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An industry-university-research integrated teaching framework for transnational biomedical-engineering postgraduate education of international students in China

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Abstract: Against the fast-growing scale of transnational biomedical engineering (BME) graduate training in China, persistent structural barriers undermine the alignment between graduate competency cultivation and global industry requirements. These constraints centre on limited teaching staff equipped for cross-cultural instruction, inflexible course architectures, insufficient intercultural support services, and incomplete end-to-end quality oversight frameworks. This paper develops a customised industry-university-research integrated teaching framework to address the unique demands of cross-border medical engineering education. Drawing on a sequential mixed-methods design, the research draws evidence from a PRISMA 2020 systematic literature review, two rounds of Delphi expert consultation, a two-year pilot intervention enrolling 62 international postgraduate learners, and multi-faceted quantitative and qualitative assessments using bespoke evaluation instruments.

The integrated model is structured around three foundational pillars: co-developed cross-border curricula, tiered intercultural adaptation services, and full-cycle quality governance, alongside four interconnected functional modules and a hybrid formative-summative evaluation mechanism. Comparative data from the pilot programme revealed statistically significant inter-group differences for most, though not all, measured outcomes. Participants in the pilot recorded an average core course score of 86.7 ± 5.3 , compared to 75.2 ± 6.1 for the control group. Within the pilot cohort, 81.2% obtained the International Medical Device R&D Professional Certification and 75.0% secured region-specific regulatory certifications matching their domestic medical standards; by contrast, zero participants from the control sample were awarded either credential. The intervention group also showed improved cross-cultural adjustment (82.3 ± 4.5 versus 70.5 ± 5.2), higher rates of cross-border employment (65.6% versus 33.3%), and more positive evaluations of transnational teaching quality (87.5% versus 62.3%).

Based on empirical evidence from a two-site quasi-experimental pilot, this training framework addresses key structural challenges observed within China's cross-border BME graduate provision. The findings suggest potential actionable reform pathways for transnational medical-engineering education. Nevertheless, generalisability is constrained by pilot-specific contextual factors, and further multi-site validation is required before this model can be regarded as a broadly transferable operational template

for other international graduate-training disciplines.

Keywords: Transnational Medical Education; Cross-border Biomedical Engineering; International Graduate Training; Industry-Education-Research Integration; Teaching System Reform; Cross-Cultural Adaptation; Educational Quality Assurance

1. Background

Biomedical engineering (BME) stands as an interdisciplinary field merging engineering, life sciences and clinical medicine, serving as a foundational driver of modern healthcare progress and population health improvement [1]. Fueled by the globalisation of medical education, the emergence of new engineering disciplines, and national strategic frameworks including the Belt and Road Initiative and Healthy China 2030, cross-border BME training has grown into a key channel for cross-border health talent mobility and international technological cooperation [2].

China has seen steady growth in its cohort of international graduate students, among whom engineering tracks—especially BME—remain highly sought after. Its strong applied value and broad global career appeal draw most overseas learners from Southeast Asian and African nations [3, 4]. Despite rising enrolment numbers, cross-border BME graduate education in China is still in an early developmental phase, held back by structural misalignment between traditional teaching architectures and the core demands of transnational medical education [5]. This disconnect manifests most visibly in unspecialised curricula, piecemeal cultural support, and fragmented quality oversight systems[6]. A body of empirical research examining existing postgraduate provision has unpacked four interlocking constraints that hinder effective overseas talent cultivation[7].

Traditional curricula are largely adapted from domestic Chinese programmes without bespoke adjustments to suit international students' varied learning foundations, cultural contexts and study priorities [8, 9]. This one-size-fits-all design widens the gap between graduates' learned capabilities and the professional benchmarks of their home healthcare markets, alongside global industrial protocols for medical devices. Few courses systematically embed international regulatory standards or cross-border manufacturing and clinical workflows, leaving Chinese training far less aligned with established overseas BME programmes.

Support systems addressing intercultural adjustment are similarly under-resourced across most participating universities. Where services exist, they tend to focus solely on basic language tuition, with little structured guidance around cross-border clinical communication norms, cultural disparities in patient care workflows, or internationally recognised codes of professional ethics [10, 11]. Longitudinal student surveys confirm that persistent linguistic and cultural barriers undermine classroom engagement and hands-on practical performance, dragging down overall training efficacy [12]. Existing evaluation frameworks compound this issue: nearly all institutional assessment tools are built around domestic student cohorts, weighting theoretical exam performance heavily while overlooking critical transnational skills, such as cross-cultural teamwork and adherence to global industry standards, which rarely feature in routine quality monitoring[13, 14].

Shortfalls in educator capacity represent another central constraint. Survey data of teaching staff at Chinese medical engineering institutions indicates only a minority have completed formal training for international English-medium instruction. Many instructors struggle to adapt lessons for multicultural cohorts, with limited practice integrating global research outputs and overseas industrial case studies into regular teaching. Most academics also lack clear pathways to translate laboratory research into cross-border clinical or commercial applications, and participation in joint international R&D projects stays minimal [15]. Multi-stakeholder collaboration structures remain underdeveloped as well: overseas enterprises and foreign medical bodies contribute minimally to curriculum development and teaching case building, while the share of international guest instructors in routine classes lags far behind leading transnational engineering programmes [16]. Taken together, weak educator cross-border literacy and shallow cross-sector collaboration hold back the overall quality of international BME graduate training [17].

These structural hurdles are compounded by BME's unique industrial ecosystem, which links basic research, clinical translation and commercial rollout, alongside the wide spectrum of career aspirations held by overseas graduate cohorts [18]. Learners differ substantially not only in nationality and cultural background but also in long-term professional objectives, making uniform training models ineffective. Industry–university–research collaboration has been documented as an effective mechanism for narrowing theory-practice divides within transnational medical education, delivering tangible gains in students' cross-border practical abilities and graduate employability [19]. Even so, such integrated models remain sparsely implemented within Chinese international BME programmes, and those currently deployed rarely incorporate targeted design for cross-border curricula, intercultural support and end-to-end quality management. This gap creates demand for a customised industry-university-research framework that embeds these three core dimensions, offering a structured path to resolve persistent training barriers and advance high-standard transnational medical engineering education [20, 21].

Beyond generic international engineering training, cross-border BME provision bears intrinsic ties to core missions of global health professions education. Biomedical engineers act as vital intermediaries connecting clinical frontlines, medical device R&D and cross-border patient care delivery; gaps in their training directly weaken consistent clinical reasoning, standardised medical equipment operation and unified patient safety protocols across disparate national healthcare systems. Though this study centres on industry-university-research integration for engineering learners, the proposed teaching architecture embeds mandatory modules covering cross-border clinical practice, interprofessional medical communication and global clinical ethics, bridging technical engineering training and the core competency benchmarks required for global healthcare practitioners.

2. Aim and Objectives

Biomedical engineering operates along a complete value chain stretching from foundational technical research through clinical translation to scaled industrial deployment, a structural reality that shapes every layer of transnational graduate training for international learners based in China. These cohorts

carry distinct cultural backgrounds and individualised learning priorities, yet existing cross-border provision fails to address three interconnected foundational demands of global medical education: coherent cross-border curricular construction, sustained intercultural support tailored to overseas students, and consistent, standardised systems for teaching quality oversight. Rooted in this practical mismatch, the present study develops a modular, competency-driven industry-university-research integrated teaching and practice framework, backed by institutional support structures and iterative quality governance mechanisms designed exclusively for transnational BME graduate contexts.

The design of this integrated framework responds to overlapping gaps observed within current cross-border training pathways, spanning educator capacity, graduate skill cultivation and institutional evaluation infrastructure. At the educator level, existing teaching teams lack cohesive development pathways to build fluent English-medium instruction for specialist BME content, translate academic research into cross-border clinical and industrial applications, and build stable cooperative links with global biomedical industry partners. For international graduates, conventional training rarely fosters balanced development of technical expertise, cross-cultural collaborative awareness and cross-border entrepreneurial thinking suited to varied national healthcare markets. Meanwhile, few institutions maintain customised evaluation systems that track cross-border competency growth and sustain long-term quality management, leaving persistent divides between classroom theory and global industrial expectations, insufficient support for students' cultural adjustment and underdeveloped practical training modules unaddressed. By constructing this unified IUR teaching system, the work seeks to redress these layered limitations and advance transnational medical graduate training aligned with international professional benchmarks.

3. Methods

3.1 Research Design

A sequential mixed-methods design underpinned this investigation. Quantitative and qualitative evidence was gathered throughout four interconnected stages: systematic literature screening, Delphi expert consultation, educational pilot delivery and multi-faceted outcome appraisal. Insights yielded from each phase guided subsequent work, establishing a continuous, evidence-driven research workflow.

3.2 Phase 1: Systematic Literature Review

All screening activities complied with PRISMA 2020 reporting standards [22]. Literature searches covered Web of Science Core Collection, Scopus, CNKI and Wanfang Data for publications issued between January 2014 and December 2023. The Boolean search syntax combined keywords for industry-university-research collaboration, biomedical-engineering instruction, international postgraduate cohorts, trans-national education and pedagogical framework development.

Eligible sources comprised peer-reviewed original investigations, systematic reviews and meta-analyses addressing industry-university-research practice within international-focused biomedical-engineering graduate training, with accessible full-text content published in Chinese or English. Conference abstracts, book reviews, unstructured case accounts, off-topic records, incomplete datasets and duplicate articles

were excluded from analysis.

Literature Screening and Quality Appraisal

Dual independent researchers carried out title-and-abstract screening, data extraction and study quality evaluation, with disagreements settled through deliberation alongside a senior third-party investigator. The full-record selection process, completed under PRISMA 2020 protocols, is summarised within **Figure S1**. The search yielded an initial 3864 entries; after the removal of 1247 duplicates, 2617 unique publications underwent preliminary screening. A total of 2415 irrelevant records were discarded, leaving 192 articles for full-text inspection, from which 124 failed eligibility requirements. The final sample of 68 papers proceeded to thematic analysis to support the development of our transnational biomedical-engineering postgraduate teaching system.

Targeted assessment instruments were deployed to judge the methodological standard of the included 68 works: AMSTAR-2 [23] for systematic-review manuscripts and JBI appraisal checklists [24] for primary empirical research. Most reviewed papers attained moderate-to-high methodological quality and presented minimal risk of research bias.

Thematic Synthesis

A thematic synthesis was undertaken upon the eligible body of literature, with analysis centred around three overarching lines of inquiry: existing industry-university-research-based pedagogical frameworks within general engineering and biomedical-engineering training, recurring features and documented obstacles facing international BME postgraduate provision, and core design tenets for trans-national medical education covering quality-governance protocols, intercultural-adjustment support and multi-stakeholder collaborative structures. Insights generated through this qualitative synthesis furnished the empirical evidence-base and theoretical grounding required for the subsequent rounds of Delphi expert consultation.

3.3 Phase 2: Delphi Consultation

3.3.1 Expert Selection

An interdisciplinary expert panel of 15 participants was recruited to capture multi-faceted perspectives on transnational biomedical-engineering graduate education, with selection criteria prioritising disciplinary representativeness, specialist proficiency and professional standing.

The panel brought together four biomedical-engineering education researchers with ten or more years leading national-level pedagogical-reform initiatives, four senior industry engineers sourced from top-tier global biomedical-engineering enterprises with hands-on familiarity with overseas industrial workflows, four international-student administrators specialising in postgraduate governance and intercultural learning support, alongside three senior practitioners devoted to trans-national medical-programme development and international quality-standard formulation, each boasting over 15 years of relevant working experience.

Most panellists held doctoral-level qualifications, possessed overseas-exchange backgrounds and had

previously taken part in cross-border medical-education initiatives. Such varied professional composition secured authoritative, well-rounded judgement throughout the Delphi inquiry.

3.3.2 Consultation Process

Two rounds of Delphi surveys were administered via Wenjuanxing, a professional online questionnaire platform, with all survey items shaped by findings from the earlier thematic literature synthesis.

The first round deployed a baseline questionnaire exploring core elements of the proposed training system, and all 15 experts submitted complete responses. Panellists rated 53 indicators across three domains (20 items for the integrated teaching framework, 15 for educators' transnational competencies, and 18 for graduate training outcomes) using a five-point Likert scale, while offering open-text qualitative feedback for further optimisation.

The questionnaire for the second round was refined according to Round 1 expert input. Any indicator was eliminated unless it met rigid consensus and practicability thresholds: a minimum mean importance score of 4.2, a minimum mean feasibility score of 3.8, and a coefficient of variation below 0.18. Additional indicators focusing on transnational clinical practice and compliance with international industry standards were also integrated into the revised survey, which once more achieved a full 100% response rate from the expert panel. Post-survey statistical analysis produced a Kendall's W value of 0.82 ($P < 0.001$), demonstrating high inter-expert consensus on the structural layout and core components of the teaching system.

3.4 Phase 3: Pilot Implementation

3.4.1 Setting

This two-year pilot intervention was carried out across two higher education institutions in Guangdong Province, a regional cluster with a dense concentration of medical device enterprises. Both universities host sizable cohorts of international postgraduates and maintain formal collaborative ties with more than 20 biomedical engineering enterprises, creating a suitable practical environment to test the proposed integrated teaching framework.

3.4.2 Participants

A matched-cohort quasi-experimental approach was adopted for participant grouping, rather than fully random allocation. The two study cohorts consisted of successive full-time international BME graduate intakes over separate two-year cycles. The 2020–2022 intake ($n = 30$) received the conventional domestic-oriented training curriculum and served as the control group, whereas the 2022–2024 intake ($n = 32$) took part in the industry-university-research pilot scheme.

To mitigate baseline confounding variables, the two cohorts were matched systematically on multiple demographic and academic dimensions, including age, national origin composition, pre-enrolment English proficiency, prior engineering academic foundations and initial cross-cultural adaptation status (**Table S1**). Comparative tests confirmed no statistically meaningful between-group disparities at baseline across all matched indicators.

3.4.3 Baseline Equivalence

Independent samples t-tests and chi-square analyses were deployed to compare baseline attributes across the two cohorts and eliminate potential confounding factors. No statistically significant intergroup gaps were observed on all measured dimensions, as documented in **Table S1**. Such balanced baseline profiles support the legitimacy of subsequent comparative analyses evaluating the pilot intervention's associated outcomes.

3.4.4 Data Collection Instruments

Five bespoke assessment tools were developed exclusively for this research to quantify the performance of the industry-university-research integrated teaching framework.

First, an Academic & Professional Performance Record was compiled drawing on official academic transcripts and professional certification examination outcomes, which jointly captured participants' command of theoretical knowledge and hands-on practical capabilities.

Second, the Cross-Cultural Adaptation Scale for International Students (CCAS-IS) was adapted from Peng and Wu's (2019) intercultural transformation measurement framework [25], originally designed to map general communication behaviours among overseas students. All subdimensions were recalibrated to a unified 0–100 continuous scoring system to resolve conflicting 1–5 Likert and percentage scoring formats present in the initial draft. Confirmatory factor analysis confirmed robust internal consistency of the revised scale, with a Cronbach's α value of 0.87.

A custom Student Satisfaction Survey (**Table S2**) collected learners' feedback covering overall teaching quality, alignment between course content and industry demands, and campus support services for overseas postgraduates.

The Faculty Competency Evaluation Form (**Table S3**) served to measure instructors' capacity to deliver BME instruction for international cohorts, centring on their mastery of cross-cultural teaching approaches and industry-university-research integrated pedagogy.

Last, a Graduate Employment Tracking Survey (**Table S4**) was distributed six months after graduation. Data was gathered through written questionnaires and short telephone interviews to record graduates' employment status, industrial sectors and workplace locations, with targeted focus on positions requiring cross-border professional engagement.

3.4.5 Control Group Conventional Training Curriculum

Control cohort participants followed the standard domestic BME postgraduate syllabus routinely provided to international learners at the two participating universities. This conventional training pathway contained no cross-border industry-university-research modules, specialised intercultural support resources, or end-to-end quality governance frameworks designed for transnational education contexts.

All curricular content was migrated directly from domestic postgraduate teaching materials without targeted adaptations for overseas students. No teaching segments covered international medical device

regulatory criteria, clinical practice frameworks matching learners' home healthcare systems, or cross-border collaborative project-based learning tasks. Practical training activities were limited entirely to on-campus laboratory exercises, with no cooperative practice channels linked to overseas biomedical enterprises or foreign medical research institutions.

In respect of teaching teams and student support, instructors delivered generic English-medium lectures without receiving systematic training for multicultural classroom instruction. No dedicated intercultural coaches, industrial technical specialists or overseas research scholars took part in routine teaching arrangements. Support services for international students were restricted to foundational Chinese language classes, with no structured intercultural adaptation workshops or laboratory peer mentoring mechanisms available.

As for assessment arrangements, learner performance was measured purely via terminal summative written exams. The traditional scheme excluded formative learning portfolio tracking, third-party evaluation feedback from industrial mentors, and independent appraisal indicators measuring cross-cultural collaborative capabilities.

3.5 Phase 4: Multi-Dimensional Evaluation

A holistic multi-layered evaluation framework was constructed to gauge the performance of the proposed industry-university-research integrated teaching model. Drawing on five self-designed assessment instruments, this framework synthesised quantitative metrics and qualitative feedback to capture multifaceted evidence concerning transnational biomedical engineering training.

3.5.1 Student Learning Effect Evaluation

Learner developmental outcomes were measured via the Evaluation Form for Cross-border Learning Effectiveness (**Table S5**), a dual-rating instrument combining student self-reflection and ongoing formative appraisal from academic supervisors. The scale originally contained 12 core indicators, supplemented with three cross-border-specific items measuring practical operational capacity, familiarity with global professional regulatory codes, and cross-cultural clinical communication proficiency.

The final composite score was weighted such that self-assessment contributed 30% and supervisor evaluation constituted the remaining 70%, a design intended to mitigate self-report bias and secure objective outcome measurement. Reliability testing confirmed strong internal consistency for the tool, with a Cronbach's α value reaching 0.89.

3.5.2 Teaching Process Evaluation

Anonymous student feedback on course delivery was collected via the Evaluation Form for Cross-border Industry–University–Research Integration Teaching Process (**Table S6**). The scale includes 12 measurement items, among which three custom cross-border dimensions were supplemented: the overall efficacy of intercultural teaching, the depth to which global industrial standards are embedded within curricula, and the practical yield of transnational educational resources. Reliability analysis

returned a Cronbach's α of 0.87, demonstrating solid internal consistency when gauging the operational quality of integrated cross-border instruction.

3.5.3 Teachers' Ability Evaluation

Instructors' transnational teaching and collaborative strengths were measured using the Faculty Cross-border Industry–University–Research Competency Evaluation Form (**Table S7**), a 14-indicator tool that expands upon the shorter 12-item student teaching assessment outlined in Table S6. Though both tools feature three identical cross-border core indicators, their scoring logics diverge markedly. The student-only process evaluation weights all items equally, while this faculty appraisal framework attaches greater significance to industry–research partnership work and multicultural classroom governance—these two domains jointly account for 40% of the final composite score, aligning with the study's focus on educators' integrated cross-border capabilities. The scale recorded a Cronbach's α coefficient of 0.91, confirming robust internal reliability for assessing teaching staff delivering international BME programmes.

3.5.4 Cross-Border IER Cooperation Effectiveness Evaluation

Partnership performance across cross-border collaborative stakeholders was measured via the Evaluation Form for Cross-border Industry–University–Research Cooperation Effectiveness (**Table S8**). The instrument facilitates reciprocal peer appraisal between all core participating bodies, encompassing host Chinese universities, overseas research institutes and international biomedical engineering enterprises.

The scale comprises 11 core indicators, augmented with three bespoke items tailored to cross-border partnership dynamics: the utility of shared transnational teaching resources, the standard of co-developed cross-border instructional case materials, and the practical impact of joint overseas training placements. Reliability testing yielded a Cronbach's α value of 0.85, signifying adequate internal consistency for appraising cross-border collaborative outcomes.

3.5.5 Comprehensive System Effect Evaluation

The overall performance of the integrated teaching framework was judged using the Comprehensive Effect Evaluation Form of Cross-border Industry–University–Research Teaching Practice System (**Table S9**). Assessment followed a dual-stage protocol: institutional teaching administrators first compiled operational data and preliminary judgements, before independent third-party specialists in transnational medical education delivered secondary validation. This layered review structure strengthens the neutrality and scholarly credibility of final evaluation outcomes.

Sixteen multi-dimensional indicators make up the full assessment framework, supplemented with three system-wide metrics that address unique transnational training priorities: the supportive impact of intercultural adjustment services, the maturity of cross-border quality oversight infrastructure, and the measurable lift in graduates' cross-border employment prospects. The tool demonstrated outstanding internal reliability, recorded at a Cronbach's α of 0.92.

3.6 Data Analysis

All quantitative outcome-related data, including core-course academic marks, specialist-certification attainment rates, transnational employment statistics and scores from the intercultural-adaptation instrument, were processed within IBM SPSS 26.0. Independent-samples t-tests handled comparisons of continuous variables between the pilot and control cohorts, while one-way ANOVA was adopted for any subsequent multi-group statistical comparison.

Qualitative material sourced from semi-structured interview records, instructor feedback questionnaires and field notes gathered throughout teaching practice underwent thematic coding and interpretation via NVivo 12. The inter-coder reliability kappa coefficient stood at 0.86, demonstrating strong agreement across researchers during qualitative coding work. A two-tailed significance threshold of $p < 0.05$ was applied for all inferential statistical testing.

4. Results

4.1 System Architecture: Industry-University-Research-Integrated Teaching-Practice Model

This research's principal output is a custom-built teaching-practice framework created for transnational biomedical-engineering postgraduate training. Developed in response to documented shortcomings uncovered by the systematic literature review and two-round Delphi expert inquiry, the framework consolidates overseas educational, industrial and clinical resources into one coordinated operational structure. It consists of four mutually-linked functional modules, three prioritised graduate-competency pillars and an integrated evaluation mechanism combining formative and summative assessment (**Figure**

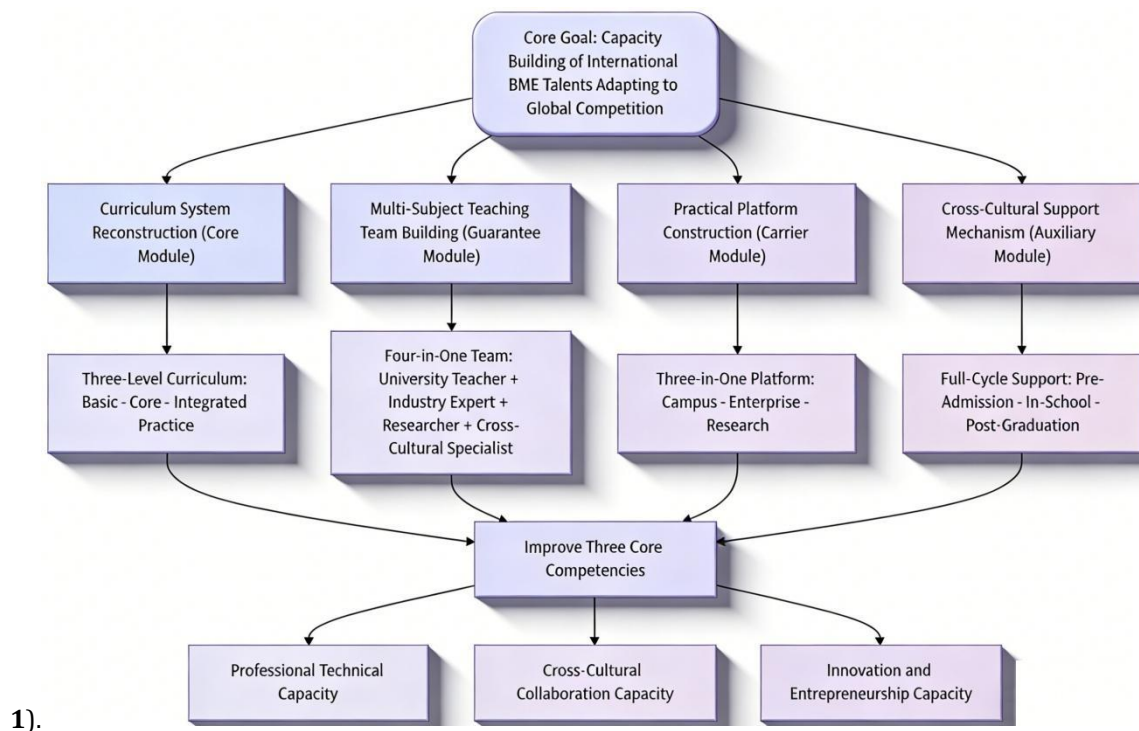


Figure 1. The Industry-University-Research-Integrated Teaching-Practice Model

4.1.1 Module 1: Cross-Border Collaborative Architecture Design

This module targets the structural misalignment between conventional BME curricula and the cultivation of globally competitive biomedical engineering professionals, establishing a refined “Three-Level, Three-Dimensional” collaborative curriculum architecture tailored to transnational graduate education. With stratified credit allocation and progressive learning objectives, the architecture systematically balances theoretical grounding, core professional literacy and practical application capacity across the entire training system.

The first tier of the curriculum comprises foundational courses, accounting for 25% of total credits. These medical and engineering basic courses are delivered from a comparative international perspective, prioritising standardised professional terminology and cross-regional knowledge system compatibility. Taking human anatomy teaching as a typical practice, the curriculum integrates English and Latin professional terminology to fully align teaching content with international educational specifications.

Professional core courses form the second tier and occupy 40% of total credits, with a primary focus on embedding global industrial regulatory criteria and universal technical norms into routine teaching. For example, the biomaterials curriculum incorporates authoritative international standards including the ISO 10993 series for medical device biological evaluation and ASTM material testing specifications. Combined with diversified cross-border industry case studies, this design enables international students to systematically grasp the technical specifications and operational requirements for global BME professional practice.

The final tier covers integrated practice courses, taking up 35% of total credits and adopting project-based learning (PBL) modes co-developed with international BME enterprises and overseas medical institutions. All practical projects are tailored to the actual healthcare demands of students’ home regions. For instance, students complete team-based development of low-cost portable pulse oximeters adapted for rural clinical scenarios in Southeast Asia. Such scenario-oriented practical training helps students apply theoretical engineering knowledge to real-world transnational healthcare contexts, effectively improving their comprehensive practical problem-solving capabilities.

4.1.2 Module 2: Multi-Level Cross-Cultural Adaptation

This module integrates cross-cultural competence cultivation into the full trajectory of transnational BME graduate training. Moving beyond superficial language instruction, it prioritises targeted professional acculturation tailored to biomedical engineering and global clinical scenarios, which is realised through two structured, complementary support mechanisms.

The first mechanism is lab-based peer mentoring. International students are matched with senior local graduate students to build long-term collaborative learning partnerships. This pairing model facilitates the transmission of tacit academic and laboratory knowledge that is seldom covered in formal coursework, including standard laboratory operational norms, safety management protocols, academic communication etiquette, and interdisciplinary teamwork conventions, helping overseas students rapidly adapt to local research and learning environments.

Complementarily, themed medical culture training workshops constitute the second core mechanism.

These specialised sessions systematically unpack cross-cultural disparities in global clinical workflows and healthcare service models. For illustrative purposes, the workshops compare the high-throughput patient-service operational model of Chinese tertiary hospitals with mainstream clinical practice frameworks prevalent in Western and African regions. Such targeted cultural training effectively prepares international students for adaptive practice during cross-border clinical engineering internships and professional rotations, bridging cultural gaps in global healthcare engineering scenarios.

4.1.3 Module 3: Cross-Border Practical Teaching Empowerment

This module builds a multi-stakeholder practical training ecosystem that unifies on-campus instructional resources, domestic affiliated hospitals, global biomedical enterprises, and overseas research institutes. Strategic institutional partnerships with five international BME corporations and three offshore research centres were established to deliver authentic, industry-embedded practical learning experiences throughout the pilot programme. The framework embodies two innovative design features that distinguish it from conventional internship arrangements.

First, the scheme adopts role-based immersive internships that replace passive observational training with substantive job-position practice. Pilot students undertook structured professional roles, including junior regulatory affairs assistants and R&D engineering support staff, enabling them to participate directly in operational workflows and cross-border engineering projects.

Second, the practical system integrates training into the global industrial value chain by leveraging students' multicultural and transnational contextual assets. Students were tasked with assisting domestic enterprises in localising technical documents and product registration materials to meet the regulatory requirements of their home jurisdictions. This design reframes international students' cultural and geographical backgrounds not as learning obstacles, but as unique professional strengths that facilitate transnational industrial collaboration and market adaptation [16, 26].

4.1.4 Module 4: Whole-Process Quality Assurance

This module constructs a closed-loop, full-cycle quality assurance framework grounded in the Plan-Do-Check-Act (PDCA) management paradigm, aiming to sustain iterative optimisation of transnational BME teaching quality and student training outcomes. Differing from the conventional end-of-semester evaluation model, this system combines ongoing formative supervision and external third-party appraisal to realise holistic, dynamic competency assessment.

Digital portfolio-based formative assessment serves as the core internal evaluation mechanism. It systematically records students' incremental growth in professional knowledge, practical skills and comprehensive literacy throughout the training cycle, effectively mitigating the limitations of single terminal examinations and enabling continuous tracking of individual learning progression.

Meanwhile, third-party industrial evaluation is introduced to enhance the objectivity and practical relevance of the assessment system. Professional industry mentors participate in student performance evaluation, with their scoring results accounting for 30% of the final composite grade. This external assessment focuses on students' professional ethics, collaborative teamwork capabilities and practical

problem-solving performance in real industrial scenarios, ensuring that graduates' core competencies closely align with the actual demands of global BME industries.

4.2 Effectiveness of Pilot Implementation

4.2.1 Academic Performance and Skill Certification

This study assessed two separate internationally recognised professional credentials, instead of one unified qualification. An aggregated overall pass-rate figure was presented within the abstract; this subsection supplies the clarified disaggregated certification outcomes. The pilot group recorded an 81.2 % pass-rate for the International Medical Device R&D Professional Certification and a 75.0 % success rate for home-nation regulatory qualifications covering local medical-device registration and clinical-engineering practice permits. No participant from the conventional-training control group secured either certification ($P < 0.01$). Such stark between-group differences indicate that the standard curriculum offered minimal preparation for industry-aligned practical competencies.

Embedding workplace-based scenarios and task-centred practical assignments into formal coursework deepened learners' subject comprehension and knowledge retention. As shown in **Table 1**, the pilot cohort attained significantly superior mean marks across every core biomedical-engineering course. The largest performance gap appeared on the BME Innovation Design module, with the intervention-group average reaching 89.2 against the control-group score of 75.3, a margin close to 14 points ($P < 0.01$).

Table 1: Comparison of Academic Performance in Core BME Courses

Course Name	Control Group (n=30) Mean $\pm$ SD	Pilot Group (n=32) Mean $\pm$ SD	t-value	P-value
Biomedical Instrumentation	76.4 $\pm$ 5.8	85.2 $\pm$ 4.9	6.45	<0.01
Biomaterials & Tissue Eng.	74.8 $\pm$ 6.2	86.1 $\pm$ 5.1	7.89	<0.01
Clinical Engineering	72.5 $\pm$ 6.5	87.4 $\pm$ 4.8	10.22	<0.01
Medical Image Processing	78.1 $\pm$ 5.5	84.9 $\pm$ 5.2	4.98	<0.01
BME Innovation Design	75.3 $\pm$ 5.8	89.2 $\pm$ 4.1	10.85	<0.01
<i>Overall Average</i>	<i>75.2 $\pm$ 6.1</i>	<i>86.7 $\pm$ 5.3</i>	<i>8.23</i>	<i><0.01</i>

Source: Longitudinal pilot study data (2022-2024).

4.2.2 Cross-Cultural Adaptation and Cross-Border Capacity Development

Measurements collected via the Cross-Cultural Adaptation Scale for International Students (CCAS-IS) verify that the multi-tiered cross-cultural adaptation module generated tangible relief from acculturative stress and enhanced intercultural coping competencies among overseas biomedical-engineering postgraduates (**Table 2**).

Across the whole research cycle, the control cohort demonstrated merely marginal growth in composite cross-cultural-adaptation scores ($\Delta = +2.7$). By comparison, the pilot intervention group attained a large, statistically meaningful score increment of $\Delta = +13.8$ ($P < 0.01$).

Qualitative evidence gathered from semi-structured interviews corroborates the quantitative outcomes. Participants from the pilot cohort repeatedly described heightened self-assurance when interacting with local supervisors and laboratory peers, alongside improved awareness of unwritten behavioural norms within research labs and clinical environments. These narratives indicate that the support module delivered professional-oriented acculturation gains that go far beyond simple foreign-language competence.

Table 2: Pre- and Post-Intervention Cross-Cultural Adaptation Scores (CCAS-IS)

Dimension	Group	Baseline (Year 1)	Post-Intervention (Year 2)	Change (Δ)
General Adaptation (Score / 100)	Control	67.8 $\pm$ 5.3	70.5 $\pm$ 5.2	+2.7
	Pilot	68.5 $\pm$ 5.1	82.3 $\pm$ 4.5	+13.8
Academic Adaptation (Likert Scale 1-5)	Control	3.2 / 5.0	3.4 / 5.0	+0.2
	Pilot	3.1 / 5.0	4.2 / 5.0	+1.1
Social Interaction (Likert Scale 1-5)	Control	3.0 / 5.0	3.1 / 5.0	+0.1
	Pilot	3.0 / 5.0	4.1 / 5.0	+1.1

Note: Data derived from pilot implementation statistics.

4.2.3 Cross-Border Employment and Satisfaction

Follow-up employment data collected six months after graduation revealed differentiated placement outcomes between the two cohorts (**Table 3**). The overall employment rate reached 90.6 % in the pilot group and 73.3 % in the control group. Chi-square testing indicated this difference in overall employment rate did ****not reach statistical significance**** ($\chi^2 = 3.17$, $*P* = 0.075$). However, a statistically significant inter-group difference was observed for cross-border-oriented employment — the primary target outcome of this training intervention. Cross-border-related employment was achieved by 65.6 % of pilot participants compared with 33.3 % of control-group graduates ($\chi^2 = 6.46$, $*P* = 0.011$).

Employer feedback provided qualitative insights regarding the industry-university-research integrated training model. Hiring managers tended to express preference for graduates from the pilot programme, highlighting their better familiarity with international medical-device regulatory standards and their capacity to facilitate communication between Chinese R&D teams and overseas market- or clinical-based stakeholders. These qualitative observations are descriptive and cannot be interpreted as definitive causal evidence of programme effectiveness.

Table 3: Employment Outcomes 6 Months Post-Graduation

Employment Status	Control Group (n=30)	Pilot Group (n=32)	Statistical Significance
Total Employment Rate	73.3%	90.6%	$\chi^2=3.17$, $P=0.075$
Cross-Border Employment*	33.3%	65.6%	$\chi^2=6.46$, $P=0.011$
- Intl. BME Enterprises	13.3%	43.8%	
- Cross-Border Medical Inst.	10.0%	15.6%	
- Tech Services	11.0%	6.2%	

Pursuing PhD	20.0%	25.0%	P > 0.05 (NS)
Unemployed/Unknown	6.7%	3.1%	

*Defined as employment in a role requiring transnational coordination (e.g., international sales, regulatory affairs for export) or located in a multinational corporation.

4.2.4 Results of Multi-Dimensional Evaluation

Multi-dimensional assessment based on five bespoke cross-border evaluation rubrics comprehensively validated the effectiveness of the industry–university–research integrated teaching model across core dimensions of transnational BME education. All domain-level average scores surpassed the 75-point satisfactory threshold predefined for cross-border medical education performance evaluation. Detailed quantitative outcomes demonstrated stable and superior operational performance of the optimized training system: student cross-border learning effectiveness (85.7 ± 4.2), cross-border teaching process quality (86.3 ± 3.8), instructors' cross-border teaching and collaborative competency (84.5 ± 4.5), cross-border industry–university–research cooperation effectiveness (83.2 ± 4.1), and overall systemic comprehensive performance (87.1 ± 3.5).

Notably, faculty professional capacity exhibited a substantial improvement compared with the pre-pilot baseline level, rising by 23.5% from the initial score of 68.2 ± 5.3 . Among all evaluated indicators, cross-cultural adaptation support efficacy and the maturity of the cross-border teaching quality assurance system achieved the highest scores. These outstanding sub-dimension outcomes further verify that the proposed model effectively addresses the key bottlenecks and inherent limitations existing in conventional transnational BME graduate training. Collectively, these favourable within-pilot evaluation outcomes suggest that, under the favourable contextual conditions of this two-site pilot setting, the integrated teaching framework may support the core-competency-building goals of standard-oriented international medical-engineering education. Caution is needed in generalising these results beyond the pilot context.

5. Discussion

This study adopted a quasi-experimental matched-cohort design to examine the effectiveness of an industry–university–research integrated teaching model for cross-border biomedical engineering graduate education. Given the lack of full randomised participant assignment, strict causal inference cannot be established between the intervention and the observed intergroup outcome disparities. Although rigorous baseline equivalence matching was performed to control confounding variables, unmeasured temporal and cohort differences may still partially account for performance gaps. Accordingly, all reported findings are interpreted as associative rather than definitive causal effects of the proposed teaching framework.

Methodologically grounded in systematic literature review, Delphi expert consultation, and a two-year longitudinal pilot implementation, this research developed and empirically validated a specialised integrated teaching practice system tailored to international BME graduate training in China. Existing industry–university–research integration studies predominantly focus on domestic engineering students

or general disciplinary contexts, with insufficient attention to the unique instructional, cultural, and industrial demands of cross-border medical engineering education [27, 28]. In this regard, the present model fills a notable research gap by targeting transnational BME talent cultivation scenarios.

As a specialised branch of transnational medical education, cross-border BME training confronts distinct challenges that differentiate it from conventional domestic engineering programmes, including pervasive cross-cultural adaptation barriers, curricular misalignment with global industrial and regulatory standards, and the absence of standardised whole-process quality assurance mechanisms for international learners [29, 30]. Centred on cultivating globally competitive biomedical engineering professionals, the proposed four-module integrated framework constructs a synergistic cross-border teaching ecosystem. Findings from this quasi-experimental pilot indicate that, within the studied settings, the proposed model may help alleviate several documented bottlenecks observed for China-based international BME graduate education. Given the absence of randomised assignment, these outcomes represent associative rather than causal observations [31].

Relative to students receiving conventional domestic-oriented training, the pilot cohort demonstrated consistent and statistically significant improvements across multi-dimensional indicators, including core course academic performance, international professional certification pass rates, CCAS-IS measured cross-cultural adaptation competency, and post-graduation transnational employment outcomes [32]. While these positive results align with established evidence regarding the efficacy of industry–university–research integration in engineering pedagogy [8, 33], this study further extends existing knowledge base through two context-specific innovations tailored to transnational education scenarios. First, it embeds a structured multi-level cross-cultural support system to address professional acculturation difficulties unique to international BME students. Second, it incorporates a PDCA-cycle-based whole-process quality assurance framework aligned with global medical device regulatory standards and industrial practice norms.

These targeted enhancements distinguish the present model from conventional integrated training schemes, which often overlook cross-cultural competency cultivation and transnational quality control. By synchronising curricular design, cultural adaptation support, industry practical empowerment, and standardised evaluation governance, the proposed system improves the practical adaptability, international compatibility, and graduate employability of cross-border BME education, delivering a context-specific optimisation and incremental advancement for transnational engineering talent training research [34].

5.1 How the Industry–University–Research-Integrated Model Builds International BME Students' Capacities

The superior performance of the proposed teaching model can be attributed to its holistic multi-dimensional design, in which four synergistic modules collaboratively foster international students' cognitive literacy, practical expertise, cross-cultural competence, and professional core capabilities for transnational biomedical engineering practice.

5.1.1 Curriculum Redesign: Linking Knowledge, Skills, and Real-World Contexts

The three-tier progressive curriculum framework integrates foundational disciplinary courses, professional core modules, and industry-oriented practical training, constructing a cohesive training pathway that unifies theoretical learning, engineering practice, scientific research, and cross-cultural adaptation. In this system, integrated practical courses account for 35% of total academic credits, with cutting-edge industrial technologies and global industry norms fully embedded into routine teaching content [35].

Contextualised and personalised learning design constitutes a core curriculum innovation. Teaching content is dynamically tailored to students' diverse national backgrounds and regional industrial demands. For instance, students from Southeast Asian regions receive targeted training on local medical device registration specifications and regional healthcare operational norms, ensuring that learning outcomes are closely aligned with their future career scenarios in home countries [36]. Meanwhile, project-based learning (PBL) is adopted as the core practical teaching approach to address context-specific cross-border engineering challenges. Typical practice is embedded within the BME Innovation Design course, where multicultural and interdisciplinary student teams develop wearable medical devices adapted to local healthcare conditions of their home regions, with systematic guidance from university academics, industrial engineers, and cross-cultural education specialists[37].

This multi-scenario training mode comprehensively cultivates students' professional technical proficiency, innovative design thinking, and core soft competencies including cross-cultural communication and interdisciplinary teamwork [38]. By grounding practical projects in students' native cultural and industrial contexts, the model transforms multicultural diversity from a potential educational barrier into a unique training advantage. The curriculum thereby achieves dual compatibility with global industrial standards and local regional demands, supporting the cultivation of globally competitive BME professionals. Furthermore, the three-tier curriculum systematically incorporates core training requirements for cross-border clinical engineering practice. It embeds standardised clinical workflow simulation, cross-cultural doctor–engineer communication training, and comparative analysis of global patient safety protocols, firmly anchoring technical engineering training in clinical reasoning and patient care literacy. This targeted design effectively resolves the disconnection between specialised BME skill cultivation and transnational medical education objectives, a critical limitation highlighted in previous studies of international engineering education.

5.1.2 Multi-Subject Teaching Team Building: Fostering Collaborative Expertise for Cross-Border Education

A distinctive strength of the industry–university–research integrated model lies in its diversified, multi-stakeholder teaching team, which brings together on-campus BME faculty, international industry experts, overseas research scholars, and professional cross-cultural instructors. This multi-subject collaborative structure breaks through the resource and perspective limitations of traditional single-university teaching teams, enabling the programme to meet the compound and interdisciplinary demands of cross-

border BME graduate education [39].

Each stakeholder group contributes complementary professional strengths to support integrated teaching. On-campus faculty ensure the systematicity, rigor and standardisation of core theoretical teaching. International industrial experts embed global talent evaluation criteria, cutting-edge engineering technologies and real-world transnational project cases into classroom instruction. Overseas academic scholars guide students in frontier cross-border research practices and align student research outputs with international academic paradigms. Professional cross-cultural specialists provide targeted linguistic and cultural adaptation support to resolve students' cross-cultural communication barriers and adaptive dilemmas throughout their studies.

Beyond optimising team composition, the model places equal emphasis on the sustainable professional development of teaching staff, focusing on improving three core cross-border competencies: international teaching proficiency, research transformation capacity, and industry-academia collaborative practice. After two years of systematic training via regular international teaching seminars and cross-institutional collaborative workshops, the average comprehensive competency score of core teachers increased from 68.2 ± 5.3 to 84.5 ± 4.5 , representing a 23.5% performance improvement.

These empirical findings corroborate existing scholarship affirming that multi-stakeholder teaching teams can effectively improve the practicality and quality of engineering education. Nevertheless, this study delivers notable incremental contributions to the literature. Different from conventional industry-academia collaboration models that focus merely on domestic industrial resources, this research incorporates professional cross-cultural instructors and prioritises the construction of teachers' cross-border comprehensive capabilities. This customised team design precisely matches the multi-dimensional growth needs of international students in academics, professional practice and cultural adaptation, significantly enhancing the model's adaptability and effectiveness in transnational BME education scenarios [40].

5.1.3 Practical Platform Construction: Bridging Academia and Global Industrial Practice

The cross-border practical training platform serves as a core carrier to bridge academic education and global industrial practice, effectively addressing the longstanding deficiency of disconnection between university coursework and transnational professional practice in traditional international BME training programmes [41].

The platform integrates three tiers of training resources: international-standard on-campus laboratories, off-campus practical bases in cooperation with global BME enterprises, and joint research platforms with overseas scientific institutions and international medical facilities.

On-campus laboratories are constructed and equipped in strict accordance with international industrial standards, providing students with standardised foundational hands-on training to master core operational skills that comply with global industry norms. Off-campus cooperative bases enable students to immerse themselves in authentic international industrial scenarios, covering product research and development, production operation, and regulatory compliance management, allowing students to fully

understand the competency requirements of cross-border BME professional roles. Overseas joint research platforms further support students' participation in frontier transnational scientific research, equipping them with international research methodologies and enabling academic collaboration with global peers.

This multi-level platform system builds a mutually beneficial symbiotic mechanism between international talent cultivation and the global BME industry. On the one hand, it dynamically aligns curriculum design and training content with the competency standards of international industrial partners. On the other hand, it delivers a steady supply of practice-ready, internationally competent BME graduates for global enterprises and research institutions [42]. Consistent with mainstream research on industry–university–research practical platforms, this study further innovates by centering on cross-border collaborative construction. Unlike traditional platforms limited to domestic cooperation, this framework fully integrates overseas industrial and research resources, fundamentally improving graduates' adaptability and competitiveness for global professional careers.

5.1.4 Cross-Cultural Support and Quality-Assurance Mechanism

One defining merit of the present teaching framework lies in its combined full-cycle intercultural support framework and stringent quality-assurance regime. This two-pronged mechanism responds to two pervasive defects within conventional transnational biomedical-engineering programmes: persistent intercultural adaptation obstacles and unstandardised teaching benchmarks inconsistent with international requirements.

Support services are delivered across three sequential phases covering pre-enrolment, the study period and post-graduation. Prior to admission, specialised academic-language workshops and cross-cultural orientation sessions build up students' English-for-academic-purposes competency and contextual awareness, facilitating speedy adjustment to local campus life and instructional settings in China.

Throughout postgraduate training, on-site intercultural-competence coursework, individualised academic guidance and the "Lab Twinning" peer-mentoring scheme assist overseas learners in overcoming specialised-terminology communication difficulties, getting accustomed to local pedagogical styles and settling inter-cultural misconceptions.

Following graduation, custom-tailored career counselling and sustained alumni follow-up services enable graduates to capitalise upon their intercultural awareness and vocational expertise when entering the worldwide biomedical-engineering labour-market, including employment based in their homeland, host-country enterprises and other international-focused appointments.

Observed improvements in CCAS-IS scores within the pilot cohort are consistent with potential benefits from this multi-stage support framework for intercultural adaptation. Nonetheless, non-random group allocation means other unmeasured cohort-level factors could also contribute to changes in adaptation scores. With obstacles stemming from cultural disparity mitigated, international students became capable of whole-hearted participation in coursework and industry-university-research-based practical assignments.

The above-mentioned results corroborate existing literature which concludes that purpose-built intercultural assistance promotes satisfactory academic achievement within international medical-related education. Most importantly, housing all cultural-adaptation initiatives inside a closed-loop, full-cycle quality-assurance system guarantees every training procedure conforms to international educational benchmarks and optimises the scheme's practical suitability for transnational biomedical-engineering instruction.

5.2 Advantages of the Formative-Summative Combined Assessment Framework

The integrated formative-summative assessment system serves as a core pillar of the model's full-cycle quality assurance mechanism, effectively remedying the inherent deficiencies of conventional assessment paradigms that rely solely on terminal evaluation. Traditional summative-only evaluation overemphasises final academic outcomes while neglecting the dynamic progression of cross-border learning growth and incremental cultural adaptation, resulting in one-sided and incomplete competency judgement for international students[43].

In contrast, the hybrid assessment framework achieves organic integration of process supervision and outcome verification, forming a multi-dimensional evaluation system tailored to the characteristics of transnational BME education.

Formative assessment realises continuous, process-oriented tracking of students' comprehensive learning performance throughout the training cycle. It comprehensively records and evaluates students' engagement in cross-cultural academic exchanges, completion of personalised assignments adapted to their home-country industrial contexts, performance in international collaborative practical training, and progressive outcomes of cross-border PBL projects. Combined with timely developmental feedback from academic supervisors and industrial mentors, this mechanism accurately identifies individual learning deficiencies and competency gaps, enabling targeted, personalised teaching intervention and iterative learning optimisation [44].

Supplementary summative assessment comprehensively validates students' final comprehensive competency attainment against international BME industry and educational benchmarks. This terminal evaluation adopts multiple authoritative indicators, including core course final examination results, internationally recognised professional skill certification qualifications, and graduation projects with practical cross-cultural application value, achieving standardised and systematic outcome assessment.

The complementary combination of formative and summative evaluation breaks the single knowledge-oriented assessment logic of traditional schemes. Beyond measuring students' theoretical knowledge reserve and professional practical skills, the framework innovatively incorporates cross-cultural adaptability and cross-cultural identity construction as core assessment dimensions. This design aligns with the theoretical connotation of culturally responsive evaluation for international education. It not only provides a scientific, standardised quality supervision tool for cross-border BME talent cultivation, but also effectively guides the whole training process to focus on the shaping of students' comprehensive global literacy, thereby supporting the output of high-competency BME graduates with authentic

transnational professional competitiveness.

5.3 Comparison with Existing Research and Innovation Points

Against the limitations of conventional industry–university–research integrated teaching systems that primarily target domestic engineering education, this study proposes three distinct, context-specific innovations tailored to the unique demands of cross-border biomedical engineering graduate training, advancing the paradigm of transnational talent cultivation.

First, the model adopts a scenario-oriented customised design that fully integrates cross-cultural adaptation cultivation into the entire curriculum system. Unlike traditional unified teaching modes that ignore the differentiated learning needs of international students, this framework optimises teaching content and instructional strategies based on students' regional backgrounds. The incorporation of region-specific medical device regulatory standards and localized industrial practical scenarios effectively addresses the prevalent problems of poor cultural adaptability and disconnection from home-country career demands encountered by international students in conventional training programmes [45].

Second, this study constructs a full-process, closed-loop quality assurance system exclusive to cross-border BME education. The system covers the complete training chain, including teaching resource input, in-process teaching management, and final outcome evaluation. The introduction of third-party evaluation from international industrial experts further enhances the objectivity, authority and practical relevance of quality supervision. This mechanism bridges the gap in existing transnational medical education research, which lacks standardised, industry-aligned quality control frameworks, ensuring that graduate competency cultivation consistently conforms to international professional norms and global industrial development demands [30].

Third, the framework builds a multi-stakeholder synergistic collaborative mechanism. It integrates high-quality resources from domestic universities, international BME enterprises, overseas research institutions and professional cross-cultural instructors, breaking through the single-discipline and single-institution limitations of traditional teaching models. This multi-dimensional resource integration realises deep synergy of education, industry and research, enabling curriculum teaching, scientific research training and industrial practice to complement and promote each other.

Collectively, these three core innovations transform the traditional domestically oriented talent cultivation paradigm into a cross-border, globally adaptive training system. The optimised model precisely responds to the inherent characteristics and core bottlenecks of transnational BME education, providing a feasible, systematic pilot-tested practical solution for high-quality international biomedical-engineering talent training under comparable institutional conditions. Further multi-institutional replication work is required to establish broader utility.

5.4 Limitations and Future Research Directions in Cross-Border Contexts

This study yields empirical insights derived from a quasi-experimental pilot, yet several key limitations must be considered when interpreting its findings.

As a matched-cohort quasi-experimental investigation, this work did not implement random participant assignment. While observable demographic and academic attributes were balanced between intervention and control groups via baseline matching, unmeasured temporal-cohort influences, shifts in institutional support over time, and latent disparities in individual participant motivation could still partly account for the observed inter-group outcome differences. For this reason, reported group-level disparities represent associative associations instead of definitive causal outcomes uniquely produced by the industry-university-research integrated training intervention.

Findings from this pilot are further bounded by contextual constraints that limit external generalisability. Data were gathered across two Guangdong-based higher-education institutions situated within a regional ecosystem featuring mature biomedical-industry clusters and well-established infrastructure for international postgraduate training. The total sample of 62 international learners had access to ample institutional, industrial and administrative resources which are not universally accessible for universities in central and western China or for institutions with limited industry-collaboration networks. Consequently, the magnitude of performance improvements observed within this pilot setting may not be replicated under resource-scarce conditions, and multi-institutional replication across geographically and administratively diverse contexts is required to verify broader applicability of the proposed framework.

Our evaluation of graduate professional outcomes relies on a relatively short six-month post-graduation follow-up window. Although this timeline permits documentation of early employment placement patterns, it cannot illuminate long-term career trajectories, sustained professional progression, or enduring work-related impacts linked to cross-border biomedical-engineering practice. Extended longitudinal tracking spanning two to five years would strengthen empirical evidence concerning the lasting practical value of the training model [46].

In terms of curriculum design, adaptive adjustments within the current framework operate primarily at the regional level and stop short of fine-grained customisation for individual nations. Given substantial cross-country divergence in medical regulatory regimes, clinical operational workflows and local labour-market expectations for biomedical-engineering professionals, one-size-fits-regional adaptations cannot fully align training content with the discrete home-country career contexts of every trainee, constraining the precision of personalised career-oriented training outputs.

Additionally, the five bespoke evaluation instruments developed specifically for this research carry potential risks of assessment circularity. These rubrics were intentionally constructed to correspond to the structural dimensions and competency goals of the very teaching framework under evaluation. Elevated assessment scores may therefore stem partially from inherent internal alignment between measurement tools and intervention design, rather than wholly transferable learning improvements. Incorporating externally validated, widely accepted measurement scales from existing transnational-education scholarship in future work will enhance result objectivity and permit direct cross-study comparisons.

Beyond methodological limitations, real-world deployment of this integrated model is contingent upon continuous multi-stakeholder resource commitments, including stable collaborative ties with biomedical

enterprises, dedicated cross-cultural teaching specialists, and adequate administrative funding. Such prerequisites create tangible practical obstacles that hinder large-scale roll-out among many higher-education institutions.

Against this backdrop of constraints, future research will prioritise iterative refinement of the cross-border-training model. Curriculum development will advance beyond regional-scale adaptation toward country-tailored adjustments, where teaching modules and practical project tasks are recalibrated to match nation-specific medical-system characteristics, regulatory stipulations and industry workforce demands. Digital enhancement of practical-training platforms will also be pursued through online collaborative infrastructure and virtual-simulation modules, which aim to mitigate geographic barriers and expand equitable access to cross-border biomedical-engineering educational resources for both students and teaching practitioners. Furthermore, deeper collaborative engagement with global professional bodies holds potential to inform the development of internationally acknowledged certification mechanisms, ultimately supporting improved global recognition for transnational biomedical-engineering postgraduate programmes delivered within China [47].

6. Conclusions

This study designed and pilot-tested a customised industry-university-research integrated teaching system for international biomedical-engineering postgraduate education in China. The framework was developed to address frequently-reported practical bottlenecks within conventional international BME training, including disconnect between classroom teaching and global-industry practice, insufficient cross-cultural-adaptation capacity among overseas students, and limited structured practical-teaching support. Guided by competency-oriented training goals, modular system integration, institutional support arrangements and evidence-based evaluation principles, the proposed architecture incorporates four inter-connected teaching modules, three core-competency development dimensions, and a hybrid formative-summative assessment mechanism. Pilot-phase observations suggest this framework may foster improvements in students' professional technical competence, cross-cultural collaborative skills, and transnational-relevant innovative literacy under favourable institutional-resource conditions.

Important limitations must be kept in mind. This quasi-experimental pilot lacks randomised participant assignment; findings are associative and derived from a limited two-site sample in a resource-rich region. The model is resource-dependent and cannot be assumed to deliver equivalent outcomes across all institutional settings. To advance understanding of its real-world utility, future work should expand multi-institutional pilot implementations across diverse resource contexts to test external validity. Curriculum optimisation will pursue finer-grained, country-specific adaptation to accommodate heterogeneous global healthcare-system and industrial-market demands. Digital transformation of cross-border practical-training platforms will also be pursued to mitigate geographical constraints and enrich accessible international teaching resources. In addition, strengthened institutional cooperation with global professional bodies may support future exploration of internationally-aligned certification pathways. Collectively, these efforts may support high-quality development for transnational BME

education, contribute to cultivating globally-oriented biomedical-engineering talent, and facilitate sustainable international technical and industrial cooperation within the biomedical-engineering domain.

7. Declarations

7.1 Ethics Approval and Consent to Participate

This study was approved by the Ethics Committee of the School of Biomedical Engineering, Guangzhou Medical University. Informed consent was obtained from all participants (international students, teachers, enterprise experts, and scientific research institution representatives) before the study. All participants were informed of the purpose, process, and potential risks of the study, and had the right to withdraw from the study at any time. The entirety of the research, including data collection and methods was carried out in accordance with relevant guidelines and regulations. This study was conducted in accordance with the WMA Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Participants.

7.2 Consent for Publication

Not Applicable.

7.3 Competing Interests

The authors declare that they have no competing interests.

7.4 Funding

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7.5 Authors' Contributions

Xiaoying Guan did the research design, interview script, the interviews, the analysis, and wrote the draft of the paper; Weisheng Guo contributed to the research design, interview script, analysis and edited the writing of the paper; Xingjie Liang contributed to the research design and edited the writing of the paper. All authors read and approved the last version of the manuscript.

7.6 Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to participant-privacy constraints and signed ethical informed-consent agreements; full public release of raw interview transcripts would compromise respondent anonymity. All questionnaire frameworks, evaluation rubrics, scale specifications, and the PRISMA flow diagram are provided in Supplementary Figures and Tables S1-S9 (supporting information), without any participant-level raw data or personally identifiable information. De-identified interview-related supporting materials (interview protocol, representative anonymised interview excerpts, thematic coding summaries) have been uploaded as peer-review-only supplementary files in the submission system for assessment by reviewers. Reasonable data access requests may be submitted to the corresponding author guanxiaoying@gzhmu.edu.cn (X. Guan). Requests will be evaluated against ethical and privacy requirements; partial de-identified aggregated data may be shared upon approval.

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