Transforming the Landscape: How Project-Based Learning is Evolving Material Science Education

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Abstract

Integration of industry-linked initiatives with project-based learning (PBL) in material science education promises to transform the way students become engaged and attained mastery of the academic contents. The involvement of industry partners, an element of this educational model, is crucial for simulating the professional scenarios in addressing real-world challenges. Students acquire invaluable insights and experiences that help bridge the gap between academia and industry. Mentorships rendered by the industry experts not only provide different perspectives that are aligned with current industry standards, but also ensure projects are theoretically sound and practically relevant. In the process, students are equipped with the essential skills to meet the demands of the material science industry for a seamless career transition. Our research highlights the benefits of PBL in facilitating the learning process and outcomes. PBL fosters a shift towards formative, skills-based assessment methods with an emphasis to promote continuous feedback and personal growth throughout the project delivery. This hands-on approach supports students' development to become life-long learners who possess higher-order cognition and 21st-century skills, including critical thinking, creativity, problem-solving, teamwork and communication. A study, involving five different projects in small groups of four, demonstrates improvements in cognitive and psychomotor abilities while the affective domain remains stable. Through PBL, students gain a profound understanding of material science principles and extend their technical skillsets. The study aims to uncover optimal strategies and best practices to develop dynamic learners with enhanced intellectual engagement, as well as promote inclusive, collaborative, and progressive educational practices that reflect industry standards.

Keywords: industry-linked, project-based learning, cognitive, psychomotor, affective skills

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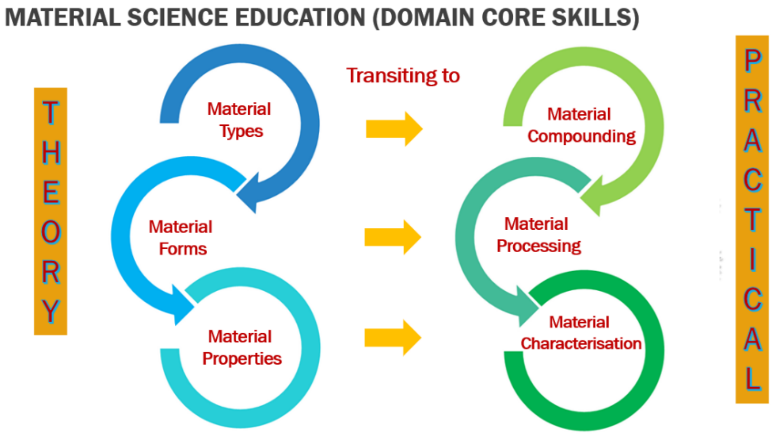
Introduction

The current research highlights the inaugural implementation of industry-linked projects within the Diploma of Applied Chemistry (DAPC), marking a significant milestone in Material Science education at Singapore Polytechnic (SP). By addressing the following two central questions, this study aims to uncover the transformative potential of industry-linked PBL in reshaping the educational landscape. As the pilot initiative in material science education at the institution, it sets the stage for future iterations and refinements, paving the way for more engaging, dynamic and impactful learning experiences.

1. How does the integration of industry collaboration within project-based learning transform the development of core skills and knowledge in material science education?
2. What impact does industry-driven project design within project-based learning have on student learning outcomes in material science education?

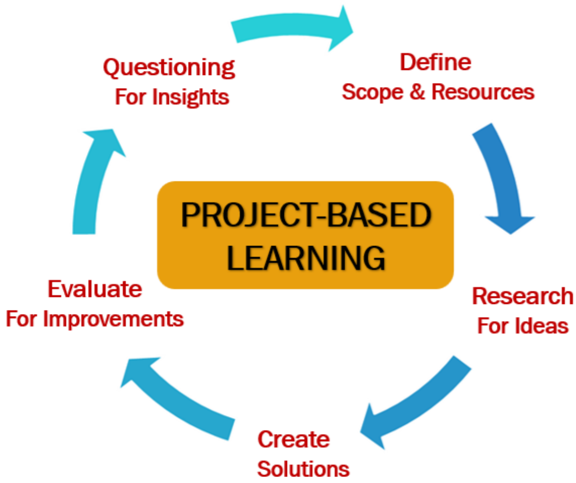
The training model (see Figure 1) is built upon a seamless integration of theoretical knowledge and practical application, cultivating a hands-on learning environment that encourages both intellectual curiosity and real-world readiness. Firstly, conceptual learning is introduced to students across a variety of materials, including but not limited to, polymers, ceramics, metals, and composites as well as their corresponding atomic structures and the fundamental principles that govern their behaviour. This understanding is further reinforced through a diverse range of instructional methods, including rigorous laboratory experiments that critically investigate how various material types and forms can directly affect their properties and performance. The hands-on experiences consolidate the development of students' analytical thinking and technical proficiency in material compounding, processing, and characterisation under varying conditions. By translating this knowledge into a prototype, the journey begins with careful material selection for compounding to meet the project brief, followed by prescribing processing techniques that unlock specific characteristics suited to the intended applications. These processing techniques not only transform raw materials into usable forms but also allow for precise tuning of material attributes. The properties of materials are subsequently characterised using appropriate instrumentation and testing methods to assess key features such as mechanical strength and thermal stability. As a result, a comprehensive understanding of the intrinsic nature of materials and interactions of processing methods and conditions are essential for material science students, empowering them to optimise material performance for a wide range of applications.

Figure 1
The Material Science Education Model



A hallmark of this initiative is its strong emphasis on PBL, which connects theoretical concepts with authentic real-world challenges faced by the industry. Students engage in optimising material performance through material compounding, processing, and characterisation. Beyond the dynamic and multidimensional integration of theory and practice, students emerge with critical thinking, problem-solving, teamwork, communication, and project management skills within a simulated professional environment, in addition to technical expertise. This development is nurtured throughout the five phases of the PBL iterative workflow, as shown in Figure 2. The process will be elaborated on in greater detail in the Methodology section.

Figure 2
The Five Phases of PBL



Literature Review

Industry-integrated PBL has emerged as both a pedagogical and practical evolution, driven by the demands of today's workforce, which are characterised by rapid technological change, global competition and evolving skill requirements for innovation. This meaningful progression aims to develop the cognitive, collaborative, and adaptive competencies that graduates need to thrive amidst the demands of the 21st century. As a result, there is an impending need for pedagogical models that more effectively align academic learning with employability (Naseer et al., 2025; Pan et al., 2023).

Traditional PBL is rooted in John Dewey's experiential learning philosophy and William Heard Kilpatrick's project method (Dewey, 1938; Kilpatrick, 1918). Empirical research on this inquiry-driven pedagogy consistently demonstrates benefits such as enhanced academic performance, positive affective attitudes, collaborative problem-solving abilities, and higher-order thinking skills (Almulla, 2020; Biazus, et al., 2022; Condliffe et al., 2017; Zhang et al., 2023). Nonetheless, traditional PBL has notable limitations. Recent reviews of higher education highlight that school or simulated scenarios are often overly simplified, lacking the unpredictability and complexity found in authentic professional environments. Ongoing challenges such as academia's readiness, the implementation of appropriate assessment strategies and the need to balance guidance, are factors that require further deliberation. (Admiraal, 2020; Marinho et al., 2020; Zhang et al., 2023).

Consequently, industry stakeholders now play a pivotal role in addressing longstanding gaps in graduate readiness, including adaptability, cross-functional collaboration, and contextual decision-making for real-world employment. By embedding industry ecosystems within the established PBL framework, students engage with open-ended, evolving projects that mirror the complexity of contemporary workplaces. Integrating external partnership requires negotiation with multiple stakeholders, management of evolving requirements, and navigation of incomplete data and contextual constraints (Admiraal, 2020; Naseer et al., 2025; Popli et al., 2024). Throughout this process, students' professional identities and capacities for adaptive expertise are deepened through mentoring, workplace familiarisation and iterative feedback from industry leaders.

Empirical studies (Marinho et al., 2020; Pan et al., 2023) have also reported that sustained partnerships benefit both academia and industry. Industry partners gain cost-effective access to innovative ideas, new opportunities, and potential solutions for challenges they may not have the internal bandwidth to address. Furthermore, key success elements include structured peer interaction and enhanced group awareness which support high-quality collaboration (Zhang et al., 2023). Academic supervisors contribute by ensuring deliverables meet both curricular standards and industry objectives. Naseer et al. (2025) also mentioned that such collaborations nurture industry-savvy, agile, and employable professionals, leading to improved self-reported employability competencies, engagement, and learning satisfaction.

Methodology

Twenty Year Two students from the Diploma of Applied Chemistry (Material Science specialisation) students (n = 20) were recruited for this study. These participants were divided into five project teams of four. Each project theme is curated and sponsored by industry partners who provided the overarching project direction and key requirements in response to current market needs. This collaboration enabled students to gain invaluable insights into authentic professional practices and industry expectations. This approach also equipped them with the requisite skills and confidence to excel in their future careers in the field of material science. Under the guidance of experienced educators and industry experts, the students were tasked with delineating specific project goals, developing innovative solutions, and managing their projects from inception to completion using PBL. In this highly collaborative environment, students were encouraged to leverage their unique strengths, thereby enhancing their collective problem-solving, decision-making, and investigative abilities. The diversity within each team simulated real-world professional settings, preparing students to navigate complex interpersonal dynamics and develop essential transferable skills.

As depicted in Table 1, the collaborative process begins with the Questioning phase, the industry partners present their pain points and challenges encountered in product development or material performance while academic stakeholders brainstorm innovative ideas to address these real-world issues. In the subsequent Define phase, clear project objectives are established, hypotheses and technical requirements are formulated, and resources are allocated with guidance from industry partners regarding their expectations, technical specifications, operational constraints, and any specialised materials provided. During the Research phase, students conduct comprehensive literature research into material compounding and properties, analysing the latest technological advancements and relevant case studies. Industry collaborators support this stage by providing proprietary data, access, and sharing best practices. In the Create phase, research findings are integrated into iterative product prototyping or solution development, accompanied by material characterisation and performance testing. The industry partners mentor by contributing practical perspectives to frame project directives as well as insightful feedback on project findings. Finally, the Evaluate phase involves reflective improvement and consolidation of deliverables for industry collaborators, with the feasibility of the proposed solution validated to ensure alignment with business goals in material science. This integrated approach ensures that both academic inquiry and industry needs are addressed throughout every stage of the collaboration.

Table 1
The Role of Academia and Industry Partners in the PBL Model

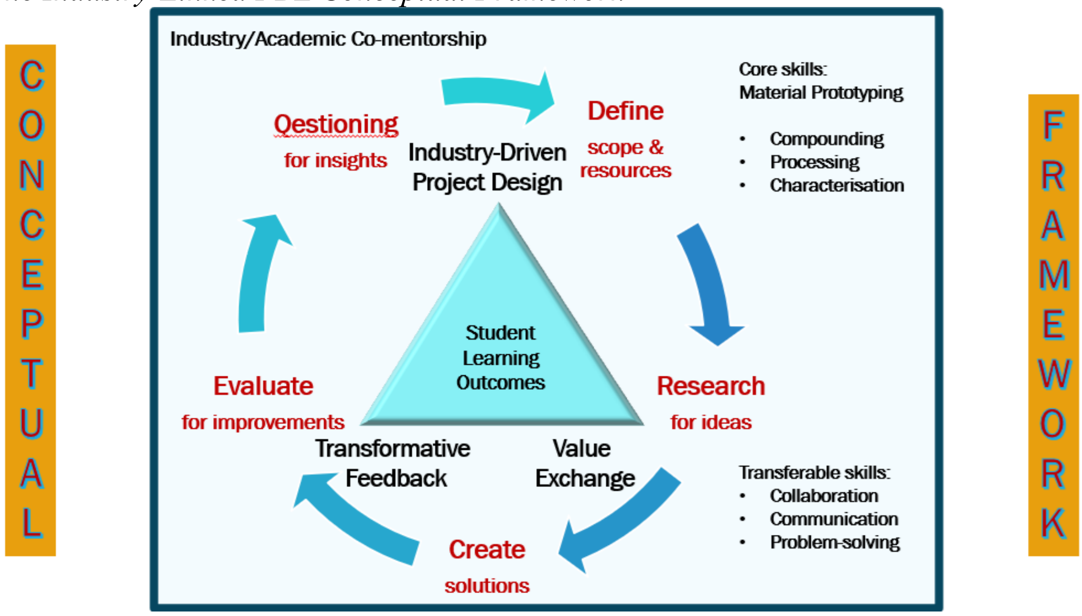
Phase	Academic Activities	Industry Engagement	Outcomes & Value Exchange
Questioning	Brainstorm for innovative ideas	Present industry pain points and challenges faced	Conceive insightful questions aligned with industry needs
Define	Define project objectives, hypotheses, technical material requirements and resources allocation	Set industry expectations and provide technical specifications, operational constraints and any specialised materials	Mutually establish project scope and measurable deliverables of currency and relevance
Research	Conduct literature research to meet project objectives	Provide proprietary data, access and best practices	Establish robust data and knowledge base, exposure to cutting-edge practices/ innovation in materials
Create	Integrate research findings into hands-on iterative product prototyping or solutioning	Mentor by contributing practical perspectives and insightful feedback on project findings	Develop prototypes or solutions collaboratively that are applicable to industry
Evaluate	Perform reflective improvements and consolidate deliverables to industry collaborators	Validate feasibility of proposed solution aligned with business goals	Foster knowledge exchange and advance innovation in materials

In order to assess students' learning, a structured questionnaire adapted from the Learning Self-Efficacy Scale (L-SES) for Clinical Skills (Kang et al., 2019), was administered. This instrument was designed to profile self-perceived learning and confidence in the cognitive, affective, and psychomotor domains, providing a multidimensional view of each student's educational development. Pre- and post-survey responses were collected at beginning and end of the semester using Microsoft forms. The self-assessment questionnaire is based on a five-point Likert scale. Participants indicate their perspective of each statement, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). This scaling provides a quantitative measure of student perceived self-efficacy in each domain. Qualitative results through interviews were also solicited around the PBL learning experiences and challenges encountered.

Results and Discussions

The integration of industry collaboration into PBL is crucial for bridging academic outcomes with real-world demands. A conceptual framework (see Figure 3) encapsulates three key pillars: industry-driven project design, value exchange and transformative feedback. The model is structured around clear milestones, measurable outcomes, and ongoing reflection. Students are empowered to track their progress, adapt their strategies, and demonstrate growth not only in technical skill but also in collaboration, problem-solving, and professional communication. The result is a holistic learning environment where students are committed to making meaningful contributions.

Figure 3
The Industry-Linked PBL Conceptual Framework



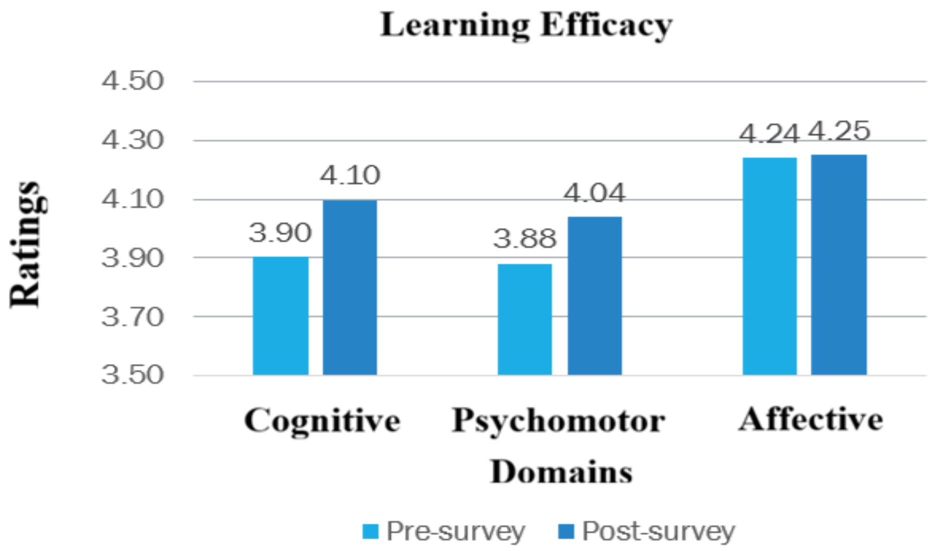
At its core lies the belief that this training will equip students with a rigorous academic foundation alongside the practical skills valued by employers. The first element, Industry-Driven Project Design, ensures the strategic partnership mirrors authentic workplace challenges. Through co-mentorship by industry professionals, students are exposed to a wide range of insights, methodologies, and real-world expectations (Lee et al., 2025; Pee, 2022; Srinivas, 2023).

The second element, Transformative Feedback, enables students to benefit from ongoing and contextualised feedback from their industry mentors, delivered through iterative sessions across the project timeline. This feedback enhances technical fluency feasibility, efficiency, and market relevance. The dynamic dialogue and critiques sharpen practical skills and nurture a mindset of innovation and resilience in students. They encourage iterative refinement, real-time adaptation and the development of essential skills in critical thinking and problem-solving.

In the final element, Value-Exchange, purposeful alignment of academic and industry efforts through co-mentorship, feedback loops, and shared resources allows all stakeholders to participate in a vibrant ecosystem of continuous improvement and co-innovation. The exchange of knowledge, resources and innovation between academia and industry offers substantial benefits to both parties. Industry partners gain direct access to emerging talent and their fresh perspectives. This synergy allows companies to explore new ideas with reduced risk and ensures that educational curricula remain aligned with industry needs (Marinho et al., 2020). Meanwhile, students receive hands-on experience, networking opportunities, and exposure to authentic industry practices and standards. They are empowered to tackle complex, real-world problems, think with agility, and transition smoothly into professional roles, while educational institutions reinforce their role as vital hubs of research and development.

Cumulative outcomes, and values that drive both educational and industrial advancement (Ahmed et al., 2024; Geetha et al., 2025; Pan et al., 2023) are presented throughout each industry-integrated PBL phase (see Table 1). In the Questioning phase, students cultivate the ability to pose insightful questions rooted in authentic industry needs, laying a foundation for relevance and impact. During the Define stage, stakeholders collaboratively establish strategic direction with a clear, shared understanding of project goals and measurable deliverables of currency and relevance. The Research phase deepens expertise by building a robust knowledge base and fostering exposure to the latest innovations in material science. In the Create stage, students and industry professionals work together to develop prototypes or solutions that have direct applicability, effectively bridging theory and practice. Finally, in the Evaluate phase, students deepen their understanding through applied feedback while industry gains access to emerging talents and novel solutions that can inform future practices in a cost-effective manner.

Figure 4
Changes in Students' Learning Efficacy Before and After Intervention



The self-reported L-SES average scores for the pre- and post-surveys are depicted in Figure 4. They offer valuable insights into the multifaceted nature of student learning and development within industry-integrated PBL context. The quantitative data reflect improvements in learning efficacy across cognitive, psychomotor, and affective domains (Vuoriainen et al., 2025; Zhang et al., 2023). The qualitative results further elaborate on these measurements (from 3.90 to 4.10) and identify areas for refinement in implementation. Within the cognitive domain, students demonstrated strengthened mental skills through both the recall and application of technical knowledge acquired in their coursework. Even though students felt some aspects of their learning are highly specialised, they managed to apply these skills for authentic challenges such as equipment failures or variations in materials. In addition, when procedural uncertainty arose, students were challenged to go beyond standard textbook approaches. They were motivated to conduct independent research, troubleshoot and make adaptive modifications to workflows and processing parameters, combining both research and experimentation. Based on their problem-solving skills and ability to reason logically in devising solutions, students could operate advanced instruments and made real-time adjustments to the processing parameters as necessary. Instead of relying exclusively on published data, students critically established appropriate process parameters via material characterisation and implemented measures to prevent equipment malfunctions. During regular communication sessions with project mentors, students demonstrated their ability to articulate technical concepts, requirements, project sequences and their interconnections clearly to the stakeholders. In the face of operational constraints, students were able to account for the underlying causes to external collaborators and make informed decisions regarding their strategies. These experiences reinforced their capacity to provide step-by-step explanations of each part of the project and its role within the overall process.

Students also showed improvement for the self-reported measurements (from 3.88 to 4.04) within the psychomotor domain. Their marked improvement in technical competency was evident through hands-on demonstrations and qualitative interviews. They were able to precisely execute the operational steps and action required for their technical assignments, as demonstrated when they confidently adjusted equipment such as extruders, TGA, DSC, and SEM during practical sessions. Many students reported completing these technical tasks smoothly and with increasing proficiency. Throughout the project, students proactively monitored their technical competency and continuously looking for ways to improve. For instance, when challenges arose, they adapted by exploring different approaches to project tasks such as modifying extruder operational parameters or SEM settings to address unexpected results. This adaptability highlights their willingness to experiment and integrate new methods in pursuit of better outcomes. Moreover, students made a conscious effort to monitor their understanding of course contents and technical skills. They regularly assessed their own progress and made necessary adjustments, ensuring alignment between theory and practice in a PBL context. Although occasional obstacles such as complex tasks or equipment limitations resulted in fluctuations in self-efficacy, students experienced notable growth in innovation and self-regulation.

In the affective domain, students' attitudes, values, emotions and motivation towards learning remained generally consistent (from 4.24 to 4.25) throughout the project. Nevertheless, the qualitative analysis showed that most students reported feeling more engaged, committed, and confident when faced with real-world challenges. Their motivation notably increased as project goals became clearer and as they observed tangible outcomes from their efforts. However, a minority noted that information-seeking behaviours might falter under deadline pressure, unfamiliar tasks and resource constraints. This range of experiences emphasises the setting of realistic expectations and providing targeted support to sustain engagement. Students repeatedly stressed they value the receipt of technical guidance, prompt feedback and practical advice, especially regarding process optimisation or mastering new techniques, when dealing with uncertainty or stress. Therefore, the ongoing guidance from supervisors and team were instrumental in fostering a sense of purpose. These can come in the form of facilitating communication with stakeholders, clarifying deliverables, ensuring quick access to resources and collective team efforts in maintaining positive emotions were all vital for enhanced outcomes when refining project approach. Despite occasional setbacks, the majority of students appreciated the practical experience gained from industry-oriented tasks. The open-ended format of the projects promoted exploration and independent learning, expanded their learning horizons.

Recommendations

The shift toward industry-linked PBL has led to advancements in students' cognitive and psychomotor abilities. However, the pilot implementation revealed that many students initially faced uncertainty in meeting industry project expectations due to perceived gaps in their competencies and available resources. To address the challenges of balancing structured guidance with student autonomy, it is strongly recommended to enhance student preparedness. Specific gaps identified through post-project interviews prompted more targeted support in strengthening technical report writing and core material science competencies, particularly in processing techniques prior to project commencement.

To mitigate the considerable stress experienced by students, measures such as built-in buffers within project timelines should be implemented, allowing for more thoughtful consolidation and reporting of findings. Regular check-ins and open forums can further alleviate anxiety as students make conscious efforts to meet the expectations of academic and industry stakeholders.

Beyond technical proficiency, it is crucial to place greater emphasis on developing transferable skills that foster students' holistic growth. Cultivating self-directed learning, effective teamwork, and a collaborative culture grounded in inclusivity, mutual respect, and open-mindedness are vital attributes for real-world success. In this environment, supervisors play a pivotal role by reinforcing positive team dynamics, celebrating collective small wins, recognising individual contributions, and fostering a sense of belonging within diverse groups. By integrating these strategies, academia can empower students to thrive as adaptable, resourceful professionals in material science. Granting students greater autonomy in project selection can further enhance their motivation and instil a stronger sense of ownership over their learning experiences.

Conclusions

Through the purposeful integration of industry collaboration within PBL, material science education at Singapore Polytechnic has experienced a transformative evolution. Joint supervision by both industry collaborators and academic mentors enables projects to be co-designed in response to current, real-world issues, ensuring that learning is grounded in robust theoretical understanding while firmly situated within practical application. This intentional bridging of theory and practice ensures that graduates are well-prepared to contribute to the material science sector. Ongoing and transformative feedback provided by industry professionals further enriches students' learning journey, shifting them from passive recipients to proactive problem-solvers. Reflective practices embedded throughout these experiences promote continuous evaluation of students' cognitive, affective and psychomotor development, aligning their growth with the technical demands of the evolving industry landscape. As cohorts progress through their projects, clear advancements, particularly in communication skills, are observed. During professional interactions with industry stakeholders, students become more equipped at articulating project workflows, outcomes, and challenges with minimal assistance from their academic mentors. Beyond the notable gains in technical execution, logical sequencing, and confidence, this holistic approach further exposes students to external perspectives that emphasise market relevance and adaptability in real-world settings. As a result, it fosters resilience and cultivates a mindset of continuous improvement. The reciprocal exchange of value between academia and industry creates a vibrant learning ecosystem, empowering students to acquire hands-on technical proficiency and develop professional networks while the industry partners benefit from fresh perspectives and cost effectiveness in project solutioning. This tripartite partnership ensures that PBL remains agile, relevant, and impactful in effectively bridging the gap between scientific theory and the practical development of material solutions, while instilling critical 21st-century transferable skills such as self-directed learning, problem-solving, collaboration, and communication. These industry-infused, hands-on experiences position students advantageously for the ever-evolving landscape of material science.

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

Generative AI tools, including Perplexity, Copilot, and ChatGPT, were used to improve the manuscript's clarity and coherence, as well as for literature searches and reference identification. The authors remain solely responsible for all substantive content, critical analysis and interpretations.

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