning. Combining engineering's modular design principles with 3D modeling skills from general technology, they will conduct preliminary device design and functional division. Through this task, students will develop engineering practical skills, cultivate scientific modeling thinking, and demonstrate their design outcomes through the "Device Prototype Sketch" and "Functional Module List." Additionally, students will need to implement environmental control systems (such as temperature control and oxygen supply systems), combining thermodynamic principles from physics with sensor programming from information technology to design system control solutions for real-world problems. Ultimately, students will demonstrate their technical application capabilities through the "Temperature Control Module Design Diagram" and "Oxygen Circulation Plan." The cross-environmental simulation testing and anomaly handling task requires students to combine cost-efficiency analysis from mathematics with exhaust gas treatment methods from chemistry for system optimization and collaborative reflection. Through the creation of a "Test Log" and an "Anomaly Improvement Plan," students will demonstrate their ability to reflect on and improve their practical operations.

3.4.4. Integration and Presentation

Finally, in Phase Four, "Integration and Presentation," students will conduct system integration and data validation, comprehensively applying scientific and engineering data to engage in interdisciplinary integration and develop critical thinking skills. Through the outcomes of the "System Operational Efficiency Report" and "Resource Closed-Loop Validation," students will demonstrate the operational effectiveness and optimization solutions of the entire system. In the "Outcome Marketplace and Reflection Iteration" task, students will combine art and language arts disciplines to design outcome display boards and write reports, clearly and concisely expressing and presenting their research outcomes, demonstrating social responsibility, and proposing feasible suggestions for Earth application migration. Through the "Outcome Display Boards" and "Earth Application Migration Proposals," students will demonstrate the outcomes of their interdisciplinary collaboration. They will also develop communication and expression skills through exhibitions and reports, and complete a reflection and iteration of the entire teaching process. Ultimately, through these diverse tasks and outcomes, students will receive comprehensive evaluations across multiple dimensions, enhancing their critical thinking, metacognition, and reflective evaluation skills.

Table 2. Teaching Process and Evaluation Design Framework

Stage	Subtasks	Subject Integration	Competency Goals	Outcome Evaluation
Stage 1: Problem Analysis and Needs Definition	Mars environment and ecosphere constraint analysis	Geography (Mars environmental parameters), Physics (closed space characteristics)	Scientific reasoning, Systems thinking	Mars Ecosphere Environmental Constraints Report
	Comparative study of Earth and Mars resource cycles	Biology (decomposition technology), Social Studies (environmental significance)	Social responsibility	Earth Kitchen Waste Treatment vs Mars Decomposition Needs Comparison Table
Stage 2: Science Team Tasks (Microbial Decomposition System)	Strain screening and cultivation experiments	Biology (microbial metabolism), Chemistry (culture medium preparation)	Scientific argumentation, Scientific inquiry	High-efficiency Decomposing Strain Screening Report
	Decomposition condition optimization (temperature, pH, oxygen)	Mathematics (data modeling), Physics (environmental simulation)	Data analysis, Model construction	Decomposition Efficiency Heat Map, Optimal Parameter Model
Stage 3: Engineering Team Tasks (Fermentation Device Design)	Device prototype design and functional module planning	Engineering (modular design), General Technology (3D modeling)	Scientific modeling, Engineering practice	Device Prototype Sketch, Functional Module List
	Environmental control system implementation (temperature control, oxygen supply)	Physics (thermodynamics), Information Technology (sensor programming)	Technology application, Problem-solving	Temperature Control Module Design, Oxygen Circulation Scheme
	Cross-environment simulation testing and anomaly handling	Mathematics (cost-efficiency analysis), Chemistry (exhaust gas treatment)	System optimization, Collaborative reflection	Test Log, Anomaly Improvement Plan
Stage 4: Integration and Presentation	System coordination and data validation	Interdisciplinary (Science + Engineering data integration)	Critical thinking	System Operation Efficiency Report, Resource Closed-loop Verification
	Achievement fair and reflective iteration	Art (display board design), Language (report writing)	Metacognition and reflective evaluation	Achievement Display Board, Earth Application Transfer Proposal

4.Implementation Strategies for STEM Education Based on Scientific Higher-Order Thinking

4.1. Building an Interdisciplinary Integration Framework Centered on Scientific Higher-Order Thinking

STEM teaching design should focus on scientific reasoning, scientific argumentation, and scientific modeling, organically integrating knowledge from multiple disciplines. During the problem definition phase, guide students to use systems thinking to analyze complex problems and identify key variables; during the scientific inquiry phase, strengthen students' scientific reasoning abilities by designing controlled experiments and controlling variables to explore causal relationships; during the engineering design phase, cultivate students' scientific argumentation abilities by requiring them to use data and evidence to argue the feasibility of design proposals (Moirano et al., 2020); during the system optimization phase, enhance students' scientific modeling abilities, balancing theoretical rigor with practical applicability, by constructing mathematical models to predict system performance and optimize it. Throughout the process, emphasis should be placed on the

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interdisciplinary connections between different fields of knowledge, such as applying physics principles to engineering design or using mathematical modeling for biological data analysis, to achieve deep integration and transferable application of knowledge (Yata et al., 2020).

4.2. Designing a chain of scientific and engineering practice tasks to cultivate students' advanced scientific thinking abilities

STEM education aimed at fostering advanced scientific thinking should revolve around scientific and engineering practices, designing a series of progressive tasks to guide students in applying advanced scientific thinking through the iterative process of design, testing, and optimization. Task design should follow the engineering design process of "problem definition, demand analysis, conceptual design, detailed design, prototype creation, and testing and validation," with advanced scientific thinking training integrated into each stage. During the needs analysis stage, students develop systems thinking; during the conceptual design stage, they strengthen their scientific reasoning abilities; during the detailed design stage, they enhance their scientific argumentation skills; and during the testing and validation stage, they hone their scientific modeling capabilities (Reider et al., 2016). Concurrently, instruction should uphold the principle that science and engineering share both distinctions and commonalities, jointly driving societal progress. Through group collaboration to complete a series of tasks, students are helped to apply interdisciplinary knowledge in practice, thereby improving their engineering design capabilities and innovative awareness (Yeung & Ng, 2024).

4.3. Establishing a diversified formative evaluation system to comprehensively assess students' scientific higher-order thinking levels

STEM teaching evaluation and monitoring based on scientific higher-order thinking should rely on a multi-level, dynamically developing evaluation system and adopt diverse evaluation methods. This can be achieved by observing students' experimental design processes, analyzing their scientific papers, and assessing their mathematical models to comprehensively examine their ability to apply scientific higher-order thinking to solve complex problems. Evaluation should also be integrated throughout the entire teaching process, combining dynamic and static evaluation methods. Dynamic evaluation can be conducted through project logs, group discussions, and other methods to focus on the development of students' thinking processes; static evaluation, on the other hand, can be conducted through final project presentations, report writing, and other forms to assess students' comprehensive abilities (Sun et al., 2025). Furthermore, evaluation should emphasize self-assessment and peer assessment to cultivate students' reflective abilities and critical thinking. Through multi-dimensional, comprehensive evaluation, it objectively reflects students' learning outcomes and provides evidence-based improvement evidence for teaching refinement (Zhou, 2022).

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