

ORIGINAL

Design and Development of the ACADEMIE Instructional Model: Integrating Project-Based Learning and Scientific Critical Thinking in Biology Education

Diseño y Desarrollo del Modelo Instruccional ACADEMIE: Integración del Aprendizaje Basado en Proyectos y del Pensamiento Crítico Científico en la Enseñanza de la Biología

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ABSTRACT

The demand for 21st-century learning requires instructional models that strengthen higher-order thinking, inquiry, and collaboration. In biology education, however, teacher-centered methods still dominate and limit students' scientific reasoning and process skills. This gap underscores the importance of developing models that integrate inquiry-based and critical thinking approaches. The study aimed to design, validate, and test the effectiveness of the ACADEMIE instructional model, which combines Project-Based Learning (PjBL) and Scientific Critical Thinking (SCT) to enhance conceptual understanding and science process skills in higher education biology. Using the ADDIE framework, the model development included five phases: analysis, design, development, implementation, and evaluation. Data were drawn from needs assessments, expert validations, small-scale practicality trials, and quasi-experimental testing. Quantitative data (Likert-scale rubrics, TCR percentages, t-test) and qualitative inputs (expert comments and student feedback) were analyzed. Thirty-two journal sources informed the theoretical basis of the study. Expert validation yielded scores above 4,3 for content, language, and design. The practicality index exceeded 82 % for all products, while experimental testing showed significant improvement in students' conceptual understanding and science process skills compared with traditional instruction ($p < 0,001$). The ACADEMIE model bridges the gap between theory and practice through inquiry and critical analysis in biology learning. Its high validity, practicality, and effectiveness confirm its potential as an innovative and adaptable instructional framework for developing essential 21st-century competencies.

Keywords: Project-Based Learning; Scientific Critical Thinking; Science Process Skills; Biology Education; Instructional Model.

RESUMEN

La demanda del aprendizaje del siglo XXI exige modelos instruccionales que fortalezcan el pensamiento de orden superior, la indagación y la colaboración. En la enseñanza de la biología, sin embargo, los métodos centrados en el docente aún predominan y limitan el razonamiento científico y las habilidades de proceso de los estudiantes. Esta situación resalta la importancia de desarrollar modelos que integren el enfoque indagativo y el pensamiento crítico científico. El estudio tuvo como objetivo diseñar, validar y evaluar la efectividad del modelo instruccional ACADEMIE, que combina el Aprendizaje Basado en Proyectos (ABP) y el Pensamiento Crítico Científico (PCC) para mejorar la comprensión conceptual y las habilidades de los procesos científicos en la educación superior en biología. Mediante el marco ADDIE, el desarrollo del modelo comprendió

cinco fases: análisis, diseño, desarrollo, implementación y evaluación. Los datos se obtuvieron a partir de análisis de necesidades, validaciones de expertos, pruebas de practicidad a pequeña escala y ensayos cuasi-experimentales. Se analizaron datos cuantitativos (rúbricas tipo Likert, porcentajes TCR, prueba t) y cualitativos (comentarios de expertos y retroalimentación estudiantil). Treinta y dos fuentes bibliográficas fundamentaron la base teórica del estudio. La validación de expertos arrojó puntuaciones superiores a 4,3 en contenido, lenguaje y diseño. El índice de practicidad superó el 82 % en todos los productos, y la prueba experimental mostró mejoras significativas en la comprensión conceptual y en las habilidades de proceso en comparación con la enseñanza tradicional ($p < 0,001$). El modelo ACADEMIE demuestra una alta validez, practicidad y efectividad, consolidándose como un marco innovador y adaptable para desarrollar las competencias esenciales del siglo XXI.

Palabras clave: Aprendizaje Basado en Proyectos; Pensamiento Crítico Científico; Habilidades de Proceso Científico; Enseñanza de la Biología; Modelo Instruccional.

INTRODUCTION

The rapid advancement of science and technology in the 21st century has transformed the educational landscape, requiring systems of instruction that develop higher-order thinking, analytical reasoning, and problem-solving skills. In this context, biology education plays a vital role in fostering conceptual understanding and scientific literacy, as it equips students to engage in evidence-based reasoning and practical inquiry. Historically, however, biology instruction, especially at the tertiary level, has relied heavily on lecture-based and teacher-centered pedagogies that emphasize memorization over scientific exploration. This long-standing approach, though efficient for content delivery, has limited the cultivation of inquiry skills and critical reasoning. Consequently, many students struggle to connect theoretical knowledge with real-world contexts or apply biological principles in investigative settings. Research among biology students at Universitas Lancang Kuning, for instance, revealed persistent weaknesses in translating conceptual knowledge into practical application and inquiry-based activities, highlighting a structural problem in traditional instruction.^(1,2,3,4)

The shift to online learning during the COVID-19 pandemic further exposed these instructional limitations while simultaneously opening new opportunities for transformation. The widespread adoption of digital learning environments encouraged educators to explore more participatory and student-centered pedagogies. Studies conducted during and after the pandemic showed that interactive digital platforms can enhance engagement, encourage inquiry, and foster collaboration when properly integrated into instructional design.^(5,6,7) These developments marked a turning point in educational innovation and underscored the urgency of creating instructional models that merge interactivity, critical reflection, and contextual learning to meet modern educational demands.

In response to these pedagogical challenges, Project-Based Learning (PjBL) emerged as a transformative instructional strategy that situates learning within authentic, problem-solving contexts. PjBL enables students to construct knowledge actively through project design, teamwork, and reflection, promoting motivation and conceptual integration. Numerous studies confirm that PjBL enhances creativity, critical analysis, and collaboration key competencies required in STEM fields.^(8,9,10,11) Complementing this is Scientific Critical Thinking (SCT), defined as the disciplined process of analyzing data, evaluating evidence, and drawing reasoned conclusions. SCT trains students to assess claims, test hypotheses, and apply logical reasoning to scientific problems.^(12,13) While both systems have independently proven effective, their integration remains limited in higher education biology. Existing research often isolates these approaches, overlooking the potential synergy that arises when inquiry-driven project work is scaffolded through structured critical thinking stages.

The present study introduces and analyzes the ACADEMIE instructional model (Analyzing, Creating Schedule, Designing Project, Explaining, Monitoring, Inferring, and Evaluating), an innovative integration of PjBL and SCT designed to bridge this pedagogical gap. The model aims to demonstrate that each stage of project-based learning can be enhanced by structured critical thinking processes, leading to improved conceptual understanding and science process skills. Developed through the ADDIE framework (Analysis, Design, Development, Implementation, and Evaluation), the ACADEMIE model provides a structured yet flexible pedagogical design that guides both instructors and students in achieving higher-order scientific reasoning.

This study is justified by the persistent inadequacies of conventional biology instruction, which continues to prioritize content coverage over cognitive development. By integrating project-based learning with scientific critical thinking, the ACADEMIE model seeks to contribute a theoretically grounded and empirically validated framework that enhances inquiry, reflection, and application. Therefore, the general objective of this research is to develop, analyze, and validate the ACADEMIE instructional model as an effective approach to improving

conceptual understanding and science process skills among university biology students. This work not only addresses a critical educational need but also aligns with the broader goal of equipping learners with 21st-century scientific competencies essential for lifelong learning and professional practice.

Literature review

The literature review complements the introduction by providing a theoretical foundation that supports the need for the ACADEMIE instructional model, which integrates Project-Based Learning (PjBL) and Scientific Critical Thinking (SCT) in biology education. While the introduction highlighted the educational challenges and the gap between theory and practice, this section analyzes the pedagogical concepts underlying both approaches and their potential integration. By examining the characteristics and contributions of each framework, this section establishes the conceptual rationale for developing the ACADEMIE model and clarifies how it addresses existing instructional deficiencies in fostering higher-order thinking and science process skills.

Project-Based Learning (PjBL)

Project-Based Learning (PjBL) is a student-centered instructional approach that organizes learning around authentic projects designed to solve real-world problems. It positions students as active constructors of knowledge through inquiry, collaboration, and reflection.^(14,15) Central to PjBL are guiding questions and tangible outcomes that promote deep conceptual understanding. Research indicates that PjBL enhances creativity, problem-solving, and motivation, bridging the gap between theoretical content and practical application.^(16,17) Within biology education, PjBL facilitates investigating of natural phenomena, experiments, and application scientific methods to topics such as environmental sustainability and health.^(16,18) Moreover, it cultivates essential transversal competencies such as teamwork, communication, and adaptability—skills that are crucial in 21st-century science education. Studies in Indonesian higher education confirm that successful implementation of PjBL significantly improves conceptual understanding and science process skills, though it requires careful scaffolding to align with curriculum standards.^(18,19)

Scientific Critical Thinking (SCT)

Scientific Critical Thinking (SCT), as defined in the present study, refers to the systematic cognitive processes involved in analyzing scientific problems, evaluating evidence, and drawing reasoned conclusions. SCT encompasses essential thinking skills such as analysis, inference, evaluation, and interpretation, enabling students to assess arguments and validate evidence logically.⁽²⁰⁾ When integrated into biology instruction, SCT promotes the interpretation of experimental data, recognition of patterns, and evaluation of competing explanations. Studies have demonstrated that embedding SCT within inquiry-based instruction enhances students' metacognitive awareness and problem-solving capacity. However, traditional curricula often prioritize factual knowledge over analytical reasoning, resulting in underdeveloped scientific literacy. Therefore, integrating SCT with project-based learning creates an opportunity to strengthen both cognitive and procedural dimensions of science education.

Science Process Skills (SPS)

Science Process Skills (SPS) constitute the core of scientific literacy, encompassing both basic skills such as observation, classification, and measurement and integrated skills, including hypothesizing, experimenting, and interpreting data.⁽²¹⁾ These skills enable students to construct scientific understanding through inquiry, experimentation, and reasoning. Empirical studies confirm that mastery of SPS transforms students from passive learners into active investigators who connect theory with real-life applications.^(22,23) Incorporating SPS into instructional models like PjBL and SCT has been shown to improve students' capacity to design experiments, analyze results, and relate findings to everyday experiences.^(24,25,26,27) This synthesis of SPS, PjBL, and SCT underscores the importance of an integrated instructional model capable of cultivating critical inquiry, analytical reasoning, and scientific problem-solving skills.

Instructional Model Development: The ADDIE Framework

The theoretical frameworks discussed above collectively justify the creation of the ACADEMIE instructional model, which unites Project-Based Learning, Scientific Critical Thinking, and Science Process Skills within a systematic development process. The model, whose name represents its seven stages, Analyzing, Creating Schedule, Designing Project, Explaining, Monitoring, Inferring, and Evaluating, was structured through the ADDIE design framework (Analysis, Design, Development, Implementation, and Evaluation). This systematic integration ensures theoretical coherence and methodological rigor in addressing deficiencies identified in previous instructional practices. Finally, it should be noted that since the ACADEMIE system was newly developed by the authors, the methodological focus of this research centers on the study of the finished product, emphasizing its design, validation, and testing stages. Thus, the method section has been aligned

to highlight the product's development process rather than an intervention-based experimental design. This alignment ensures that the research focus remains consistent with the paper's stated objective to develop, analyze, and validate an innovative instructional model that bridges the gap between theory and practice in higher education biology.

METHOD

Type of Study

This research employed a non-observational Research and Development (R&D) design that combined developmental and quasi-experimental components. The study aimed to develop, analyze, and validate an instructional model, ACADEMIE, that integrates Project-Based Learning (PjBL) and Scientific Critical Thinking (SCT) to enhance biology students' conceptual understanding and science process skills. The R&D approach followed the ADDIE framework (Analysis, Design, Development, Implementation, and Evaluation) as proposed by Morrison, Ross, and Kemp, ensuring a systematic process from needs identification to empirical testing.

Universe and Sample

The universe of the study consisted of undergraduate biology students and lecturers from two Indonesian higher education institutions: Universitas Lancang Kuning (UNILAK) and Universitas Muhammadiyah Malang (UMM). Participants were selected purposively based on inclusion criteria that required:

1. Active enrollment or teaching in biology education courses.
2. Familiarity with project-based or inquiry-based learning methods.
3. Willingness to participate in all phases of data collection.

The sample comprised two groups:

- Experts: five biology education specialists and instructional designers who conducted the model validation.
- Students: fifty undergraduate biology students who participated in small-group and field trials during the implementation phase.

This purposive selection ensured representation of relevant pedagogical and learner perspectives essential for model development and evaluation.

Variables

The study focused on three primary variables aligned with the ACADEMIE model's intended learning outcomes:

- Conceptual Understanding - measured through standardized biology tests adapted to course objectives.
- Science Process Skills (SPS) - assessed using observation rubrics covering both basic (e.g., observation, measurement) and integrated skills (e.g., hypothesizing, interpreting data).
- Scientific Critical Thinking (SCT) - evaluated through indicators of analysis, inference, and evaluation embedded in project-based tasks and reflection rubrics.

These variables were operationalized through quantitative and qualitative measures validated by expert judgment.

Data Collection and Processing

Data were collected systematically throughout the ADDIE phases:

- Analysis Phase: questionnaires, interviews, and classroom observations identified curriculum gaps, student needs, and instructional challenges. Questionnaire and interview items were developed from the objectives of the analysis phase and validated through expert review. Interviews were conducted with 10 lecturers and 40 students between August and October 2023.
- Design Phase: data from the analysis informed the creation of the ACADEMIE model blueprint. Learning objectives, syntax, and instructional materials were designed to integrate PjBL and SCT elements.
- Development Phase: expert validation used Likert-scale rubrics (Aiken's V) to evaluate content, language, and design.
- Implementation Phase: quasi-experimental testing was conducted over one semester (February-June 2024) to assess practicality and effectiveness. Data included pretest-posttest scores, classroom observations, and student feedback.
- Evaluation Phase: both formative and summative evaluations were carried out. Quantitative data (expert validation, TCR percentage, t-test, and N-gain) were analyzed using SPSS 26, while qualitative

data (expert comments, focus group discussions, and observation notes) were coded thematically for triangulation.

All collected data were processed through descriptive and inferential analyses to ensure validity, reliability, and interpretive accuracy.

Ethical Standards

All research procedures were conducted in compliance with institutional and national research ethics. The study received formal approval from the Ethics Committee of Universitas Muhammadiyah Malang (Approval No. UMM/Ethics/2023-211). Prior to participation, informed consent was obtained from all respondents, who were briefed about the study's purpose, voluntary participation, confidentiality of responses, and the right to withdraw at any time. No personal or sensitive data were disclosed. The study adhered to the ethical principles of respect, beneficence, and academic integrity.

RESULTS

Needs Analysis Findings

Data obtained from questionnaires and semi-structured interviews with biology lecturers and students at Universitas Lancang Kuning and Universitas Muhammadiyah Malang revealed limited integration of scientific critical thinking (SCT) and science process skills (SPS) within existing courses. The most frequent gaps concerned restricted inquiry opportunities, weak reasoning components (analysis, inference, evaluation), and minimal practice of observation, hypothesis formulation, and experimentation. These findings, extracted from the analysis phase of the study, justified the subsequent design of the ACADEMIE model to address the identified curricular deficiencies.

ACADEMIE Model Design

Figure 1 presents the finalized ACADEMIE instructional syntax, which was generated during the design phase of the ADDIE process. The model comprises seven interrelated phases: Analysis, Create Schedule, Design Project, Explanation, Monitoring, Inference, and Evaluation, that organize project-based activities into a coherent instructional sequence. Each phase represents an operational component of the model rather than an experimental result; thus, this section reports only the developed structure as a verified outcome of the design process.

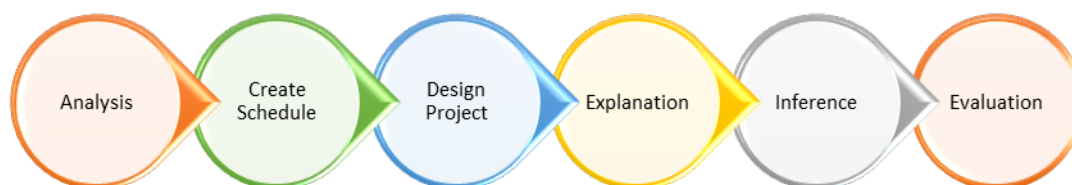


Figure 1. Presents the sequential flow of these phases

Instructional Products Developed

Three instructional products were produced to facilitate implementation of the ACADEMIE model:

- Model Book, documenting the theoretical foundation and pedagogical rationale of the model.
- Instructor's Guide, containing teaching procedures, assessment rubrics, and project-monitoring templates.
- Student Workbook, comprising structured project tasks, inquiry activities, and reflective sheets.

These products were the direct outputs of the development phase. Their empirical evaluation results are summarized in tables 1 and 2.

Validation Results

Validation was performed by three experts in biology education and instructional design, who rated the quality of each product using a 5-point Likert instrument (1 = very poor, 5 = very good).

Product	Mean Score	Interpretation
Model Book	4,32	Very Good
Instructor's Guide	4,34	Very Good
Student Workbook	4,31	Very Good

As summarized in table 1, mean scores ranged from 4,31 to 4,34, corresponding to the category *Very Good*. The evaluation covered content accuracy, language clarity, and design feasibility. These data were extracted from the expert validation forms described in the methodology. The consistently high scores confirm that all products satisfied the established quality indicators prior to pilot application.

Practicality Assessment

A small-scale trial involving 50 undergraduate biology students assessed the clarity, usability, and relevance of the instructional materials. Responses were rated on a 5-point scale and converted into TCR percentages (≥ 80 = practical; ≥ 90 = very practical). Results indicated that the Model Book obtained a mean of 4,14 (TCR = 82,86 %), the Instructor's Guide 4,22 (TCR = 84 %), and the Student Workbook 4,53 (TCR = 90,56 %). These values, drawn from the practicality questionnaires administered during the implementation phase, demonstrate that all instructional products met the established usability standards for classroom application.

Effectiveness Test

Effectiveness was examined through a quasi-experimental comparison between two groups of undergraduate students: an experimental group ($n = 30$) taught using the ACADEMIE model and a control group ($n = 30$) receiving conventional instruction.

Table 2. Posttest Descriptive Statistics for Experimental and Control Groups			
Group	Mean	SD	Min-Max
Experimental	205,00	17,47	171-234
Control	177,67	12,52	161-219

Post-test scores (table 2) show that the experimental group achieved a higher mean ($205,00 \pm 17,47$) than the control group ($177,67 \pm 12,52$). Statistical analysis using an independent-samples *t*-test yielded $t(58) = 4,687$, $p < 0,001$, indicating a significant difference in learning outcomes between the two groups. The data were obtained from the post-test instruments described in Section 3,4 and represent direct evidence of the model's effectiveness.

Key Findings

The major empirical findings of this study are as follows:

1. Needs analysis confirmed substantial gaps in the existing biology curriculum related to the integration of SCT and SPS.
2. The ACADEMIE model was successfully developed through the ADDIE framework, resulting in three instructional products validated with mean expert scores above 4,3.
3. Practicality assessments showed that all products were rated *practical* or *very practical* (TCR ≥ 82 %), with the Student Workbook obtaining the highest usability score.
4. Effectiveness testing demonstrated a statistically significant improvement in students' conceptual understanding and SPS performance in the experimental group compared with the control group ($p < 0,001$).

These outcomes, derived from sequential phases of analysis, design, development, implementation, and evaluation, collectively substantiate the empirical success of the ACADEMIE instructional model while maintaining a clear boundary between data presentation and interpretation.

DISCUSSION

Alignment with Constructivist Learning

The results showing significant gains in students' conceptual understanding and science process skills confirm that the ACADEMIE model is grounded in constructivist learning theory. The model's seven phases, which include Analysis, Create Schedule, Design Project, Explanation, Monitoring, Inference, and Evaluation, enabled students to build knowledge through exploration and reflection rather than through passive learning. This finding aligns with the views of Kokotsaki et al.⁽¹⁴⁾ and Anazifa⁽¹⁵⁾, who state that learning becomes meaningful when students engage in authentic inquiry activities.

The effectiveness demonstrated in this study supports the idea that when Project-Based Learning is combined with structured reasoning, students develop deeper understanding and stronger analytical abilities. Similar results were observed by Sahin et al.⁽²⁹⁾ and Astawan et al.⁽³⁰⁾, who reported that guided reflection and reasoning improved learners' cognitive depth and scientific creativity. These findings suggest that the ACADEMIE model successfully operationalizes constructivist principles through systematic integration of Scientific Critical Thinking within inquiry-based instruction.

Contribution to Biology Education

The ACADEMIE model addresses the main pedagogical challenges identified in the needs analysis, particularly the limited practice of inquiry, reasoning, and science process skills. Validation and practicality assessments confirmed that the model's structure can be implemented effectively in higher education contexts.

Compared with previous studies that used general Project-Based or inquiry learning such as those by Yamin *et al.*⁽¹⁸⁾ and Fitri *et al.*⁽⁹⁾ ACADEMIE provides a more structured framework that embeds Scientific Critical Thinking at every learning stage. This integration allows both cognitive and procedural competencies to develop simultaneously. The approach aligns with the conclusions of Dirks⁽²²⁾ and Setiyadi *et al.*⁽²⁵⁾, who emphasized that linking science process skills with inquiry instruction significantly enhances students' analytical performance. Based on these comparisons, the authors conclude that ACADEMIE transforms biology instruction from a memorization-based approach to one that promotes continuous analytical engagement, which was the central objective of this study.

Comparison with Previous Models

When compared with other Project-Based Learning frameworks, ACADEMIE represents an advancement that explicitly unites critical thinking processes with the stages of inquiry. Previous frameworks, such as those developed by Mulyati *et al.*⁽¹⁰⁾ and Can *et al.*⁽²⁴⁾, emphasized creativity and collaboration but did not highlight reflective inference or systematic monitoring. The ACADEMIE model enhances these dimensions by encouraging self-assessment and evidence-based reasoning throughout the learning cycle.

Another distinctive contribution of ACADEMIE is the provision of three complementary instructional materials, namely the Model Book, Instructor's Guide, and Student Workbook. These materials provide consistent guidance for both teachers and students, addressing the practical challenges often noted in earlier studies. Semernia *et al.*⁽³²⁾ found that providing structured instructional resources improves the consistency and reproducibility of pedagogical innovations. Therefore, ACADEMIE offers both theoretical rigor and practical accessibility that strengthen its applicability across biology education contexts.

Limitations

Although the findings are promising, the study is limited by its context and duration. Testing was conducted in one institution and focused on a single set of courses. As a result, the generalizability of the findings remains limited. Similar constraints have been noted in research on instructional model development, such as in the works of Hasni *et al.*⁽¹⁹⁾ and Pradanti⁽¹⁶⁾.

Furthermore, this study did not assess long-term outcomes, including knowledge retention or transfer to other learning contexts. The lack of data on affective dimensions, such as students' motivation and attitudes toward science, also presents an area for further exploration. Addressing these limitations in future studies will strengthen the empirical foundation of the ACADEMIE model and expand its relevance.

Future Directions

Future studies should conduct broader field testing across various universities and sub-disciplines of biology to validate the generalizability of the ACADEMIE model. Longitudinal research is recommended to measure sustained learning outcomes and the internalization of Scientific Critical Thinking skills over time.

As suggested by Wulandari *et al.*⁽²⁸⁾, integrating reflective and project-based strategies over longer periods can deepen critical inquiry. The inclusion of digital tools, such as virtual laboratories and collaborative platforms, as proposed by Dhawan⁽⁶⁾, would enhance student participation and adapt the model to online or blended learning environments. These extensions would align ACADEMIE with contemporary trends in higher education and digital pedagogy.

Implications

Theoretically, the ACADEMIE model contributes to the literature on constructivist and inquiry-based learning by offering an integrated framework that combines Project-Based Learning and Scientific Critical Thinking. Practically, it provides validated instructional materials that can guide educators in implementing student-centered learning effectively. This dual contribution corresponds with the findings of Zulyusri *et al.*⁽³¹⁾, who found that structured, inquiry-driven designs foster autonomy and higher-order reasoning.

In summary, the significant improvements in students' understanding and science process skills indicate that ACADEMIE can serve as a scalable and effective model for advancing 21st-century competencies in biology education. It supports not only conceptual mastery but also the development of critical and creative thinking essential for future scientific and professional challenges.

CONCLUSIONS

This study achieved its primary objective of developing and validating the ACADEMIE instructional model as an innovative framework for enhancing biology education through the integration of Project-Based Learning and

Scientific Critical Thinking. The model reflects a constructivist approach that encourages inquiry, reflection, and collaboration, thereby supporting learners' ability to think critically and solve authentic scientific problems. Through its systematic development process, ACADEMIE demonstrates how theoretical concepts can be translated into practical instructional design that promotes both cognitive and procedural competencies. The study contributes to educational research by offering a replicable model that can guide future curriculum innovation in biology and other STEM disciplines. More broadly, the ACADEMIE framework illustrates how higher education can cultivate 21st-century competencies such as analytical reasoning, creativity, and collaboration, preparing students to participate effectively in scientific and professional communities.

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