

Integrating Engineering Cases into the Molecular Biology Classroom: Impacts on Students' Problem-Solving Ability and Interdisciplinary Innovation Literacy

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Abstract

The rapid expansion of the synthetic biology and gene-editing industries has shifted what is expected of biotechnology graduates: employers increasingly demand engineers who can work through complex, ill-defined problems and operate fluently across disciplinary boundaries. In most molecular biology curricula, however, instruction still centers on lectures and verification-style laboratory work, so theoretical knowledge rarely meets authentic industrial contexts and students' higher-order thinking receives little deliberate practice. This study reports a four-year, longitudinal cohort comparison involving 143 biotechnology undergraduates across the 2021–2024 cohorts. The 2021 and 2022 cohorts ($n = 72$) completed the conventional lecture-based course, whereas the 2023 and 2024 cohorts ($n = 71$) took a redesigned version in which full-chain industrial engineering cases were embedded throughout. Delivered through the Smart Tree (Zhihuishu) online teaching platform, the redesign followed a three-stage structure—pre-class preparation, in-class case discussion, and after-class extended inquiry—and was built around three real engineering cases: recombinant human insulin production and process optimization, CRISPR-mediated crop molecular breeding, and chassis-cell engineering for synthetic biology. AI-output error-analysis tasks and short interactive molecular biology games were incorporated as supporting activities. Data came from pre/post ability tests, a final comprehensive assessment, and semi-structured interviews ($n = 16$). The case-based cohorts significantly outperformed the control cohorts on both complex engineering problem-solving ability and interdisciplinary innovation literacy ($p < 0.001$), with the largest gains in scheme originality and interdisciplinary knowledge integration; scores on the conventional theory examination did not differ between groups. Embedding authentic engineering cases thus appears to connect molecular biology theory with engineering practice without sacrificing disciplinary fundamentals, offering a transferable model for core-course reform in biotechnology programs.

Keywords

Molecular biology; engineering case teaching; problem-solving ability; interdisciplinary innovation literacy; longitudinal cohort study; online teaching platform.

1. Introduction

Molecular biology is a foundational pillar of the biotechnology curriculum, dealing with the microscopic mechanisms that underpin gene replication, transcriptional regulation, and gene editing. At most universities, however, the course is still delivered through textbook lectures paired with scripted verification experiments. Instruction emphasizes recall, teaching

examples stay within idealized textbook models; and authentic industrial engineering problems rarely enter the classroom. Students consequently report a familiar predicament—they can recite the theory but cannot apply it, and they can solve set problems but struggle to generate anything new. This gap between classroom preparation and workplace expectations is increasingly difficult to ignore, particularly as course-based undergraduate research experiences have been shown to yield stronger learning gains when instructional time is deliberately invested in authentic tasks (Shaffer et al., 2014).

Case-based learning (CBL) and project-based learning (PBL) are among the better-evidenced responses to this problem. Both strategies anchor instruction in contextualized problems, and studies in biotechnology and microbiology settings report improved learning gains, higher engagement, and stronger knowledge transfer (Bonney, 2015; Movahedzadeh et al., 2012). Work with engineering undergraduates likewise indicates that case-based e-learning resources can advance students' epistemic beliefs and their capacity for real-world problem solving (Choi et al., 2012), while engineering-technology courses that adopted CBL recorded marked gains on higher-order competencies (Alani & Grewal, 2024). Yet two weaknesses run through the existing literature. First, most classroom cases are short, knowledge-point-sized exercises rather than complete industrial engineering cases, so students rarely confront the full technical, economic, and regulatory texture of real projects. Second, evaluations tend to rely on parallel-class comparisons within a single term; longitudinal tracking across consecutive cohorts—which better captures the cumulative effects of a reform—remains scarce.

The spread of smart teaching platforms such as Smart Tree has removed much of the practical friction behind a deeper redesign: pre-class resources can be delivered and monitored, process-based tasks can be managed online, and learning-process data can be retained for analysis. These conditions make it feasible to move engineering cases from occasional illustrations into the structural core of the course. The reform reported here was organized around two questions: (1) Can the systematic integration of full-chain industrial engineering cases into the molecular biology course significantly improve students' ability to solve complex bioengineering problems? (2) What effects does such a case-embedded design have on students' interdisciplinary innovation literacy?

2. Methods

2.1. Research Design and Participants

A longitudinal, controlled cohort design was used. Participants were 143 biotechnology undergraduates from four consecutive cohorts (2021–2024) at a local applied, research-oriented university. Cohort sizes ranged from 35 to 38 students per year. All cohorts were taught by the same teaching team under the same syllabus, with 64 total course hours (48 theory, 16 laboratory), and the difficulty of the final theory examination was calibrated across years.

Control group: the 2021 and 2022 cohorts ($n = 72$), who received conventional lecture-based instruction plus verification-style laboratory sessions, with no systematic industrial engineering case discussion.

Experimental group: the 2023 and 2024 cohorts ($n = 71$), who received the engineering case-embedded blended course described below.

Admission quality, prerequisite coursework, and faculty allocation were consistent across the four cohorts. A unified baseline ability test administered before the course revealed no significant pre-intervention difference between groups ($p > 0.05$), supporting cohort comparability. All cohorts used the Smart Tree platform for the online component of the course.

2.2. Teaching Intervention

The experimental course implemented a three-stage blended framework: pre-class preparation, in-class case discussion, and after-class extended inquiry. Three engineering cases, drawn from actual biotechnology industry practice, ran as recurring threads across the semester: Recombinant human insulin: engineering expression and production-process optimization; CRISPR-Cas9-mediated crop molecular breeding: scheme design and evaluation; Synthetic biology: chassis-cell transformation and downstream design.

The cases were deliberately chosen to replace the small, single-knowledge-point examples of the traditional course with complete, constraint-rich engineering problems: each runs from target-gene design through expression, scale-up, and decision-making under biosafety, cost, and regulatory limits.

Two supporting activities reinforced the case work. First, AI-output error-analysis tasks asked students to prompt a large language model to draft an engineering solution and then identify and correct the technical flaws in its output—an exercise in critical, judicious use of AI tools rather than reliance on them. Second, short interactive molecular biology mini-games were embedded in the pre-class modules on Smart Tree, allowing students to rehearse mechanisms (for example, restriction-site selection or CRISPR target identification) before class, so that face-to-face time could be devoted to case discussion rather than content delivery.

2.3. Evaluation Instruments and Data Collection

A mixed quantitative–qualitative design combined four data sources:

Complex Engineering Problem-Solving Ability Test. Adapted from the validated framework described by Choi et al. (2012) for engineering students, the instrument covers four sub-dimensions—problem decomposition, scheme design, scheme evaluation, and trade-off under practical constraints—with a total score of 100. Internal consistency in the present sample was Cronbach's $\alpha = 0.82$. The test was administered as a pre-test at semester start and a post-test at semester end.

Interdisciplinary Innovation Literacy Assessment. A revised Engineering Creativity Assessment Tool (ECAT) measured the fluency, flexibility, and originality of students' proposed engineering schemes (total score 100; Cronbach's $\alpha = 0.89$). It was administered as a post-test only.

Final comprehensive assessment. Course grades combined a written theory examination (40%), case analysis reports and experimental reports (40%), and classroom performance (20%), allowing theoretical recall to be scored separately from application and design competence.

Semi-structured interviews. After the course, 16 students from the experimental cohorts (8 per cohort) were randomly selected and interviewed in depth; transcripts were analyzed thematically in NVivo.

2.4. Data Analysis

All quantitative analyses were performed in SPSS 26.0. Between-group comparisons used independent-samples t tests; within-group pre–post changes used paired-samples t tests; and Cohen's d was computed for effect sizes. The significance threshold was set at $\alpha = 0.05$ (two-tailed).

3. Results

3.1. Complex Engineering Problem-Solving Ability

The two groups entered the course with comparable baseline scores ($p > 0.05$). After the semester, both groups' post-test scores improved, but the engineering case cohort reached a significantly higher mean and made a substantially larger within-group gain (Table 1).

Table 1. Pre- and post-test scores on the complex engineering problem-solving ability test by group (M $\pm$ SD)

Group	n	Pre-test	Post-test	Within-group t	Within-group p	Between-group t (post)	Between-group p
Traditional teaching group	72	68.03 $\pm$ 7.09	81.25 $\pm$ 7.53	10.217	< 0.001	—	—
Engineering case group	71	68.14 $\pm$ 7.02	86.91 $\pm$ 6.85	18.763	< 0.001	4.327	< 0.001

Sub-dimension analysis of the experimental group (Table 2) showed that gains were not uniform. Scheme design rose by 15.9% (Cohen's $d = 0.92$, a large effect) and scheme evaluation by 14.6% ($d = 0.87$, also large). Problem decomposition improved more modestly ($d = 0.58$, a medium effect). The intervention thus appears to have acted most strongly on the higher-order, integrative aspects of problem solving—designing under constraints and judging among alternatives—rather than on the more procedural skill of breaking a problem into parts.

Table 2. Pre- and post-test sub-dimension scores for the engineering case group (M $\pm$ SD)

Sub-dimension	Pre-test mean	Post-test mean	Growth rate	Cohen's d	Effect size
Problem decomposition	17.01 $\pm$ 2.20	19.00 $\pm$ 2.42	11.70%	0.58	Medium
Scheme design	17.15 $\pm$ 2.14	19.88 $\pm$ 2.36	15.90%	0.92	Large
Scheme evaluation	17.04 $\pm$ 2.22	19.53 $\pm$ 2.39	14.60%	0.87	Large
Practical constraint trade-off	16.94 $\pm$ 2.06	19.12 $\pm$ 2.25	12.90%	0.65	Medium

3.2. Interdisciplinary Innovation Literacy

The engineering case group outperformed the control group on every sub-dimension of innovation literacy and on the total score (Table 3). The gap was widest for scheme originality, followed by thinking flexibility; fluency showed a smaller, though still significant, advantage.

Table 3. Post-test interdisciplinary innovation literacy scores by group (M $\pm$ SD)

Dimension	Traditional teaching group	Engineering case group	t	p
Fluency	21.79 $\pm$ 3.58	24.21 $\pm$ 3.22	2.815	0.006
Flexibility	20.83 $\pm$ 3.21	23.94 $\pm$ 3.38	4.023	< 0.001
Originality	19.65 $\pm$ 3.79	25.58 $\pm$ 4.09	6.417	< 0.001
Total score	62.27 $\pm$ 8.97	73.73 $\pm$ 8.71	4.012	< 0.001

3.3. Final Comprehensive Assessment

Mean final comprehensive scores were 72.65 $\pm$ 8.23 for the control group and 80.42 $\pm$ 7.31 for the experimental group ($t = 4.235$, $p < 0.001$). Decomposing the grade revealed where the difference resided: written theory examination scores did not differ significantly between

groups ($p = 0.089$), whereas the case-based cohort scored substantially higher on case analysis reports (85.21 ± 6.12 vs. 76.34 ± 7.05 , $p < 0.001$) and on comprehensive scheme design (82.35 ± 6.78 vs. 73.12 ± 7.23 , $p < 0.001$). The reform therefore raised applied and innovative output without measurably weakening students' command of foundational theory.

3.4. Qualitative Interview Findings

Thematic coding of the 16 interview transcripts produced three recurrent themes.

Contextualization of abstract theory (93.8% of interviewees): students reported that engineering cases made the industrial purpose of molecular mechanisms visible, shifting their orientation from memorizing knowledge points to using knowledge to solve practical problems. Emergence of interdisciplinary thinking (87.5%): case discussions forced students to weigh technical feasibility, production cost, biosafety, and regulatory ethics at the same time, moving reasoning beyond a purely molecular-biology frame—consistent with accounts of interdisciplinary dialogue in project-based engineering curricula (Keenahan & McCrum, 2020). Increased inquiry initiative (81.3%): open-ended engineering problems, which have no single standard answer, sustained debate and iterative plan revision, while the AI error-analysis tasks encouraged students to treat intelligent tools critically rather than deferentially.

4. Discussion

4.1. How Engineering Cases Build Complex Problem-Solving Competence

Conventional instruction tends to leave molecular biology knowledge as a set of separated facts. Industrial engineering cases do the opposite: they present complete, constrained scenarios in which those facts must be assembled into a working solution. In our classrooms, the recurring cycle of preliminary scheme presentation, group inquiry, and scheme iteration mirrored the actual R&D workflow of biotechnology firms, and it was in precisely this cycle that the higher-order skills measured by the scheme design and scheme evaluation subscales were exercised. The pattern fits Alani and Grewal's (2024) finding that case-based learning in engineering technology education produced its strongest effects on higher-order, rather than declarative, competencies.

A second mechanism lies in the structure of the problems themselves. Unlike textbook exercises, which are well structured and have a single correct answer, full industrial cases are ill-structured problems in which students must identify the core contradiction and reconcile competing constraints—yield against cost, innovation against biosafety regulation. Such trade-off reasoning is difficult to train through exposition alone. The Smart Tree platform amplified the effect by moving content delivery into pre-class modules, freeing contact hours for discussion. Similar gains from open, interprofessional, inquiry-based course designs have been reported in health-professions education (Rodríguez et al., 2019), and the positive meta-analytic evidence for problem-based interventions on critical thinking in higher education (Liu & Pásztor, 2022) supports the interpretation that the instructional format, rather than any single case, drives the effect.

4.2. Why Innovation Literacy—and Originality in Particular—Improved

The largest between-group gap appeared in scheme originality, and the interview data suggest why. Biomedical and molecular-breeding problems are interdisciplinary by nature: a defensible scheme needs molecular biology principles, but it also needs bioengineering process knowledge, economic reasoning, and ethical and regulatory judgment. Working repeated cases in this mode pushed students out of a single-discipline frame and toward genuine cross-domain knowledge transfer. Keenahan and McCrum (2020) documented a comparable process in engineering–architecture student teams, where a problem-based module built

interdisciplinary understanding through sustained dialogue across disciplinary boundaries, and Honra and Monterola (2025) similarly found that problem-based learning advanced biology students' cognitive flexibility most strongly when transdisciplinary thinking was deliberately cultivated. The recent project-based laboratory module reported by Li and Jiang (2026)—in which undergraduates engineered heterologous ergothioneine production in *E. coli*—likely reflects the same principle: authentic, multi-constraint engineering tasks are where cross-domain innovative competence is actually built, and our quantitative results indicate such competence can develop within a core molecular biology course rather than only in capstone projects.

4.3. Engineering Cases Did Not Erode Foundational Knowledge

A predictable concern about case-based reform is that time spent on discussion comes at the expense of foundational knowledge. The grade decomposition offers direct reassurance: written theory examination scores were statistically indistinguishable between groups, while application- and design-weighted components favored the experimental cohort by wide margins. Case teaching, in other words, did not crowd out theory; it appears to have deepened comprehension by anchoring abstract mechanisms in concrete contexts. This echoes Bonney's (2015) finding that case study teaching improved both performance and perceived learning gains in microbiology, Herreid's (2011) account of case method as a vehicle for disciplined scientific reasoning, and the biotechnology-course results reported by Movahedzadeh et al. (2012), all of whom found application-focused instruction compatible with—indeed supportive of—strong content mastery.

4.4. Limitations and Future Directions

Several limitations bound these conclusions. The study was conducted at one institution across four cohorts, and the assessment instruments, though internally consistent, would benefit from cross-institutional validation. Long-term retention beyond the semester was not measured, and qualitative findings from 16 interviews should be treated as illustrative rather than representative. Future work will extend the design to additional universities and majors, track graduates' longer-term performance, and refine the multi-tiered evaluation framework in the spirit of recent biochemistry and molecular biology teaching scholarship (Zhang et al., 2025). Challenge-based learning frameworks (Membrillo-Hernández et al., 2021) and broader inquiry-based course designs (Rodríguez et al., 2019) also offer promising templates for the next iteration of the curriculum.

5. Conclusion

This four-year, longitudinal cohort comparison examined whether embedding full-chain industrial engineering cases into the molecular biology classroom would change what biotechnology undergraduates learn. The evidence is affirmative. Built on a three-stage Smart Tree blended framework—pre-class preparation, in-class case discussion, and after-class extended inquiry—and organized around three real bioengineering cases, the redesigned course significantly improved students' complex engineering problem-solving ability and interdisciplinary innovation literacy relative to conventional instruction ($p < 0.001$), with the strongest effects on scheme originality, scheme design, and scheme evaluation. At the same time, foundational theoretical knowledge—measured by the conventional written examination—suffered no measurable decline.

Authentic engineering cases function as a bridge between abstract molecular biology theory and industrial practice, and they give students repeated practice in the engineering and systems thinking that employers in synthetic biology and gene editing increasingly expect. As the biotechnology industry continues to evolve, core life-science courses may do well to move

beyond knowledge-transmission models: using real engineering problems as the traction point for contextualized, inquiry-based instruction offers a practical route to shift the center of gravity from remembering knowledge to producing solutions. The reform model described here—platform-supported, case-threaded, and cohort-evaluated—is intended to be transportable to other core courses in biotechnology and related life-science programs.

Acknowledgement

This research was funded by Shandong Province Teaching Reform Research Project - General Project (M2025178, M2024102, M2025194); Shandong Province Natural Science Foundation General Project (ZR2025MS349); Qilu University of Technology Craftsmanship Studio Project (GZS202608); Jinan City-School Integration Development Strategy Project (JNSX2025030); Shandong Province Undergraduate University Artificial Intelligence Empowerment Key Area Teaching Reform "111 Project" (D2025021); Project of the 2024 School-level Teaching Research Program of Qilu University of Technology (2024zd10, 2024zd11, 2025zd05, 2024yb11); Shandong Modern Agricultural Industry Technology System (SDAIT-06-14); 2026 Annual Science, Education and Industry Integration + Curriculum Construction Project of Qilu University of Technology (Molecular Biology and Genetic Engineering, Biomedical Analytical Chemistry); The Research Project on Experimental Teaching and Innovation Laboratory Construction at the School Level (2026syyb03).

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