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REVIEW ARTICLE

Toward a conceptual framework for digital transformation in chemical engineering education: The role of MOOCs in fostering intercultural communicative competence

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ABSTRACT

The creation, delivery, and dissemination of chemical engineering knowledge in a globally interconnected setting are being redefined by the digital transformation of higher education. Massive Open Online Courses (MOOCs) have emerged as important venues for increasing access to engineering education while fostering interdisciplinary cooperation and cross-cultural learning. In order to investigate how MOOCs promote digital transformation and Intercultural Communicative Competence (ICC) in chemical engineering education, this study systematically reviews 24 peer-reviewed articles (2020-2025) using the PRISMA methodology. According to research, MOOCs foster educational innovation by incorporating flipped learning, simulation-based experimentation, and group projects that improve students' technical and intercultural competencies. In order to solve sustainability and process-design issues, they also enable interdisciplinary integration by linking chemical, computational, and environmental disciplines. However, enduring obstacles include unequal access to technology, a lack of established ICC evaluation tools, and poor cultural contextualisation limit wider impact. This review offers a conceptual framework for a Global Chemical Engineering Education Ecosystem based on constructivist, connectivist, and intercultural communication theories. MOOCs are positioned as socio-technical environments that connect digital, interdisciplinary, and intercultural learning processes. The study comes to the conclusion that pedagogical intentionality, institutional backing, and inclusive digital infrastructures that train internationally competent and morally conscious engineers are necessary for MOOCs to have their revolutionary potential.

Keywords: chemical engineering education; Massive Open Online Courses (MOOCs); digital transformation; interdisciplinary learning; intercultural communicative competence (icc); global engineering education

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1. Introduction

The combined forces of globalisation and digitalisation are changing the face of chemical engineering education[1]. Teachers must educate students with disciplinary skills as well as the capacity to work across disciplinary, linguistic, and cultural barriers as the engineering profession becomes more interconnected[2]. In this regard, the capacity to communicate successfully and responsibly with people from other cultural backgrounds is known as Intercultural Communicative Competence (ICC), and it has become a crucial graduation quality for engineers in the twenty-first century[3]. Chemical engineering provides a relevant field for investigating how intercultural and communicative abilities can be developed through creative instructional approaches because of its international corporate relationships and collaborative research culture[4].

Opportunities for scalable, adaptable, and interactive learning have increased concurrently with the digital transformation of higher education[5]. Massive Open Online Courses (MOOCs) are one of these technologies that have come to represent the democratisation of global education[6]. Through MOOCs, students from various locations can interact with interdisciplinary content outside of traditional institutional borders, access top-notch educational resources, and take part in global learning communities[7]. MOOCs are digital ecosystems that foster cross-cultural interactions where students work together, negotiate meaning, and consider other viewpoints in contexts of shared problem-solving[8]. This global reach has enormous potential to promote intercultural cooperation on sustainability, ethics, and technical innovation for engineering education, especially chemical engineering[9].

Research specifically evaluating the connection between MOOCs and ICC development is still scarce, despite the growing scholarly interest in MOOCs within engineering education[10]. Technological affordances, learning analytics, instructional efficiency, and learner performance indicators are the main focus of existing research, whereas intercultural outcomes are frequently viewed as auxiliary or implicit rather than as fundamental educational goals[11]. Additionally, when ICC is discussed, it usually takes place in language education or general STEM contexts, with little focus on how discipline-specific pedagogies in chemical engineering—like virtual laboratories, systems modelling, process simulation, and interdisciplinary design projects—mediate intercultural learning processes[12]. Because of this, there isn't a comprehensive, discipline-sensitive paradigm in the literature that describes how MOOC-based chemical engineering learning environments give rise to ICC.

Rethinking MOOCs as dynamic learning ecologies that facilitate intercultural communication and collaborative meaning-making is necessary to close this gap. This is consistent with new viewpoints in media ecology and digital pedagogy that highlight the ways in which online platforms mediate identity, cooperation, and communicative agency[13]. A social infrastructure for intercultural engagement is created by learners' interactions within MOOCs through forums, peer evaluations, and project-based partnerships[14]. These environments can foster empathy, flexibility, and global awareness—three essential components of ICC—when they are bolstered by inclusive design, reflective tasks, and culturally sensitive facilitation[15].

In light of this, a conceptual synthesis that positions MOOCs within chemical engineering education as socio-technical environments that can support intercultural communicative competence through digitally mediated, interdisciplinary learning practices is clearly needed. By undertaking a systematic literature review (SLR) that looks at how MOOCs support the development of intercultural communication skills in chemical engineering and related STEM fields, the current study adds to this expanding conversation. The SLR integrates insights from many educational contexts and methodological approaches by synthesising peer-reviewed empirical and conceptual studies produced between 2020 and 2025. The study aims to (a) map current research trends, (b) pinpoint the advantages and disadvantages of present MOOC-based ICC projects, and (c) offer a conceptual framework for comprehending MOOCs as scalable intercultural learning paths.

The review is guided by four research questions:

RQ1: How have MOOCs been applied in chemical engineering and related STEM fields to support digital transformation and global learning?

RQ2: In what ways do MOOCs facilitate the development of intercultural communicative competence (ICC) among learners?

RQ3: What pedagogical strategies, design features, and technological affordances characterize effective ICC-oriented MOOCs?

RQ4: What gaps and future directions emerge from current research on MOOCs and intercultural competence development?

This study attempts to improve instructional practice and theoretical knowledge by tackling these issues. Theoretically, it conceptualises MOOCs as settings for mediated cultural learning by combining ideas from engineering pedagogy, intercultural communication, and digital learning theory. For educators, curriculum designers, and legislators looking to match chemical engineering education with the objectives of international cooperation and global sustainability, it offers practical implications.

2. Theoretical perspective

IIn order to explain how particular MOOC design elements translate into observable learning processes and outcomes in chemical engineering education, this review's theoretical framework blends several complementary perspectives. Specifically, the analysis is guided by three intersecting strands: (1) interdisciplinary learning and knowledge-integration theories, which explain how chemical engineering knowledge is co-constructed across disciplinary boundaries through collaborative digital tasks; (2) constructivist and connectivist learning theories, which inform the design of simulation-based, project-oriented, and networked MOOC learning activities; and (3) intercultural communicative competence (ICC) frameworks, which conceptualise reflective dialogue, intercultural teamwork, and communicative adaptability as important learning outcomes in culturally diverse online environments.

When combined, these frameworks offer a clear theory-design-outcome lens for comprehending how digital transformation is changing the socio-communicative and cognitive aspects of chemical engineering education in the twenty-first century.

2.1. Constructivist and connectivist perspectives on digital learning

According to constructivist learning theory, students actively create knowledge through interaction, introspection, and social negotiation as opposed to passively receiving information[16,17]. This theoretical position directly supports the use of simulation-based learning, virtual laboratories, and project-based design assignments that are frequently incorporated into MOOCs in chemical engineering education, where students are required to apply theoretical concepts to actual industrial and environmental circumstances. MOOC-based constructivist designs, like process simulation exercises and virtual lab experimentation, improve conceptual understanding, problem-solving ability, and self-directed learning, according to recent studies[18,19].

MOOCs use peer cooperation, interactivity, and worldwide access to expand this constructivist foundation. In order to reinforce active knowledge production, learners engage in peer-reviewed design projects, group problem-solving exercises, and virtual laboratories that call for explanation, introspection, and iterative feedback[20].

Connectivism, which builds on constructivism, views learning as the ability to create, negotiate, and utilise networks of people, resources, and digital systems[21]. From the standpoint of MOOC design, connectivism outlines how learners can share process knowledge, compare engineering methods across settings, and co-create solutions to challenging challenges through discussion forums, global peer engagement, and distributed cooperation[22]. This is demonstrated in chemical engineering MOOCs where students from various academic and cultural backgrounds work together to investigate subjects like sustainability modelling, process optimisation, and catalysis[23]. According to Zhang et al.[24], learners' capacity to select resources, incorporate cross-contextual insights, and engage in distributed problem-solving networks empirically reflects connectivist learning outcomes.

When combined, the constructivist–connectivist framework positions MOOCs as ecosystems of distributed expertise rather than static content repositories by connecting MOOC design elements (such as simulations, peer networks, and collaborative platforms) to learning outcomes like epistemic agency, interdisciplinary reasoning, and intercultural engagement.

2.2. Interdisciplinary learning and knowledge integration

The cognitive foundation of modern chemical engineering education is interdisciplinary learning, where creativity depends on combining information from environmental engineering, physics, data science, and chemistry. Boundary-crossing and knowledge-integration theoriesdescribe how students reconcile disciplinary perspectives, languages, and problem-framing techniques to gain a better understanding[25]. These ideas are used to design practices in MOOCs, such as cross-domain project assignments, systems-based modelling activities, and sustainability-focused case studies, which call for students to combine many types of expertise.

According to recent research, multidisciplinary MOOC designs foster design-oriented reasoning, cognitive flexibility, and systems thinking, especially in contexts related to sustainability and process engineering[26,27]. In order to develop epistemic fluency through multidisciplinary communication and negotiation, courses like Sustainable Chemical Process Design and Circular Economy Engineering frequently require students to co-create solutions with peers from a variety of academic and professional backgrounds[28]. Because students must express, translate, and defend disciplinary viewpoints across cultural and technical divides, this interdisciplinary synthesis also functions as a communication process.

Therefore, interdisciplinary learning in MOOCs serves as a cognitive and communicative mechanism that directly supports the development of intercultural adaptability in global engineering practice and strengthens technological integration[29].

2.3. Intercultural communicative competence (ICC)

The socio-communicative basis for international chemical engineering education is provided by Intercultural Communicative Competence (ICC). Byram and Deardorff[30,31] claim that ICC includes critical cultural awareness, cultural knowledge, attitudes of openness, and abilities of interpretation and engagement. ICC is viewed in this review as a result of certain MOOC interactional and reflective design elements rather than as an abstract property.

Peer review, intercultural collaboration, and technology-mediated communication all contribute to the development of ICC in MOOCs[32]. Learners are exposed to a variety of professional practices and communication norms through discussion boards, peer evaluation systems, and cooperative design projects[33]. By encouraging metacognitive awareness, motivational openness, and adaptive communicative behaviour, these interactional processes operationalise ICC theory and improve cultural intelligence[34]. Research demonstrates that international online cooperation in engineering MOOCs fosters intercultural sensitivity, empathy, and ambiguity tolerance—all of which are crucial markers of ICC development[35].

These skills are particularly important for chemical engineering students in situations involving ethical decision-making, safety management, and international research. As a result, MOOCs serve as socio-technical spaces for developing global professionalism and ethical engineering identity in addition to being technical learning platforms.

This study uses an integrative paradigm that explicitly connects learning theories to MOOC design elements and measurable learning results by synthesising various viewpoints (**Figure 1**). Interdisciplinary learning theory explains how cross-domain collaboration supports systems thinking; constructivist and connectivist theories explain how simulations, virtual labs, and peer networks enable knowledge construction; and ICC theory frames reflective dialogue and intercultural teamwork as key outcomes. The main idea that MOOCs may methodically develop chemical engineers who are ethically global, communicatively flexible, and cognitively integrative is supported by these theories taken together.

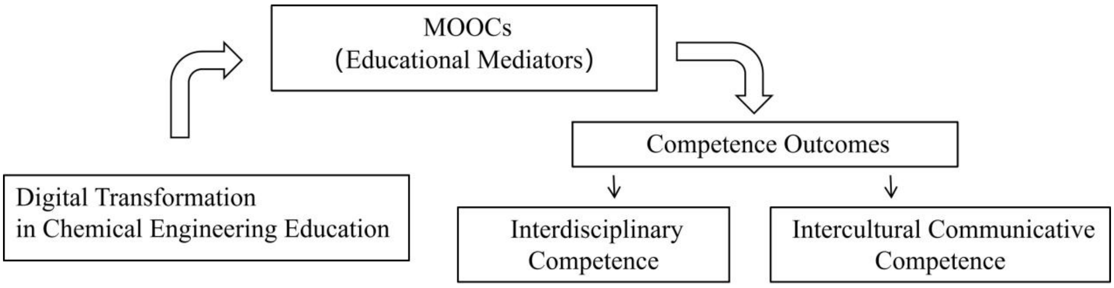

Figure 1. Conceptual framework base on the literature.

3. Materials and methods

In order to review and assess the body of empirical and conceptual research on the function of Massive Open Online Courses (MOOCs) in promoting interdisciplinary and intercultural communicative competence (ICC) within chemical engineering education, this study uses a Systematic Literature Review (SLR) approach. The review guarantees methodological transparency, replicability, and thorough coverage of pertinent literature by adhering to the PRISMA 2020 requirements[36]. Planning and procedure development, systematic literature search, screening and eligibility evaluation, and data extraction, synthesis, and analysis were the four main steps of the workflow.

3.1. Inclusion and exclusion criteria

In order to guarantee the quality and applicability of research materials, To guarantee the selection of literature closely related to the study's subject, inclusion and exclusion criteria were developed (**Table 1**).

Table 1. Inclusion and exclusion criteria.

Criterion	Inclusion Criteria	Exclusion Criteria
Document Type	Articles published in academic journals, full text available.	Full text unavailable.
Publication Period	Published between 2020 to 2025	Studies published before 2020.
Research Focus	Research topic relates to addressed MOOCs, digital learning platforms, or online education models applied to chemical engineering education or related STEM disciplines (e.g., materials, environmental, or process engineering)	Publications unrelated to the topic; content focused solely on non-chemical engineering or non-STEM or purely linguistic MOOCs unrelated to engineering education.
Research Methodology	The review included empirical primary studies utilizing quantitative, qualitative, or mixed-methods research designs.	Studies employing research approaches outside of quantitative, qualitative, or mixed-methods designs.
Peer Review	Peer-reviewed studies.	Non-peer-reviewed studies.
Publication Language	Academic articles written in English.	Non-English content.
Research Context	Content relates to examined or discussed elements related to interdisciplinary learning, collaborative problem-solving, communication skills, or intercultural competence development.	Content discussed MOOCs in general terms without educational or competence development outcomes.

3.2. Search strategy

A systematic search string was designed to capture the intersection of MOOCs, chemical to find the junction of MOOCs, chemical engineering education, and intercultural competency, a methodical search string was created. The key ideas were combined using boolean operators (AND, OR) (**Table 2**).

Table 2. Full search strings used in five databases.

Databases	Full Search Strings	Count
Scopus	ALL(("MOOC" OR "Massive Open Online Course*" OR "online learning" OR "digital education" OR "e-learning") AND ("chemical engineering" OR "process engineering" OR "materials engineering" OR "environmental engineering" OR "STEM education") AND ("intercultural competence" OR "cross-cultural communication" OR "global competence" OR "intercultural communicative competence"))	**3**
WoS		**67**
SpringerLink		**433**
Taylor & Francis		**25**
Google Scholar		**16**
	Total	**544**

The initial search yielded 544 records across all databases.

3.3. Screening and quality assessment

To guarantee methodological rigour, transparency, and reproducibility, the screening process followed the four-stage PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol.

Identification is the first step. For methodical de-duplication, all recovered records were imported into the Zotero reference management program. After 110 duplicate entries were eliminated, 434 distinct research were left for initial assessment.

Stage 2: Abstract and Title Screening. To ascertain their applicability to MOOCs, chemical engineering education, and competency development, two impartial reviewers looked at the titles and abstracts. Excluded were studies that had nothing to do with intercultural competency, engineering pedagogy, or digital learning. 112 potentially eligible studies for additional assessment were produced by this method.

Step 3: Evaluate the entire text. The 112 studies' entire texts were obtained and evaluated in accordance with the predetermined inclusion and exclusion criteria. 88 papers were eliminated during this phase because they lacked empirical support, conceptual significance, or methodological detail. As a result, 24 studies were kept for qualitative synthesis since they satisfied every requirement.

Data extraction and coding are the fourth stage. A structured coding template was used to methodically extract key information from each included study, including publication details, methodological approach, target population, digital tools used, and outcomes pertaining to interdisciplinary learning and intercultural communicative competence (ICC). Both reviewers independently cross-checked to ensure consistency, and any disagreements were settled through consensus talks.

The PRISMA flow diagram (**Figure 2**) depicts the entire selection and screening process, while **Table 2** summarises the specific outcomes of the database search.

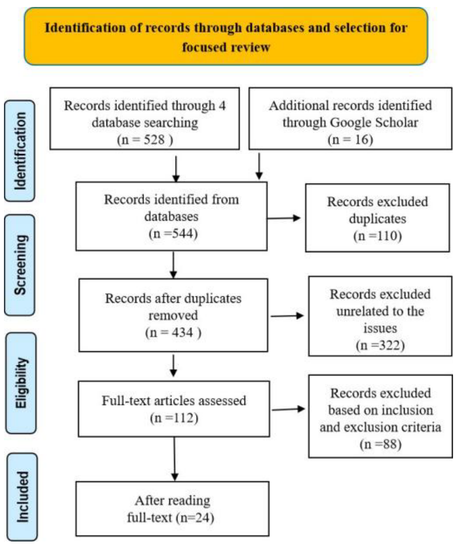

Figure 2. PRISMA flow diagram of the study.

3.4. Analytical framework and synthesis method

Since the majority of MOOC research in chemical engineering education is still qualitative and conceptual, the primary analytical method employed in this review was thematic synthesis[37]. The synthesis method involved three iterative phases. Text passages that captured relevant concepts were given descriptive codes pertaining to intercultural interaction mechanisms, multidisciplinary practices, and digital learning design during the first coding step. During the category grouping phase, these codes were grouped into higher-order thematic categories that represented recurring themes in the research, paying particular attention to the ways in which social interactions, technology affordances, and learning activities support intercultural communicative competence (ICC).

These thematic categories were combined into a single conceptual framework (**Figure 3**) during the final synthesis stage, which shows how particular MOOC elements—like curriculum access, virtual laboratories, collaborative platforms, and interdisciplinary project design—serve as socio-technical mechanisms assisting ICC development in chemical engineering education. Curriculum access, for instance, makes it possible for students from different cultural backgrounds to participate, fostering intercultural exposure; virtual labs and simulation-based tasks encourage cooperative problem-solving and communicative negotiation; and interdisciplinary group projects encourage introspective discussion, perspective-taking, and intercultural teamwork in globally dispersed learning environments. By explicitly connecting digital and pedagogical structures to ICC-related learning processes and outcomes, the framework transcends a descriptive model.

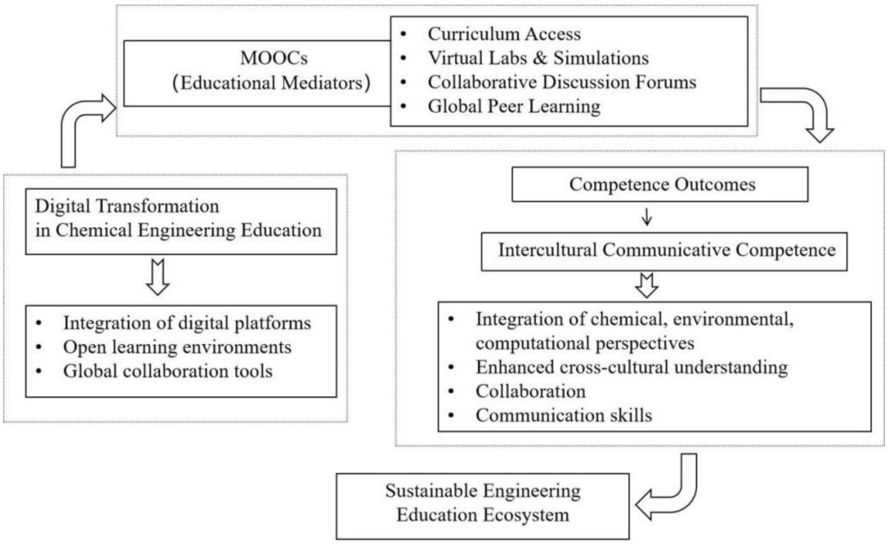

Figure 3. Conceptual framework of this study.

Important features were gathered and coded using Microsoft Excel, including publication year, geographic breadth, study methods, and mediating/moderating variables. To guarantee coherence between the empirical themes and the framework dimensions, these extracted variables were then mapped onto the conceptual framework's components. In order to provide comprehensive coverage across engineering, educational, and transdisciplinary domains, several academic databases were systematically searched between June and July 2025. This strengthened the analytical congruence between the suggested framework and the literature synthesis.

4. Results

4.1. Overview of selected studies

24 peer-reviewed articles with a wide range of geographical and methodological diversity that were published between 2020 and 2025 were found in the systematic review (**Table 3**). Research from Asia (n = 6),

Europe (n = 4), North America (n = 6), South America (n = 1), and multi-regional partnerships (n = 7) were all included in the sample. In terms of methodology, research used mixed-method (n = 17), quantitative (n = 2), and qualitative (n = 7) techniques, indicating a growing trend towards triangulated, design-based, and context-sensitive inquiry.

The theme analysis was structured to guarantee a clear connection between the review objectives and the reported findings, guided by RQ1–RQ4. The literature revealed five main theme clusters: (1) the role of intercultural communicative competence (ICC) in preparing engineering graduates who are globally competent (addressing RQ2); (2) digital pedagogical approaches like MOOCs, COIL, and AI-supported learning environments that enable global and scalable engineering education (addressing RQ1); (3) curriculum design and instructional integration strategies that link ICC with sustainability-oriented, interdisciplinary, and active learning practices (addressing RQ3); (4) empirical outcomes and learner perceptions regarding ICC development in digital learning contexts, including institutional constraints, cultural barriers, and equity issues, which highlight research gaps and future directions (addressing RQ4).

By showing how each cluster helps to address the review questions, this clear mapping of thematic clusters to the research questions improves the traceability between the study's analytical framework and its conclusions. When taken as a whole, these themes show how chemical engineering education is changing from traditional, discipline-bound instruction to digitally mediated, globally networked, interculturally responsive learning ecosystems that combine technical know-how with communicative and ethical skills.

Table 3. List of studies review.

Authors	Year	Title	Country of study	Research design	Key findings about mediating variable
Alekseeva et al.[38]	2020	"Digital Transformation of Additional Professional Education: Features of the LK-14 Educational Platform"	Russia, Europe	Mixed methods	Personalized teacher development tailored learning paths
Antón-Sancho et al.[39]	2023	"Digital Generation Influence on the Post-COVID-19 Use of Digital Technologies in Engineering Education: A Statistical Study"	Multination	Quantitative	Information and Communication Technologies (ICT) use in teaching activities such as interaction, communication, content sharing, and evaluation
Børsen et al.[40]	2021	"Initiatives, experiences and best practices for teaching social and ecological responsibility in ethics education for science and engineering students"	Multination	Qualitative	Active learning methods Interdisciplinary and intercultural collaboration Institutional support
Chen & Pfluger[41]	2024	"Work-In-Progress: Integrating Sustainability Across the Chemical Engineering Curriculum"	USA, North America	Mixed methods	PISA and PSRDM frameworks
Diahyleva et al.[42]	2025	"Exploring the effectiveness of online learning tools and technologies while teaching Maritime English to future ship engineers"	Ukraine, Europe	Mixed methods	Course access virtual labs and simulations, collaborative discussion forums global peer learning
Franco et al.[43]	2023	"A competency-based chemical engineering curriculum at the University of Campinas in Brazil"	Brazil, South America	Mixed methods	General socio-emotional) and specific (technical) competencies; Active learning methodologies Assessment strategies
Janenoppakarn & Rajprasit[44]	2025	"Development of a New 'Engineering English for Intercultural Communication'Online Course to Prepare New Engineers for Working in Intercultural Workplace Settings"	Thailand, Asia	Mixed methods	Stakeholder needs language skills

Authors	Year	Title	Country of study	Research design	Key findings about mediating variable
Johnson et al.[45]	2020	"Effect of a place-based learning community on belonging, persistence, and equity gaps for first-year STEM students"	USA, North America	Quantitative	Local Indigenous communities environmental issues
Karim et al.[46]	2023	"Language ideology, development of English proficiency, and performance in professional communication: voices of STEM+ business graduates of English medium university"	Bangladesh, Asia	Qualitative	EMI
Kulturel-Konak[47]	2020	"Person-centered analysis of factors related to STEM students' global awareness"	USA, North America	Mixed methods	International experiences High academic engagement
Ndubuisi et al.[48]	2022	"Developing global competence in global virtual team projects: a qualitative exploration of engineering students' experiences"	Canada, North America	Qualitative	use of digital tools such as MS Teams, One Drive, Padlet, and Zoom for virtual collaboration
Nykyporets & Kriutchenko [49]	2025	"Empowering future engineers with crosscultural communication: Erasmus+, Fulbright, and English language classroom activities"	Multination	Mixed methods	Virtual labs and simulations (e.g., cross-cultural virtual team projects) Collaborative discussion forums (e.g., international team collaboration) Global peer learning (e.g., Erasmus+ and Fulbright programs)
Pinnell et al.[50]	2024	"Enhancing the Cultural Competence of K-12 STEM Teachers through a Global Research Experience"	Multination	Mixed methods	Cultural norms personal growth
Starr et al.[51]	2022	"Intercultural competence outcomes of a STEM living–learning community"	USA, North America	Mixed methods	Living-learning community (TLC)
Udeozor et al.[52]	2021	"Perceptions of the use of virtual reality games for chemical engineering education and professional training"	UK, Europe	Mixed methods	Virtual labs and simulations Collaborative discussion forums Global peer learning
Udugama et al.[1]	2023	"Digital tools in chemical engineering education: The needs and the desires"	UK, Europe	Mixed methods	Course access Virtual labs and simulations Collaborative discussion forums Global peer learning
Vaquerizo et al.[53]	2025	"Collaborative Online International Learning (COIL) in chemical engineering: Preparing students for multicultural and international work environments"	Multination	Mixed methods	Virtual labs and simulations collaborative discussion forums global peer learning
Wang [54]	2022	"PLS-SEM Model of Integrated Stem Education Concept and Network Teaching Model of Architectural Engineering Course"	China, Asia	Mixed methods	Virtual labs and simulations, collaborative discussion forums global peer learning
Yap & Tan [55]	2022	"Lifelong learning competencies among chemical engineering students at Monash University Malaysia during the COVID-19 pandemic"	Malaysia, Asia	Mixed methods	Online learning virtual tools digital competencies

Authors	Year	Title	Country of study	Research design	Key findings about mediating variable
Yoon et al.[56]	2025	"Cultural STEM Night: An Online Collaboration for Culturally Responsive Teaching Between American and Korean Teacher Candidates"	Multination	Mixed methods	Virtual cultural exchanges Collaborative STEM lesson design Synchronous and asynchronous online collaboration Use of digital tools such as Padlet, Zoom, Microsoft Teams, and Jamboard
Zak et al.[57]	2021	"Virtual versus in-person presentation as a project deliverable differentially impacts student engaged-learning outcomes in a chemical engineering core course"	USA, North America	Qualitative	Demands of industry academia with global skills change to the pedagogical environment
Zhang & Wang[58]	2025	"Integrating STEM Education with Bilingual Instruction: An Innovative Teaching Design for Introduction to Civil Engineering in Sino-foreign Cooperative Education"	China, Asia	Mixed methods	Interdisciplinary learning Student engagement
Zhang et al.[59]	2025	"Enhancing intercultural competence in technical higher education through AI-driven frameworks"	Malaysia, Asia	Mixed methods	AI-driven frameworks virtual simulations data analysis techniques
Zmire & Chen[60]	2024	"AI's Role in Enhancing Cross Cultural Competence and Leadership through Online Education Programs"	Multination	Qualitative	Virtual labs and simulations Collaborative discussion forums Global peer learning Personalized learning experiences

Table 3. (*Continued*)

4.2. Importance of ICC for global chemical engineering graduates

For graduates of chemical engineering with a worldwide perspective, intercultural communication competence (ICC) has become a crucial employment criteria. ICC improves graduates' preparedness for transnational teamwork, global project management, and intercultural collaboration, according to evidence from numerous research.

According to studies on Collaborative Online International Learning (COIL), for example, students reported improved critical thinking, more confidence in technical knowledge, and increased readiness for multicultural work situations[53]. Stronger problem-solving dynamics and intercultural involvement were demonstrated by teams with diversified institutional representation, especially those that kept single-institution dominance to less than 50%. Intercultural competency also promotes trust, flexibility, and communication fluency in multinational engineering projects, according to research on global virtual teams[48].

Together, these results support the idea that ICC is a disciplinary requirement rather than a supplementary soft skill, essential to modern chemical engineering practice and the ability to handle global sustainability and process issues among networks of professionals from different cultural backgrounds.

4.3. Digital pedagogical approaches for ICC cultivation

4.3.1. MOOCs and collaborative online international learning (COIL)

Through digitally mediated collaboration, MOOCs and COIL platforms act as powerful catalysts for the development of ICC. Cross-institutional teamwork and simulation exercises were incorporated into COIL-based chemical engineering courses, which produced quantifiable improvements in students' critical thinking, problem-solving, and cross-cultural communication skills[53]. Structured timetables, technology parity, shared communication platforms, and orientation sessions to match expectations were all necessary for pedagogical success.

In addition, Global Competence Modules (GCMs) based on Kolb's experiential learning theory, the Community of Inquiry (CoI) framework, and social constructivism encouraged introspective, cross-cultural cooperation[48]. Engagement, contextual comprehension, and learning continuity were further enhanced by hybrid formats, which combined synchronous COIL sessions with asynchronous MOOCs[47,58].

4.3.2. AI and adaptive learning technologies in ICC development

New research shows how AI-powered adaptive learning methods can be used to customise ICC development. For instance, Zhang et al. (2025) found high positive correlations (r = 0.714–0.972) between instructional activities and ICC characteristics (attitude, knowledge, skills, and consciousness) using Apriori algorithms and fuzzy logic models[59]. MOOC platforms are able to customise content and feedback to learners' linguistic and cultural backgrounds thanks to this data-driven personalisation. Despite these developments, there is still little empirical support for AI-supported ICC pedagogies in engineering settings[45,55].

4.3.3. Immersive and interactive digital tools

Technologies such as virtual, augmented, and mixed reality (VR/AR/MR) have been used to replicate cross-cultural cooperation and contextualise learning. According to studies, VR-based courses improved conceptual knowledge and participation in sustainability, safety, and process design[1]. Although students' worries about accessibility and classroom integration remained, interactive VR games also promoted intercultural cooperation and spatial problem-solving[52]. All things considered, immersive media support experience learning that is in line with multidisciplinary and intercultural goals.

4.4. Curriculum design and integration strategies

4.4.1. Competency-based and sustainable curriculum models

ICC and sustainability are incorporated into competency-based frameworks for chemical engineering education in recent curriculum models. In order to integrate intercultural reflection into project-based courses, Chen and Pfluger established Sustainability-in-Action Elements (SAEs) that are in line with the Engineering for One Planet (EOP) and PISA Global Competence frameworks[41]. In order to promote the pedagogical change towards active, globally relevant learning, Franco et al. also placed a strong emphasis on faculty training and assessment alignment[43].

While integrated EMI (English-Medium Instruction) modules have improved linguistic and cultural preparedness[49], AI-based analytics have made competence profiling and customised curricular pathways possible[59]. Linking ethics, sustainability, and cultural aspects in engineering education has also been successfully accomplished through bottom-up curriculum design, which is backed by institutional policy and resource allocation[40].

4.4.2. Culturally responsive and inclusive course design

Multicultural cooperation and technology accessibility are key components of inclusive digital design. By supporting a variety of devices and operating systems, platforms like LK-14 enable equal participation[38]. Mutual participation is improved by international project architecture that guarantee a diverse team makeup, common digital tools, and cross-institutional mentorship[53]. Additionally, learners can co-create and update information using collaborative tools like Wiki-based project systems, which fosters intercultural communication and transparency[42].

4.5. Empirical evidence and outcomes

4.5.1. Student competence and perceptions

Students' enjoyment with digitally mediated intercultural interactions was consistently high across all investigations. 97% of participants in GCM-based programs said they were "satisfied" or "very satisfied," noting improvements in intercultural empathy, project collaboration, and global awareness[48]. Additionally, quantitative analysis showed statistically significant gains in English proficiency and ICC dimensions[59]. Furthermore, although differences in perceived and actual ICC skill continued, AI-enabled translation and VR-based immersion improved intercultural curiosity and openness[60].

4.5.2. Faculty development and institutional readiness

Faculty preparedness and institutional capacity-building are still relatively understudied aspects of ICC-oriented MOOC deployment, despite these pedagogical developments. Studies already conducted show that although most instructors recognise the importance of intercultural and global learning objectives, many report inadequate training in digital pedagogy, little experience with intercultural facilitation, and uncertainty about matching ICC outcomes with technical course requirements[46,51].

Numerous studies highlight the need for pedagogical expertise in managing culturally diverse online interactions, creating reflective learning tasks, and evaluating intercultural effects in addition to technological proficiency for effective ICC-focused MOOC delivery. However, there are still few organised professional development programs that combine intercultural training with digital teaching abilities, and institutional support systems like workload recognition, help with instructional design, and incentives at the policy level are frequently disjointed or nonexistent.

Therefore, the lack of integrated faculty development strategies and unequal resource distribution limit the scalability and sustainability of ICC-oriented digital curriculum. The lack of empirical evidence is now clearly recognised as a crucial area for further study, especially when it comes to long-term institutional transformation and faculty learning trajectories.

4.6. Challenges and limitations in implementation

Key issues include uneven team composition, poor digital access, and the unavailability of established ICC assessment tools. Undefined competency frameworks impede standardised measurement[59], and unequal representation in international teams lowers the quality of collaboration[53]. There are still gaps in language and cultural integration, particularly in EMI settings[49]. To overcome these constraints, intercultural frameworks must be incorporated into MOOC governance structures, fair technology access must be guaranteed, and ICC components must be quantified using mixed-method evaluation models like fuzzy comprehensive assessment.

4.7. Summary of findings

Overall, the comprehensive data shows that by combining multidisciplinary information exchange with the development of intercultural communication, Massive Open Online Courses (MOOCs) and associated digital learning ecosystems have revolutionised chemical engineering education. Anchored in constructivist and connectivist principles, MOOCs extend learning beyond physical classrooms, fostering global collaboration and epistemic flexibility.

However, the digital revolution is still unequal due to fragmented institutional initiatives, lack of cultural contextualisation, and differences in infrastructure. The results highlight the necessity of hybrid frameworks that combine MOOCs with localised mentoring, intercultural facilitation, and institutional policy reform in order to have sustainable global influence. This alignment will guarantee that the digital transformation of chemical engineering education promotes social inclusion, cultural reciprocity, and intercultural communicative competency among future engineers in addition to technology innovation and pedagogical modernisation.

5. Discussion

In order to improve intercultural communicative competence (ICC) in chemical engineering education, this study looked at MOOCs as theory-informed socio-technical environments. Based on clear connections between constructivist, connectivist, and intercultural communication theories, interdisciplinary learning design, and ICC outcomes, the results show that MOOCs are a pedagogical and cultural shift in addition to a technological advancement. The debate, which is guided by RQs 1-4, demonstrates how particular MOOC design elements—such as virtual labs, international peer interaction, and multidisciplinary projects—operationalize learning theories and yield quantifiable intercultural, cognitive, and communicative effects. Instead of being empirically validated through primary data gathering, the framework is evidence-based and theory-informed, having been produced from a comprehensive synthesis of 24 peer-reviewed publications.

5.1. Conceptual framework for ICC enhancement through MOOCs

The suggested framework, which builds on the theoretical synthesis, views MOOCs as integrative digital ecosystems where learning theories are implemented through tangible pedagogical designs and measurable results. The three interconnected dimensions of the framework—digital transformation, interdisciplinary integration, and ICC enhancement—are each directly influenced by the research questions and backed by empirical results from the studies that were examined. Each component was derived inductively from recurrent patterns in the literature (for example, the ICC component was influenced by studies reporting intercultural learning effects, while the digital and multidisciplinary dimensions were informed by simulation-based MOOCs and COIL efforts). For each dimension, measurable indicators are proposed to support empirical evaluation and practical implementation.

5.1.1. Digital transformation in learning environments

Constructivist concepts of active and experiential learning are reflected in MOOCs, which serve as scalable digital infrastructures that facilitate data-driven design projects, virtual laboratories, and simulation-based experiments. By illustrating how digital tools facilitate globalised chemical engineering education, these affordances directly address RQ1. The utilisation of process simulation, virtual labs, and project-based activities, where students actively apply mass transfer, thermodynamics, and reaction engineering concepts to real-world, open-ended issues, is supported by constructivist learning theory. From a theoretical standpoint, connectivism describes how learners participate in distributed knowledge networks, while constructivism explains how these tools promote deep conceptual comprehension. Participation in virtual labs or simulations, performance in digital problem-solving exercises, and platform engagement metrics (e.g., logins, activity completion rates) are examples of potentially quantifiable indications.

5.1.2. Interdisciplinary integration of knowledge domains

By converting interdisciplinary learning theory into cross-domain project design and cooperative problem-solving challenges, MOOCs function as convergence spaces for the chemical, computer, and environmental sciences. This dimension supports RQ3 and demonstrates that multidisciplinary synthesis is not accidental but is purposefully incorporated into successful MOOC designs. Through communicative interaction across disciplinary and cultural borders, learners acquire epistemic fluency and systems thinking. In line with modern chemical engineering pedagogy that emphasises digital modelling, data analytics, and collaborative design, connectivist theory is operationalised through networked learning structures like peer-supported troubleshooting of simulation models, collaborative interpretation of process data, and distributed problem-solving. Interdisciplinary project scores, the variety of fields represented in cooperation networks, and learner outputs that demonstrate integrative reasoning are examples of quantifiable indicators.

5.1.3. Intercultural communicative competence development

Through organised peer interaction, introspective discussion, and global collaboration, MOOCs facilitate the development of ICC and operationalise ICC theory in virtual settings. This directly addresses RQ2 by showing how MOOC design elements perform interaction, reflection, and viewpoint transformation—all of which are essential components of Deardorff's model[31]. Thus, consistent involvement in globally networked learning communities leads to the development of intercultural competence. Through internationally dispersed lab discussions, cross-cultural project teams, and reflective communication exercises, intercultural communication theory is integrated. Students negotiate design choices, articulate technical reasoning, and take cultural safety, sustainability, and ethical considerations into account. The quantity and calibre of cross-cultural interactions, reflective journal analyses, peer evaluations of cross-cultural cooperation, and verified ICC survey data modified for online learning environments are some suggested quantifiable markers.

The Global Chemical Engineering Education Ecosystem, which integrates recognised gaps and future directions to address RQ4, is located at the intersection of these dimensions. The "Networked Engineer," a professional with technological know-how, multidisciplinary reasoning, and intercultural communication flexibility, is the result of this ecosystem. By connecting each theoretical dimension with operational indicators, the framework supports future hypothesis testing and design-based research in chemical engineering education and offers a framework for empirical validation and practical application.

A coherent paradigm for future course design, policy development, and institutional strategies aimed at advancing global engineering competence through MOOCs is provided by the framework, which integrates established pedagogical and intercultural theories and offers an explicit structure that connects empirical findings to each research question (**Figure 4**).

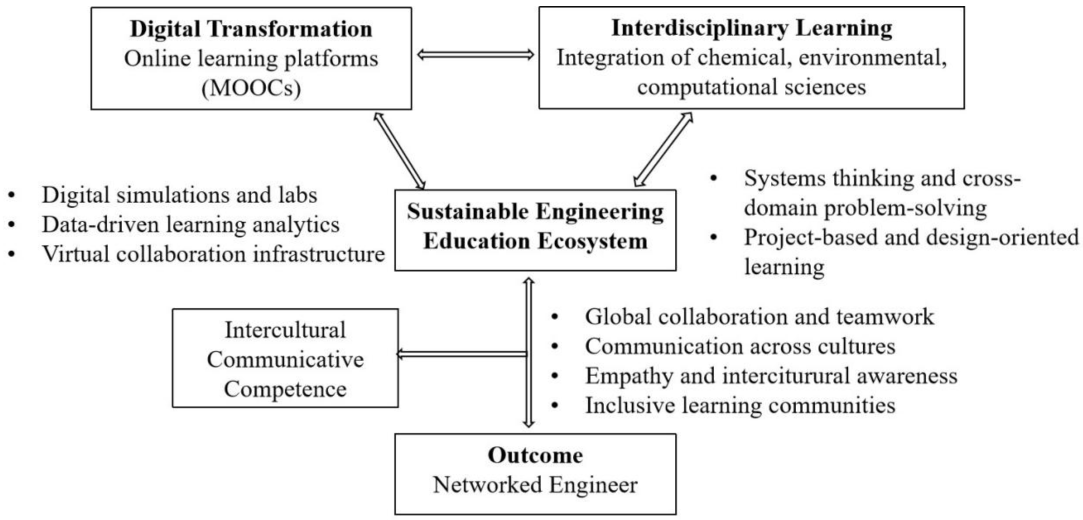

Figure 4. Framework for Global Chemical Engineering Education through MOOCs.

5.2. Limitations

A number of limitations should be noted notwithstanding the conceptual and integrative insights provided by this analysis.

First, because it is a literature-based synthesis, the methodological quality and representativeness of earlier research determine the study's scope and robustness. The design and setting of many research on MOOCs in engineering education are still inconsistent, and they frequently concentrate on broad STEM or language-learning MOOCs rather than chemical engineering-specific platforms.

Second, potential biases in the chosen literature, such as the predominance of English-language publications, the concentration of studies in high-income situations, and unequal geographical representation, limit the framework's application. This restricts the findings' applicability to places in the Global South that have very diverse digital infrastructure, educational methods, and linguistic ecologies.

Third, the majority of current research relies on self-report measures or short-term evaluations that are unable to capture the longitudinal or transformative nature of intercultural learning within engineering practice because intercultural communicative competence (ICC) encompasses attitudinal, behavioural, and interactional dimensions.

Lastly, although integrating digital, interdisciplinary, and intercultural aspects of learning, the suggested framework has not yet been empirically validated through design-based or mixed-method research inside MOOCs that are relevant to chemical engineering.

5.3. Implications

For many stakeholders in international chemical engineering education, the reviews has a number of consequences.

MOOCs should be rethought by educators and instructional designers as dynamic, reflective ecosystems that include international communication, interdisciplinary interaction, and technical simulation. Incorporating reflective learning activities, like global case studies, cross-national design challenges, and peer-dialogue journals, can foster both technical proficiency and deeper ICC development.

Comprehensive and adaptable design concepts are essential for developers and course platforms. Collaborative data laboratories, culturally sensitive feedback systems, and AI-assisted translation can all work together to improve student engagement across disciplinary and linguistic barriers and promote equitable participation. In order to facilitate theory, experimentation, and cross-cultural collaboration, MOOCs for chemical engineers should also make use of virtual labs and simulation-based assignments.

MOOCs offer a way for chemical engineering courses to be internationalised without the limitations of physical mobility programs for educational institutions and policymakers. In order to promote international cooperation and digital literacy in line with sustainable and ethical engineering practice, universities and professional associations could include global MOOCs as credit-bearing or micro-credential components inside engineering curricula.

5.4. Future research directions

To fill in the shortcomings found in this synthesis, future research on MOOCs and intercultural communication competency (ICC) in chemical engineering education should use a comprehensive, context-sensitive approach. There are four primary directions suggested:

(1)Mixed-method and longitudinal research using specific ICC evaluation instruments: Future studies should monitor how students' ICC changes over time in MOOCs for chemical engineering. Reflective interviews, learning analytics, behavioural analytics, discourse analysis of MOOC interactions, and validated ICC measurement tools modified for digital settings can all be combined to offer complex insights into how peer interaction, problem-solving, and digital collaboration promote intercultural development[62].

(2)Comparative cross-cultural research: Cross-regional studies are necessary to examine how institutional, linguistic, and cultural differences affect learning outcomes and engagement patterns. How students comprehend, negotiate, and apply engineering concepts across cultural boundaries can be clarified by looking at regional educational traditions and communication norms[63].

(3)Design-based and experimental approaches: The effects of pedagogical interventions, such as AI-mediated peer mentoring, immersive VR labs, or multilingual collaboration modules, on interdisciplinary learning and ICC development can be assessed through design-based research (DBR) and quasi-experimental studies that include validated digital ICC assessment tools and structured pre/post-intervention measures[64]. These methods facilitate the development of culturally aware, scalable courses.

(4)Institutional and policy-level analyses: Studies should examine how MOOC consortia, institutions, and accreditation bodies incorporate intercultural and digital learning goals. International partnerships, governance models, and legal frameworks that support inclusive, sustainable global learning ecosystems are among the focus areas[65].

These research paths can be used to further validate and operationalise the Global Chemical Engineering Education Ecosystem that is suggested here. Future research can support MOOCs as transformative infrastructures for developing globally competent, ethically aware, and networked chemical engineers by including digital innovation, interdisciplinary collaboration, and intercultural engagement.

6. Conclusion

Through the synergistic processes of digital transformation, multidisciplinary integration, and intercultural communicative competency (ICC) development, this review extends our knowledge of how Massive Open Online Courses (MOOCs) are changing chemical engineering education. The analysis, which synthesises findings from 24 studies published between 2020 and 2025, shows that MOOCs have developed from static warehouses of educational content into dynamic digital environments that foster intercultural participation, global collaboration, and technological innovation.

These settings foster cognitive flexibility, systems thinking, and ethical awareness—competencies essential to chemical engineers in the context of Industry 4.0 and sustainable development—by connecting theory to practice through simulation-based experimentation, data analytics, and project-oriented learning. MOOCs foster multidisciplinary synthesis and problem-solving skills necessary for tackling challenging engineering problems including decarbonisation, circular economy design, and process optimisation by linking chemical, computational, and environmental sciences.

MOOCs are equally important since they act as platforms for intercultural learning, bringing together learners from all over the world through discussion, collaboration, and introspective communication. These exchanges foster cultural intelligence, empathy, and adaptability—essential qualities of the globally capable "networked engineer." Learners internalise the relational aspects of professional engineering in multicultural and multinational environments by being exposed to a variety of communication styles and collaborative conventions.

The review notes persistent issues, such as unequal internet access, inadequate institutional integration of MOOCs inside formal curricula, and little cultural contextualisation of information, despite these revolutionary potentials. In order to overcome these obstacles, MOOCs must be integrated into larger internationalisation and digital transformation agendas through strategic institutional collaborations, inclusive policy frameworks, and faculty training in intercultural and digital pedagogy.

MOOCs constitute a paradigm change towards a Global Chemical Engineering Education Ecosystem that is digitally mediated, interdisciplinarily connected, and culturally sensitive—more than just a technological advancement. In order to assess learning trajectories, verify competency outcomes, and develop sustainable models for international engineering education, future research should make use of longitudinal, cross-cultural, and design-based approaches. MOOCs can continue to develop as revolutionary infrastructures for producing chemical engineers who are morally conscious, internationally connected, and prepared for the future through such initiatives.

Author contributions

Conceptualization, Dejuan Mao, Fathiyah Mohd Kamaruzaman, and Ahmad Zamri Mansor; Methodology, Dejuan Mao; Software, Dejuan Mao; Validation, Dejuan Mao, Fathiyah Mohd Kamaruzaman, and Ahmad Zamri Mansor; Formal Analysis, Dejuan Mao; Investigation, Dejuan Mao; Resources, Dejuan Mao; Data Curation, Dejuan Mao; Writing—Original Draft Preparation, Dejuan Mao; Writing—Review & Editing, Dejuan Mao; Visualization, Dejuan Mao; Supervision, Fathiyah Mohd Kamaruzaman and Ahmad Zamri Mansor; Project Administration, Fathiyah Mohd Kamaruzaman and Ahmad Zamri Mansor. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

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