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Development and application of a triadic integration teaching model in newly established undergraduate programs: synergistic project-, practice-, and competition-based learning

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The cultivation of high-quality engineering talent in newly established undergraduate programs presents significant challenges, particularly in integrating theoretical knowledge with practical and innovative capabilities. This study proposes and implements a "triadic integration" teaching model that synergistically combines project-based learning, interactive teaching, and practice-oriented instruction to enhance students' engineering competencies in a materials innovation course. Project-based learning forms the backbone of the model, guiding students through progressively complex tasks—from foundational to comprehensive and advanced projects—while integrating engineering-material innovation competitions to create a closed-loop "teach–learn–compete" pathway. Interactive teaching strategies, including heuristic, inquiry-based, and participatory methods, foster a student-centered learning ecosystem that enhances engagement, collaboration, and critical thinking. Practice-oriented instruction translates theoretical knowledge into practical application through laboratory experiments, simulation, and full-cycle research projects, cultivating problem-solving and innovation skills in authentic engineering contexts. The model's effectiveness was evaluated through student performance, competition achievements, and iterative seminar-based reflection among instructors. Results indicate that the triadic approach not only improves students' technical competence and innovative capacity but also provides a scalable, replicable framework for curriculum innovation in newly established undergraduate programs. This study offers valuable insights for the design and reform of engineering education curricula worldwide.

KEYWORDS

curriculum innovation, engineering education, interactive teaching, practice-oriented instruction, project-based learning, triadic integration

1 Introduction

China is currently undergoing a critical phase of economic restructuring, transformation of growth drivers, and the development of new productive forces. These national trends have generated an urgent need for highly skilled and application-oriented professionals capable of contributing to technological advancement and industrial upgrading (Brühl, 2025; Si et al., 2025; Huang et al., 2025). As the primary institutions responsible for cultivating such talent, universities—especially newly established undergraduate institutions—face a series of challenges arising from rapidly evolving educational environments, diverse student cohorts, and developing faculty structures (Xie and Dou, 2025). Within this context, identifying an integrative and effective teaching model that can address these challenges and cultivate high-quality application-oriented professionals has become both essential and timely.

In recent years, driven by ongoing socio-economic development and reforms in higher education, scholarly interest in innovative pedagogical strategies has increased significantly (Yang and Zhang, 2025). Chinese universities have accumulated extensive experience in project-based learning, practice-oriented instruction, and discipline competition–driven evaluation (Qi et al., 2025). For instance, institutions such as Peking University and Tsinghua University have demonstrated the value of project-based models in enhancing students' practical abilities, creativity, and interdisciplinary application capacity. Similarly, the adoption of practice-oriented teaching approaches has strengthened students' hands-on competencies, enabling them to bridge theoretical knowledge with real-world engineering tasks. Furthermore, discipline competitions have been widely incorporated as mechanisms for assessing educational outcomes, cultivating students' problem-solving ability, and motivating them to pursue innovative solutions. These competitions have also played a vital role in identifying outstanding talent with strong potential for future academic or industrial development. Internationally, countries such as Germany and Switzerland have long-standing and exemplary vocational education systems grounded in practice-based training, producing generations of highly qualified engineers and technicians (Zutavern and Seifried, 2022). Global academic competitions—ranging from mathematics olympiads to engineering design contests—have likewise served as platforms for stimulating innovation and facilitating the recognition of exceptional talents worldwide.

Qinghai University of Technology, a newly established full-time public undergraduate institution founded by the Qinghai Provincial Government in 2019 and formally approved by the Ministry of Education in May 2024, provides a representative case for exploring a new pathway for constructing high-quality engineering education in emerging universities. Situated in western China, the university faces unique developmental tasks but also possesses opportunities for innovation. This study takes Qinghai University of Technology as a case institution and proposes a "triadic integration" teaching model that integrates project-based learning as the guiding principle, practice-oriented instruction as the foundation, and discipline competitions as the evaluative mechanism. Theoretically, this model contributes to the enrichment of existing educational theories by offering a structured and coherent framework tailored to the characteristics of newly established undergraduate institutions. Practically, it supports faculty professional development, enhances teaching and research capacity, and facilitates the transformation of instructors from "craftsmen of teaching" to "educators in essence." At the institutional level, the model encourages the integration and optimization of resources, improves resource efficiency, and supports the development of high-quality university teaching systems.

The triadic integration model is rooted in established educational theories that underpin its pedagogical validity. Kolb's Experiential Learning Theory emphasizes a cyclical learning process involving concrete experience, reflective observation, abstract conceptualization, and active experimentation, which aligns closely with the recursive project–practice–competition structure of this model (Lehane, 2025; Kolb and Kolb, 2005). Vygotsky's Social Constructivism highlights the role of social interaction, peer collaboration, and co-construction of knowledge in cognitive development (Moore, 2011), principles reflected in teamwork-based project learning and interactive classroom activities. Biggs's Constructive Alignment Theory provides a clear framework for aligning learning outcomes, teaching activities, and assessment mechanisms—including project evaluation and competition performance—to form coherent learning pathways that support deeper understanding (Biggs, 1996). Complementing these perspectives, Self-Determination Theory explains how autonomy, competence, and relatedness foster intrinsic motivation and sustained engagement in experiential learning tasks (Ryan and Deci, 2000). Collectively, these theories provide the conceptual foundation for the triadic integration model, ensuring its pedagogical coherence and offering analytical support for evaluating its implementation and outcomes.

2 Development of teaching content

Engineering Materials Design and Innovation is a foundational course that emphasizes practical training, engineering thinking, and creative problem-solving. Building upon this course, the present study develops and implements a "triadic integration" teaching model tailored specifically to the developmental characteristics and educational needs of newly established undergraduate universities. By integrating project-based learning, practice-oriented instruction, and discipline competitions into a coherent instructional framework, the model aims to cultivate students' practical competence, innovative capacity, and professional values. Moreover, the model seeks to provide a replicable and scalable pedagogical paradigm that can serve as a reference for similar institutions undergoing rapid development and reform (Yuan et al., 2024; Yu and Wang, 2025; Gao et al., 2025).

To ensure that the design of the teaching content is pedagogically sound, the triadic model is anchored in several well-established educational theories. Kolb's Experiential Learning Theory provides the foundational logic for structuring project, practice, and competition activities in iterative cycles of experience, reflection, conceptualization, and experimentation (Javahery and Bavandi, 2025). Vygotsky's Social Constructivism supports the integration of team-based learning, peer collaboration, and co-construction of knowledge, all of which are central to project-driven tasks (Shabani, 2016). Biggs's Constructive Alignment Theory informs the alignment of course objectives, instructional activities, and multi-dimensional assessments—including competition-based assessments—to ensure coherence and measurable learning progression (Wang et al., 2012). Additionally, Self-Determination Theory explains how autonomy, competence, and relatedness embedded in the triadic approach promote strong intrinsic motivation, sustained engagement, and deeper learning. Together, these theories justify and reinforce the structuring of teaching content under the triadic integration model, enabling both pedagogical rigor and practical applicability.

2.1 Experiential learning theory (Kolb)

Kolb's experiential learning theory provides the foundational pedagogical rationale for establishing the teaching objectives of

Engineering Materials Design and Innovation within the triadic integration model (Lehane, 2025; Javahery and Bavandi, 2025). The course's emphasis on project orientation, case-based analysis, and blended instruction aligns closely with the theory's four-stage learning cycle—concrete experience, reflective observation, abstract conceptualization, and active experimentation. By mapping the course objectives onto this recursive learning process, the model ensures that students progress from acquiring disciplinary knowledge to developing applied competencies and ultimately cultivating professional values such as craftsmanship and innovation.

First, the course objective of knowledge acquisition corresponds to the transition from concrete experience to reflective observation. Through structured theoretical instruction, laboratory demonstrations, and simulation-supported learning, students encounter real material systems and engineering problems firsthand. Engaging with material composition, microstructure, and processing–property relationships provides the "experience base" upon which reflection occurs. Students analyze observations, compare case outcomes, and begin forming a systematic disciplinary understanding—an essential step toward higher-order conceptualization.

Second, the objective of competence development mirrors Kolb's stage of abstract conceptualization, where students integrate interdisciplinary knowledge and derive engineering principles that guide problem-solving. Project-based learning and practice-oriented tasks encourage students to articulate hypotheses, design processing routes, interpret experimental data, and evaluate material performance. As they iterate on their projects and receive targeted instructor feedback, they develop the ability to diagnose real-world engineering issues, select appropriate analytical tools, and implement feasible technical solutions. These competencies are further strengthened when students participate in discipline competitions, which function as authentic environments for testing and refining their conceptual understanding.

Third, the cultivation of professional values and the craftsmanship ethos aligns with Kolb's stage of active experimentation. Students apply their accumulated knowledge and skills to increasingly complex design tasks, competition challenges, and innovation projects. This stage reinforces rigorous attitudes toward engineering practice—precision in measurement, responsibility in design decisions, and the pursuit of excellence in project outcomes. Simultaneously, repeated cycles of ideation, trial, and refinement stimulate students' innovative spirit and entrepreneurial mindset. Through these experiences, learners internalize values that extend beyond technical competence, contributing to both long-term career development and the nurturing of new productive forces in China.

Overall, situating the teaching objectives within Kolb's experiential learning framework underscores the theoretical coherence of the triadic integration teaching model. The alignment of project → practice → competition with experience → reflection → conceptualization → experimentation ensures that students not only master fundamental theories of engineering materials but also achieve continuous competence growth and sustained value formation. This theoretically grounded structure reinforces the model's applicability and provides a replicable pathway for talent cultivation in newly established undergraduate universities.

2.2 Social constructivism (Vygotsky)

Vygotsky's theory of social constructivism provides a robust conceptual foundation for the design of the triadic integration teaching model (Moore, 2011; Shabani, 2016). Central to this perspective is the belief that knowledge is constructed through social interaction, peer collaboration, and culturally mediated learning processes. These principles align directly with the pedagogical logic of the integrated model, which combines project-based learning, practice-oriented instruction, and interactive learning activities to promote the co-construction of knowledge in authentic engineering contexts. By embedding learning tasks within collaborative environments, the model enables students to progress through their zone of proximal development (ZPD) with the support of instructors, peers, and structured scaffolding.

At the core of this instructional framework is project-based learning, which serves as a primary mechanism for socially mediated knowledge construction. Projects require students to work in teams, negotiate problem-solving strategies, and synthesize ideas from multiple disciplinary perspectives—activities that reflect Vygotsky's emphasis on cognitive development through social interaction. The three-tiered project sequence further embodies this theoretical stance:

Foundational projects introduce students to essential concepts and experimental techniques. Working collaboratively, students observe material behaviors, share interpretations, and collectively refine their understanding of core principles, thereby moving from assisted to increasingly independent learning within their ZPD.

Comprehensive projects encourage students to co-develop research plans under faculty guidance. Through group deliberation, division of labor, and shared analysis, students deepen their ability to address complex engineering challenges while internalizing disciplinary reasoning patterns through social engagement.

Advanced projects challenge teams to undertake open-ended, simulation-supported tasks that demand creativity, autonomy, and collective problem-solving. These projects enable students to transition from guided participation to advanced collaborative inquiry, demonstrating the internalization of higher-order thinking fostered through scaffolded interaction.

The second component of the model, practice-oriented instruction, also reflects Vygotskian principles by situating learning within meaningful sociocultural and technological contexts. In laboratory environments, students jointly operate instruments, discuss measurement errors, interpret data as a group, and negotiate explanations for observed material behaviors. Field visits to industrial production lines and research laboratories further immerse students in real-world engineering cultures, allowing them to appropriate expert practices through observation, guided participation, and peer discussion. Computer-based simulations create shared virtual spaces in which students collaboratively manipulate parameters, compare outcomes, and collectively reason about processing–property relationships.

The third pillar, interactive learning, operationalizes social constructivism through structured communication and reflective dialog. Group discussions, peer review, and class-wide debates encourage students to articulate disciplinary concepts in their own words, challenge differing viewpoints, and co-construct more sophisticated understandings. Under faculty mentorship, students collaboratively develop research proposals, engage in joint data interpretation, and critically evaluate design decisions. Reflective activities—including learning journals and group feedback sessions—provide additional opportunities for metacognitive development by prompting students to examine how interaction, collaboration, and shared inquiry contribute to their learning.

Taken together, the integration of project-based learning, practice-oriented instruction, and interactive engagement illustrates how the triadic model operationalizes the core tenets of Vygotsky's social constructivism. By emphasizing peer interaction, collaborative knowledge building, and scaffolded learning within the ZPD, the model not only strengthens students' engineering competencies but also fosters communicative capacity, teamwork, and the capacity for socially mediated innovation. These outcomes are essential for preparing students in newly established universities to participate confidently in future scientific research, engineering practice, and national or international competitions.

2.3 Constructive alignment (Biggs)

Biggs's theory of constructive alignment offers a systematic basis for designing an assessment framework that ensures coherence among learning outcomes, instructional activities, and evaluation mechanisms (Hamdoun, 2023; Biggs and Tang, 2020). Under this framework, students are expected to actively construct knowledge through meaningful learning tasks, while assessments should authentically measure the skills and competencies those tasks are intended to cultivate. The triadic integration model adheres closely to this principle by aligning project-based learning, practice-oriented instruction, and competition-based engagement with assessment methods that capture both theoretical mastery and practical innovation capabilities.

Building on constructive alignment, the course employs a multi-dimensional assessment system that reflects students' developmental trajectories and the iterative nature of project-based inquiry. The assessment strategy not only measures learning outcomes at different stages but also reinforces the pedagogical emphasis on authentic, reflective, and socially situated learning.

2.3.1 Conventional assessment aligned with learning outcomes

The course adopts a comprehensive evaluation system that integrates formative and summative components. Formative assessment—constituting 60% of the final grade—captures students' ongoing engagement in the co-construction of knowledge. Indicators such as classroom participation, collaborative contributions, reflective insights, originality of ideas, and progress in online learning tasks are evaluated to ensure that assessment aligns with the intended learning goals of critical thinking, teamwork, and conceptual understanding. This continuous assessment process mirrors constructive alignment by ensuring that the tasks students perform throughout the semester directly contribute to the achievement of expected outcomes.

The summative assessment, weighted at 40%, evaluates research reports derived from comprehensive and advanced projects. These reports require students to articulate research objectives, justify methodological approaches, analyze data, and interpret results, thereby demonstrating their progression through the learning cycle. By assessing both theoretical understanding and the ability to solve complex engineering problems, the summative component operationalizes Biggs's principle that assessments should authentically represent the competencies the course seeks to cultivate.

2.3.2 Competition-based assessment for authentic performance evaluation

A distinctive feature of the assessment framework is the incorporation of a "competition-as-assessment" strategy, which aligns evaluation with real-world performance tasks and the course's innovation-oriented objectives. Consistent with constructive alignment, competitions are not treated as extracurricular enrichment but as formal assessment components that validate students' ability to transfer theoretical knowledge to challenging, practice-based contexts.

In participation at university, provincial, and national competitions, students engage in a range of professional tasks—project planning, solution design, materials processing, data analysis, experimental optimization, and results presentation. These activities replicate authentic engineering problem-solving environments and mirror the higher-level learning outcomes targeted by the triadic model, including teamwork, creativity, professional communication, and interdisciplinary integration. Competition outcomes are directly incorporated into the course grade, thereby strengthening the link between intended outcomes, learning tasks, and evaluation.

This competition-based approach facilitates deeper learning by establishing a clear incentive structure: students recognize that their innovative outputs, collaborative competence, and practical problem-solving skills carry tangible academic weight. In turn, this motivates them to pursue excellence, refine their research designs, and engage more actively with industry-relevant challenges. The evaluation process thus becomes a catalyst for learning rather than merely a measure of attainment, aligning seamlessly with Biggs's emphasis on coherence between outcomes, pedagogy, and assessment.

2.4 Self-determination theory (Deci and Ryan)

Self-Determination Theory (SDT) posits that human motivation is fundamentally shaped by the fulfillment of three innate psychological needs: autonomy, competence, and relatedness (Ryan and Deci, 2017; Ryan and Deci, 2022). When these needs are satisfied, learners exhibit enhanced intrinsic motivation, deeper engagement, and greater persistence—qualities essential for sustained participation in complex engineering learning tasks. The triadic integration teaching model embeds these motivational mechanisms into its design, making SDT an important theoretical foundation for understanding how the model promotes active and long-term learning.

Autonomy is supported through student-centered and self-directed learning processes. In project-based modules, students independently define research topics, develop design plans, determine implementation pathways, and make iterative decisions based on experimental outcomes. This autonomy empowers students to take ownership of their learning trajectories, transforming them from passive recipients of knowledge into active constructors of meaning. The freedom to explore, redesign, and optimize their work not only heightens intrinsic motivation but also encourages creativity and initiative.

Competence is cultivated through hands-on practice and continuous feedback embedded in the model's practice-oriented instruction. Laboratory experiments, field-based observations, and simulation analyses allow students to repeatedly apply theoretical concepts to concrete engineering problems. Through cycles of trial, error, and refinement, students gradually build confidence in their technical skills and analytical abilities. The alignment between learning tasks, feedback mechanisms, and assessment standards ensures that students experience consistent competence gains, reinforcing their willingness to tackle increasingly complex challenges.

Relatedness is strengthened through collaborative teamwork and interactive learning environments. Group-based project development, peer discussions, and faculty mentorship create a supportive and interconnected learning community. These collaborative processes foster intellectual exchange, shared problem-solving, and a sense of belonging—social factors that further enhance motivation and resilience. As students work together to overcome engineering constraints and prepare for competitions, they form meaningful academic relationships that reinforce sustained engagement.

Within the triadic integration model, the interplay of autonomy, competence, and relatedness produces a reinforcing mechanism that elevates students' learning motivation and persistence. Student-centered project tasks satisfy autonomy; iterative practice builds competence; and collaborative discussions and team-based competitions cultivate relatedness. Collectively, these psychological satisfiers help explain why students demonstrate higher levels of participation, deeper cognitive investment, and greater willingness to engage with challenging engineering problems. Thus, SDT not only illuminates the motivational dynamics behind students' learning behaviors but also validates the design of the triadic integration teaching model from a motivational and psychological perspective.

Taken together, these four theoretical perspectives provide a unified and coherent foundation for the triadic integration teaching model. Kolb's experiential learning theory explains the recursive project–practice–competition cycle; Vygotsky's social constructivism highlights the collaborative and interactive nature of team-based PBL tasks; Biggs's constructive alignment underscores the systematic linkage between learning outcomes, instructional activities, and assessment; and Self-Determination Theory illuminates the motivational mechanisms driving student engagement. Collectively, these theories justify the integration of project-based learning, interactive learning, and practice-based instructional approaches into a single, coherent pedagogical model tailored for engineering education. They not only clarify why this integrated model can enhance students' cognitive development, practical competence, intrinsic motivation, and innovation capacity, but also offer a rigorous analytical lens for evaluating its design, implementation, and learning outcomes.

3 Design of the "triadic integration" teaching model

The design of the "triadic integration" teaching model is grounded in the systematic combination of project-based learning, interactive teaching, and practice-oriented instruction (Hu et al., 2025). Each component plays a complementary role: project-based learning emphasizes progressive task-driven exploration; interactive teaching highlights collaboration, discussion, and critical thinking; and practice-oriented instruction reinforces the transformation of theoretical knowledge into authentic application. Collectively, these three approaches create a dynamic, student-centered learning ecosystem that not only strengthens engineering knowledge and skills but also fosters innovation, problem-solving capacity, and professional identit (Paucar-Curasma et al., 2025). The following subsections detail the implementation strategies of each approach.

3.1 Course context and objectives

The course Engineering Materials Design and Innovation serves as the primary instructional platform for implementing the triadic integration teaching model. As a core module in the materials and engineering curriculum of newly established undergraduate universities, the course emphasizes both theoretical understanding and practical application. Designed to cultivate students' engineering literacy, innovative capacity, and problem-solving competence, it provides an appropriate context for integrating project-based learning, practice-oriented instruction, and competition-driven evaluation into a coherent pedagogical framework.

The overarching objectives of the course are threefold. First, it aims to develop solid foundational knowledge of material composition, microstructure, processing methods, and performance evaluation, thereby preparing students for advanced study and research. Second, the course seeks to strengthen students' ability to address real engineering problems through hands-on practice, experimental inquiry, and interdisciplinary integration. Third, it promotes the formation of innovative thinking, craftsmanship spirit, and teamwork ability—competencies essential for future technological development and engineering practice.

Within this context, project-based learning constitutes the core component of the triadic integration model. By situating students in authentic or near-authentic engineering scenarios, the course progressively enhances their capacity to apply theoretical concepts to practice, tackle complex problems, and generate creative solutions. Projects are organized into a three-tiered progression—foundational, comprehensive, and advanced—forming a spiral and iterative learning pathway.

Foundational projects emphasize conceptual understanding and the acquisition of essential experimental skills. For instance, tasks such as analyzing the effects of heat treatment on the microstructure and properties of low-carbon steel help students master fundamental laboratory operations and data analysis techniques.

Comprehensive projects require students, under faculty guidance, to design research plans and conduct in-depth investigations. A typical example is microstructural and mechanical performance analysis of representative components, which promotes independent thinking, methodological rigor, and multidisciplinary integration.

Advanced projects emphasize autonomy, creativity, and higher-order problem-solving. Tasks such as failure analysis of components combined with simulation-based optimization of heat-treatment parameters challenge students to address complex engineering issues in realistic contexts and cultivate innovation competence.

Instructionally, teachers introduce project contexts, research methodologies, and technical requirements at the outset. As students move through successive project stages, direct supervision is gradually reduced to encourage self-directed inquiry and autonomous problem-solving. Formative evaluations are embedded at key checkpoints to monitor progress, provide feedback, and support iterative refinement of project outcomes, thereby enhancing students' ability to regulate their own learning.

3.2 Structure of the triadic integration model

The triadic integration model consists of three mutually reinforcing components—project-based learning, interactive teaching, and practice-oriented instruction. Together, they form a coherent instructional framework that integrates knowledge acquisition, active engagement, and practical application to cultivate students' engineering competence and innovation capacity.

3.2.1 Project-based learning

Project-Based Learning constitutes the core component of the triadic integration model, providing the structural backbone for organizing teaching activities and guiding students' progressive skill development. Projects are arranged along a tiered progression—from foundational to comprehensive and advanced levels—to create a spiral, iterative learning trajectory.

Foundational projects focus on basic concepts and essential experimental skills, such as analyzing the relationship between heat treatment, microstructure, and mechanical properties of low-carbon steel.

Comprehensive projects require students to independently formulate research plans and conduct integrated investigations—for example, the microstructural and performance analysis of representative engineering components.

Advanced projects emphasize autonomy and innovation through open-ended tasks such as failure analysis and heat-treatment process simulation of industrial components.

Throughout the project process, instructors provide contextual guidance in the early stages and gradually reduce direct supervision as students acquire the ability to conduct inquiry independently. Formative evaluations embedded at key milestones facilitate reflective learning, timely feedback, and iterative refinement of research processes. As the core framework, project-based learning anchors the other two instructional dimensions, ensuring that all activities consistently serve project progression and learning outcomes.

3.2.2 Interactive teaching

Interactive teaching complements the project framework by cultivating knowledge comprehension, critical thinking, and collaborative problem-solving. It follows a structured sequence consisting of pre-class preparation, in-class engagement, and post-class research reporting.

Pre-class self-learning equips students with the theoretical background necessary for meaningful participation. Learning materials extend beyond textbooks to include research literature, engineering cases, and experimental datasets.

In-class interaction involves group discussions, case-based reasoning, and inquiry-driven tasks closely aligned with project themes. Students collaboratively design research plans, analyze experimental results, and refine methodologies, while instructors provide targeted scaffolding to maintain scientific rigor.

Research reporting and discussion reinforce reflective learning and communication competence, requiring students to interpret data, justify decisions, and present their findings to peers.

By integrating heuristic, inquiry-based, and participatory methods, interactive teaching strengthens students' conceptual understanding and fosters critical, creative, and analytical thinking. It also enhances engagement and responsibility, enabling students to take an active role in advancing their learning throughout the project cycle.

3.2.3 Practice-oriented instruction

Practice-oriented instruction establishes the application-driven dimension of the triadic model, ensuring that students develop professional-level operational skills and engineering judgment through authentic, hands-on experience.

Structured laboratory practice provides opportunities for students to conduct experiments in material processing, microstructural characterization, and mechanical testing. These activities reinforce theoretical concepts while developing systematic observation, data acquisition, and analytical skills.

Engineering case analysis and simulation immerse students in realistic industrial scenarios—such as component failure analysis or optimization of heat-treatment parameters—requiring integration of multidisciplinary knowledge and use of engineering tools including metallography and finite-element simulation.

Competition-integrated practice extends learning into high-intensity, real-world application contexts. Participation in material innovation competitions or component design challenges strengthens students' abilities in planning, experimentation, teamwork, and technical communication. Competition tasks also reinforce higher-order thinking and innovation capacity.

Through these layered practice activities, students continuously apply and validate their knowledge, bridging classroom learning with real engineering contexts. This ensures the development of robust practical competence and supports the cultivation of industry-ready, innovative engineering graduates.

3.3 Continuous improvement via seminar mechanism

A continuous improvement mechanism is essential for ensuring the long-term effectiveness, adaptability, and sustainability of the triadic integration teaching model. To this end, a structured seminar mechanism has been established to support iterative refinement of teaching design, project implementation, and learning outcomes. This mechanism operates through regular instructor seminars, student discussion sessions, and joint faculty–student review meetings, forming a cyclical feedback system that drives ongoing enhancement of both pedagogy and curriculum content.

Instructor seminars focus on diagnosing instructional challenges, reviewing project progression, and evaluating students' performance across the project-based, interactive, and practice-oriented components. Instructors collectively analyze issues observed in experimental operations, project design feasibility, students' inquiry depth, and the alignment between teaching activities and expected learning outcomes. These discussions support evidence-based adjustment of project difficulty, instructional guidance strategies, and assessment criteria, ensuring that the teaching model remains responsive to student needs and emerging trends in engineering materials education.

Student-centered discussion sessions provide a structured platform for learners to reflect on their experiences, share project insights, and raise difficulties encountered during experimentation, simulation, or group collaboration. By facilitating open dialog among peers, these sessions strengthen students' metacognitive skills and encourage them to articulate scientific reasoning, critique research methodologies, and collaboratively refine project approaches. Students' reflections and feedback also serve as a valuable empirical basis for instructors to identify areas requiring pedagogical adjustment.

Joint faculty–student review meetings integrate multiple perspectives to assess the overall operation of the teaching model. These meetings examine project outputs, laboratory performance, data analysis quality, teamwork dynamics, and the alignment between course activities and innovation competition requirements. Through collaborative evaluation, the course team gains a holistic understanding of strengths and deficiencies, enabling targeted improvement of project design, teaching materials, laboratory resources, and support mechanisms for student innovation.

By embedding reflection, feedback, and collaborative evaluation into the entire instructional process, the seminar mechanism ensures that the triadic integration model evolves in a systematic and data-informed manner. This continuous improvement cycle not only enhances the quality and efficiency of teaching but also cultivates a culture of shared responsibility and academic dialog among faculty and students. Ultimately, it guarantees that the course remains forward-looking, adaptive to disciplinary developments, and capable of sustaining high-level training for innovative engineering talent.

3.4 Seminar-based implementation and continuous improvement mechanism

To address the multifaceted challenges inherent in newly established courses, we developed a formalized seminar mechanism designed to support iterative course improvement. The mechanism comprises the following components:

Organization and Participants: Seminars are convened by the course coordinator and include the teaching team, representatives from academic affairs, laboratory technicians, and invited external practitioners or industry experts as needed.

Frequency and Formats: Regular seminars are held monthly, with targeted workshops at key academic milestones (pre-course planning, midterm review, end-of-term synthesis). Formats include classroom observations, case reviews, lesson-plan workshops, micro-teaching sessions, and expert critiques.

Agenda and Outputs: Each seminar focuses on a specific agenda item—such as project design refinements, laboratory safety and equipment allocation, assessment rubric alignment, or competition-support strategies. Tangible outputs include revised lesson plans, standardized laboratory protocols, assessment rubrics, recorded exemplar lessons, and action-research reports.

Feedback and Evaluation: Improvement measures are assessed through seminar minutes, teacher reflective logs, student feedback, and instructional data (e.g., formative-assessment trends and competition outcomes). Key performance indicators (KPIs) may include adoption rates of revised practices, changes in classroom observation scores, measurable gains in students' practical competencies, and competition achievement rates.

Institutionalization and Dissemination: Exemplary practices are documented and archived in the college teaching repository; periodic dissemination events and faculty training sessions are organized to facilitate internal and cross-institutional replication.

Crucially, this seminar-driven, evidence-based improvement mechanism functions as more than a forum for exchange: it operationalizes action research that undergirds the triadic model. Seminars identify and frame problems for project-based learning, refine facilitation strategies for interactive teaching, and secure resource allocations for practice-oriented instruction, thereby ensuring both the fidelity and sustainability of the "project–practice–competition" (triadic integration) approach.

The practical implementation and evaluation of the triadic integration model are detailed in Section 4, which outlines participants, timeline, and data collection strategies.

4 Research design

4.1 Participants and setting

The study was conducted across two Chinese higher education institutions—Qinghai University of Technology and Henan Institute of Technology—both of which offer application-oriented engineering programs and have recently expanded their curricula to strengthen innovation-driven talent development. These universities were selected because they share comparable educational orientations, adopt similar training standards in engineering disciplines, and actively promote teaching reforms involving project-based learning, laboratory innovation, and competition-oriented instruction. Their institutional contexts therefore provided an appropriate and representative setting for implementing and evaluating the triadic integration teaching model.

Qinghai University of Technology, located in Xining, is a provincial key institution known for its engineering programs in materials, energy, and mechanical disciplines. Its teaching laboratories—including the Materials Testing Center, Metallographic Analysis Laboratory, and Advanced Manufacturing Training Base—are equipped to support hands-on experimentation, data analysis, and prototype development. The university has also established school-level innovation platforms that regularly participate in provincial and national competitions, providing a conducive environment for competition-based learning.

Henan Institute of Technology, situated in Xinxiang, is recognized for its strong orientation toward practical engineering education. The university maintains a comprehensive system of practice bases, simulation laboratories, and industry–university cooperation centers, all of which offer stable conditions for project implementation and experiment-driven instruction. It has a long tradition of encouraging students' participation in discipline competitions such as the National Metallographic Skills Competition and the "Internet+" Innovation and Entrepreneurship Contest, making it an advantageous site for implementing competition-integrated teaching models.

Across the two universities, the study involved three intact teaching classes, generating a total sample of more than 150 undergraduate students. Participants were distributed across three engineering majors:

Materials Science and Engineering,

Mechanical Design and Manufacturing, and

Energy Engineering.

Students ranged from first- to second-year cohorts, ensuring diversity in academic backgrounds and levels of prior exposure to laboratory and project-based learning. To maintain comparability between groups and enhance internal validity, students in each class were further organized into six heterogeneous project teams, balancing academic performance, gender distribution, and prior experience in innovation activities.

All teaching activities were delivered within students' regular course schedule, emphasizing ecological validity. Rather than utilizing controlled laboratory settings, the instructional intervention unfolded in authentic classrooms, practice centers, and engineering laboratories routinely used for undergraduate teaching. This design ensured that students' engagement and behavioral responses reflected their natural learning environment.

The triadic integration teaching model was implemented over a full 18-week academic semester, corresponding to one complete instructional cycle of the course Engineering Materials Design and Innovation. Throughout the semester, students experienced a sequenced learning pathway involving project-based learning, interactive discussions, laboratory-based experimentation, and competition-oriented application. Institutional facilities—including experimental laboratories, computer simulation rooms, and maker spaces—were fully utilized to support project execution and practice-based inquiry.

Overall, the participant composition and instructional setting provided a robust and representative sample that allowed for a rigorous evaluation of the implementation process, learning experiences, and outcomes associated with the triadic integration teaching model.

4.2 Implementation timeline

The implementation of the triadic integration teaching model followed a structured 18-week timeline that corresponded to the full duration of the course. As illustrated in Figure 1, the intervention consisted of four sequential and interlinked phases designed to progressively scaffold students' cognitive development, practical skills, and innovation capacities.

4.2.1 Phase 1: Preparation phase (Weeks 1–2)

During the initial two weeks, pre-course surveys were administered to establish a baseline of students.

4.2.2 Phase 2: Project-based implementation (Weeks 3–8)

This phase focused on the systematic execution of foundational and comprehensive projects. Guided by instructors, students reviewe.

4.2.3 Phase 3: Practice and experimentation(Weeks 9–14)

Students engaged in intensive laboratory work involving materials processing, microstructural characterization, mechanical testing, and simulation-based analysis. Hands-on pra.

4.2.4 Phase 4: Competiton and reflection phase(Weeks 15–18)

In the concluding period, students synthesized their project outcomes and participated in discipline-specific compete.

A graphical representation of the 18-week timeline is provided in Figure 1, which visually outlines the four structured phases and their associated tasks.

4.3 Data collection and analysis

To comprehensively evaluate the effectiveness of the triadic integration teaching model, a mixed-methods data collection strategy was employed. Both quantitative and qualitative data were gathered throughout the 18-week instructional cycle to ensure triangulation, enhance validity, and provide multi-dimensional evidence of students' learning outcomes, engagement, and innovation capacity.

4.3.1 Quantitative data collection

Quantitative evidence was collected from multiple sources to capture students' cognitive, behavioral, and applied performance throughout the course. Standardized pre- and post-course surveys

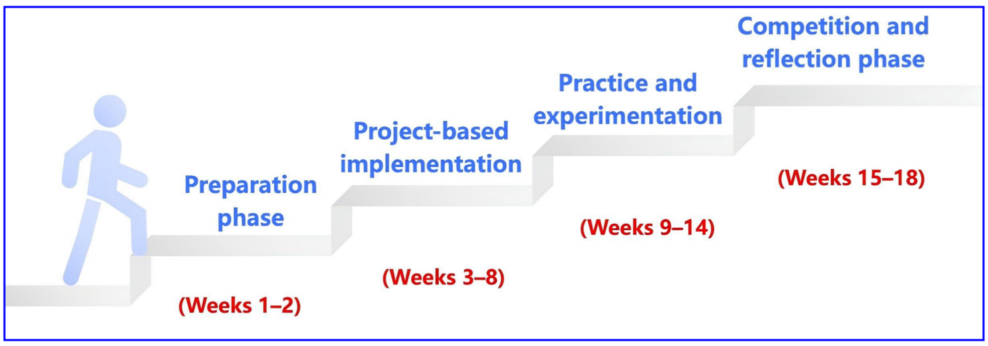

FIGURE 1
Implementation schedule of the triadic integration model.

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were administered in Weeks 1 and 18 to track changes in learning motivation, self-directed learning ability, teamwork competence, and confidence in solving engineering problems. The use of Likert-scale items ensured comparability across time points.

In-class project performance was evaluated through analytic rubrics applied to foundational, comprehensive, and advanced projects. The rubrics assessed knowledge application, process engagement, experimental proficiency, and innovation output, thereby providing consistent and objective measures of students' progress across key learning dimensions.

To complement course-based assessments, competition outcomes—covering university-level, provincial, and national events such as the National Metallographic Skills Competition, the "Challenge Cup," and the "Internet+" Innovation Competition—were systematically documented. Records of participation and awards offered authentic, externally validated indicators of students' applied competence and innovation ability under real-world standards.

4.3.2 Qualitative data collection

Qualitative evidence was gathered to capture the internal learning processes, behavioral dynamics, and instructional adjustments that could not be fully reflected through quantitative indicators alone. Throughout project-based and practice-oriented sessions, non-intrusive classroom and laboratory observations were conducted to document students' engagement behaviors, collaboration patterns, problem-solving approaches, and responses to instructional scaffolding.

To further reveal students' cognitive and emotional trajectories, reflective learning logs were collected during the practice and competition phases. These journals detailed students' perceived challenges, strategies adopted, moments of insight, and self-evaluations of progress, providing rich accounts of metacognitive regulation and motivational changes during the iterative learning cycle.

Complementing the student-centered data, weekly instructor seminars served as part of the course's continuous improvement mechanism. Notes from these discussions captured teachers' reflections on instructional effectiveness, encountered difficulties, and emerging trends in student performance. Together, these multi-source qualitative materials offered deep, triangulated insights into the workings of the triadic integration model and the evolving learning processes it triggered.

4.3.3 Data analysis

Quantitative data (survey scores, rubric evaluations, and competition results) were analyzed using descriptive statistics and gain-score comparisons to identify shifts in students' abilities and performance across the semester. Qualitative data (observations, reflective logs, and seminar notes) were analyzed through thematic coding to extract recurring themes related to engagement, motivation, difficulties, and learning strategies. Integration of both datasets enabled a comprehensive understanding of the model's effectiveness and its impact on students' cognitive, practical, and innovative development.

To operationalize the triadic integration teaching model, both quantitative and qualitative data sources were incorporated into the evaluation framework. While the present study reports primarily on quantitative outcomes—namely student satisfaction levels and competition performance—the qualitative components (e.g., classroom observations, reflective logs, and seminar notes) were used mainly as formative references during implementation rather than as formal analytic data for this manuscript. The qualitative indicators are therefore introduced as part of a broader methodological framework that institutions may adapt based on their specific teaching contexts, course characteristics, and evaluation needs. In this sense, the study provides a flexible assessment approach that can be extended with richer qualitative analyses in future implementations.

5 Results

To evaluate the effectiveness of the triadic integration model, both quantitative and qualitative indicators were analyzed. Quantitative evidence was derived primarily from student satisfaction data and competition outcomes, while qualitative insights from instructor observations and student reflections further substantiated the findings. This section reports the key results, with a particular focus on the analyses of Student Satisfaction and Competition Outcomes.

5.1 Student satisfaction

Student satisfaction with the triadic integration model was collected across six consecutive semesters. Figure 2 presents the percentage of students rating the course as "satisfied" or "highly satisfied."

The results indicate a consistently positive trend. As shown in Figure 2, overall satisfaction remains above 95% for all semesters, with minimal fluctuation. The sustained high ratings suggest that students affirm the model's capacity to enhance learning engagement, clarify conceptual understanding, and improve the perceived relevance of course content. Several qualitative comments also support this pattern, noting that hands-on sessions, clearer knowledge–practice alignment, and the seminar-based feedback loop enhanced learners' sense of achievement and agency. Collectively, the data confirm that the triadic integration model meaningfully improves students' learning experience and course satisfaction.

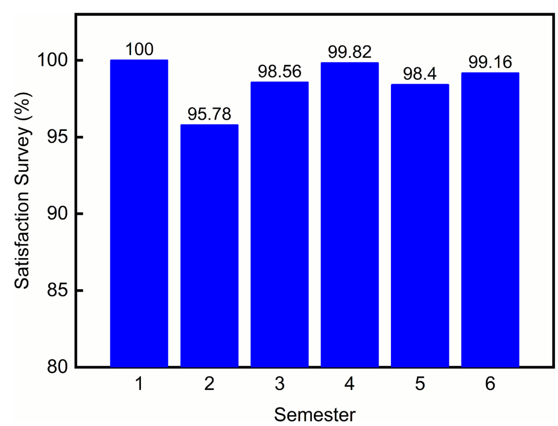

FIGURE 2
Student satisfaction with the triadic integration teaching model.

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5.2 Impact on competition outcomes

To further assess learning effectiveness, students' performance in discipline-related competitions was examined, with Figure 3 comparing the 2019 cohort under the traditional teaching model and the 2020 cohort following the full implementation of the triadic integration model.

The contrast between the two cohorts is substantial. As shown in Figure 3, the 2019 cohort achieved only 9 university-level and 7 provincial-level awards. In comparison, the 2020 cohort achieved 39 university-level and 51 provincial-level awards after participating in the triadic integration model. This dramatic improvement demonstrates that the model significantly enhances students' innovation capacity, experimental skills, and problem-solving readiness. The structured practice-based tasks, scaffolded research opportunities, and continued formative feedback through seminars helped students develop stronger technical skills and greater confidence in participating in academic competitions.

Overall, the competition outcomes provide strong empirical support that the triadic integration model not only enhances course learning outcomes but also effectively translates into measurable external achievements, thus validating its educational value.

6 Discussion

The results of this study demonstrate that the triadic integration model effectively aligns contemporary pedagogical theory with the practical demands of engineering education. By integrating progressively structured learning tasks, interactive discursive mechanisms, authentic laboratory activities, and external evaluative platforms, the model provides a coherent pathway for cultivating both cognitive understanding and applied competencies. The following discussion elaborates on five dimensions through which the model advances student learning.

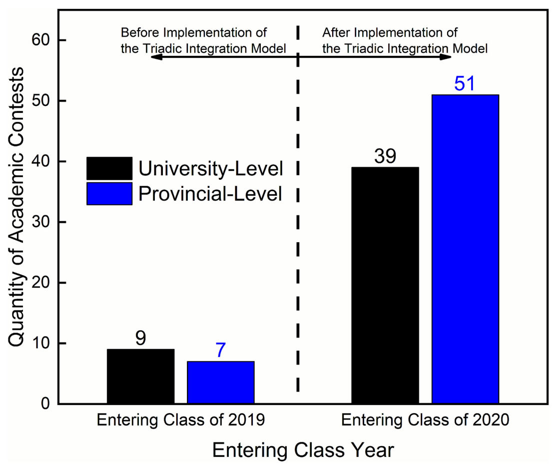

FIGURE 3
Impact of the triadic integration model on student participation in discipline-specific competitions.

6.1 Transforming passive learning into active exploration

A central contribution of the triadic integration model lies in its ability to shift students from passive recipients of information to active constructors of knowledge. Through the staged design of fundamental experiments, comprehensive tasks, and independent research projects, students engage with progressively complex challenges that require inquiry, decision-making, and iterative refinement. This scaffolded progression not only enhances operational proficiency but also encourages students to formulate questions, test hypotheses, and reflect on outcomes—behaviors characteristic of active learning and experiential engagement. Such a structural shift aligns with constructivist perspectives, which emphasize that meaningful learning emerges from interaction with authentic problems rather than rote content absorption.

6.2 Fostering deeper cognitive engagement via interactive discursive activities

The integration of seminar-based teaching further deepens students' cognitive involvement. Instructor–student and student–student discussions create a discursive space in which learners articulate reasoning, negotiate interpretations, and evaluate alternative solutions. This dialogic process stimulates higher-order thinking, including analysis, synthesis, and metacognitive reflection. As students verbalize experimental logic or troubleshoot design constraints within a collaborative environment, they consolidate conceptual understanding and internalize disciplinary norms of scientific argumentation. Thus, the seminar mechanism functions not only as a feedback channel but also as a catalyst for deeper cognitive engagement.

6.3 Bridging theory and application through authentic laboratory and simulation tasks

Authenticity in learning tasks is essential in engineering education, and the triadic integration model emphasizes this through extensive laboratory work and supported simulation-based exercises. These environments enable students to apply theoretical principles to real-world scenarios, observe material behaviors firsthand, and solve engineering problems under realistic constraints. Such alignment between theoretical constructs and empirical operations reinforces the durability of learning and enhances transferability across contexts. The model ensures that students not only understand the "why" of engineering concepts but also the "how" of practical implementation.

6.4 Connecting learning with external validation via competitions

External academic competitions serve as an important extension of the curriculum, providing students with opportunities to test their competencies beyond classroom settings. Under the triadic integration model, students exhibit increased participation and improved performance in these competitions, demonstrating heightened initiative, creativity, and problem-solving ability. Competitions offer external validation, motivating students to refine their technical expertise and gain recognition from broader academic and professional communities. This connection between coursework and competitive platforms fosters a results-oriented mindset and strengthens students' confidence in applying their skills in public, evaluative contexts.

6.5 Cultivating motivation and professional identity consistent with self-determination theory

The observed improvements in student motivation and engagement can be interpreted through the lens of Self-Determination Theory. The triadic integration model supports students' basic psychological needs in the following ways:

6.5.1 Autonomy

Students gain decision-making power through project selection, experimental design, and research planning.

6.5.2 Competence

Progressive challenges, seminar guidance, and competition achievements reinforce their sense of capability.

6.5.3 Relatedness

Collaborative discourse, laboratory teamwork, and instructor support strengthen their connection to peers and the professional community.

As these needs are met, students develop deeper intrinsic motivation and a clearer sense of professional identity. They begin to view themselves not merely as learners but as emerging engineers capable of contributing to innovation and practical problem-solving. This transformation aligns with the ultimate objectives of engineering education—cultivating professionals equipped with sustained curiosity, technical resilience, and a commitment to lifelong learning.

7 Conclusion

This study developed and implemented a "triadic integration" teaching model that systematically combines project-based learning, interactive instruction, and practice-oriented teaching to cultivate engineering capabilities in newly established undergraduate courses. The model was applied in the course Engineering Materials Design and Innovation at Qinghai University of Technology and Henan Institute of Technology, providing a practical framework for integrating theoretical knowledge, applied skills, and competitive experiences. The key findings and implications are summarized as follows:

7.1 Integration of project-based learning and competitions creates a "teach–learn–compete" closed loop

The course incorporated modular projects aligned with representative material research problems, progressing through foundational, comprehensive, and advanced stages. By embedding engineering-material innovation competitions into the instructional sequence, the study established an integrated "course project–competition theme–research practice" task chain. This framework stimulated students' interest in engineering, enhanced their practical problem-solving capabilities, and significantly improved performance in competitions such as the National Metallography Skills Competition and Internet+ Innovation Challenge. The closed-loop structure reinforces the reciprocal relationship between teaching, learning, and applied performance, offering a replicable pathway for linking classroom instruction with real-world evaluation.

7.2 Multi-dimensional interactive teaching mechanism fosters a student-centered learning ecosystem

Heuristic, inquiry-based, discussion-oriented, and participatory strategies strengthened students' active engagement in learning tasks. Through team collaboration, staged presentations, reflective seminars, and peer feedback, students developed higher-order thinking, communication skills, and collaborative competencies. The interactive mechanisms effectively shifted the classroom paradigm from teacher-centered to student-centered learning, allowing adaptive instructional support and fostering an exploratory, reflective, and motivated learning environment. This approach demonstrates the potential of structured interaction to deepen cognitive engagement and enhance learning outcomes in engineering education.

7.3 Engineering-oriented practice teaching system develops an output-oriented competency model

Practice-oriented instruction, including laboratory experiments, field visits, and simulation-based problem solving, transformed theoretical knowledge into tangible engineering skills. Students completed full-cycle activities covering data collection, experimental operation, analysis, reporting, and solution design. Projects emphasized real-world tasks such as material composition optimization, structural performance evaluation, and failure analysis, thereby cultivating both technical proficiency and innovative capacity. This output-oriented framework supports the development of professional competencies and fosters readiness for industrial or research careers.

7.4 Implications for curriculum innovation and pedagogical reform

The triadic integration model demonstrates a scalable and adaptable strategy for engineering education, particularly in newly established universities seeking to enhance application-oriented training. Its theoretical grounding in Experiential Learning, Social Constructivism, Constructive Alignment, and Self-Determination Theory ensures that instructional design aligns with cognitive, motivational, and social dimensions of learning. The model provides practical guidance for curriculum designers, enabling coherent integration of projects, practice, interaction, and competitions to strengthen student engagement and professional readiness.

7.5 study limitations and future directions

While the study yielded positive outcomes in student satisfaction, competition performance, and applied skills, several limitations warrant consideration. First, the research was conducted within two institutions and three classes, which may limit generalizability to broader contexts or disciplines. Second, the measurement of long-term retention and career impacts of the model remains unexamined. Future research could expand the implementation across diverse universities, track longitudinal learning and professional outcomes, and explore the transferability of the triadic integration approach to other engineering domains or interdisciplinary courses.

Overall, the "triadic integration" teaching model represents a coherent, theoretically informed, and practice-oriented framework that successfully bridges pedagogical theory with engineering education practice. By combining structured project work, interactive learning, and authentic practice opportunities, complemented by competition-based assessment, the model cultivates high-quality application-oriented talent. Its conceptual and operational design offers a practical paradigm for curriculum innovation, instructional reform, and the systematic development of professional competencies in higher education worldwide.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

GS: Supervision, Writing – original draft, Formal analysis, Writing – review & editing, Investigation, Project administration, Conceptualization. WW: Project administration, Conceptualization, Writing – original draft, Formal analysis, Investigation. CQ: Writing – review & editing, Formal analysis, Data curation, Methodology, Investigation, Visualization, Conceptualization. LX: Formal analysis, Writing – original draft, Methodology, Investigation, Data curation. QW: Visualization, Formal analysis, Supervision, Writing – review & editing, Data curation, Conceptualization, Investigation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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