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Original Article

Bridging Borders and Disciplines: A Systems Thinking Approach to International Education in Sustainable Chemistry and Engineering

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GRAPHICAL ABSTRACT

ABSTRACT

Graduates in sustainable chemistry and engineering increasingly require advanced multicultural and interdisciplinary competencies, yet traditional curricula often fail to provide these. Collaborative Online International Learning (COIL) offers an accessible, scalable solution. This article analyzes the outcomes of two interventions connecting Chemistry undergraduates (University of York, UK) with Chemical Engineering postgraduates (University of Zaragoza, Spain). The objective was to foster these transversal skills alongside a holistic, systems-thinking understanding of biorefinery concepts. Over 6-week projects, two cohorts worked in international, interdisciplinary pairs, including both fully remote "e-pairs" and co-located "in-place" pairs, to produce scientific media. The findings demonstrate exceptional student engagement and the cultivation of a systems-thinking approach. The model fostered sociocultural competencies: non-native speakers enhanced professional fluency, while native speakers learned to moderate their language for inclusive communication. Critically, this study revealed that fully remote "e-pairs" outperformed co-located "in-place" pairs in digital-age skills, notably in their proactive use of social media for dissemination and their intuitive creation of more inclusive, accessible outputs. This work validates the COIL framework as an alternative to physical mobility, concluding that a well-structured virtual exchange can be effective for cultivating the digital and intercultural competencies required by the next generation of global scientists and engineers.

Keywords Collaborative Online International Learning (COIL), Interdisciplinary education, Systems thinking, Sociocultural competence, Biorefinery

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1 Introduction

In today's professional landscape, the ability to work effectively within multidisciplinary and multicultural environments has become one of the most sought-after competencies by employers, particularly in globally interconnected fields such as sustainable chemistry and chemical engineering.[1] Addressing the complex challenges associated with sustainable development demands a new generation of professionals equipped not only with profound technical expertise but also with advanced sociocultural and cooperative skills.[2] Traditional higher education curricula, however, often exhibit significant limitations in cultivating these competencies. Collaborative activities are typically conducted within homogeneous frameworks, where students share similar degree programs, nationalities, and languages. This reality starkly contrasts with the diverse professional environments they will encounter upon graduation.

International mobility schemes, such as the Erasmus+ program,[3] have played a crucial role in promoting students' cultural immersion and autonomy.[4] Nevertheless, their reach is limited; not all students possess the financial resources or personal circumstances to undertake a period of study abroad. Furthermore, interaction within these programs does not always guarantee genuine multi (or inter-) disciplinary collaboration, as students often remain within their specific fields of study. This educational gap has been thrown into sharper relief in the postpandemic era, which has accelerated the transition toward virtual working models and highlighted the critical importance of digital communication skills for remote collaboration.[5]

To address these shortcomings, there is an urgent need to implement innovative pedagogical models that offer a more inclusive and accessible form of internationalization. This article proposes and analyzes virtual international collaboration experiences as a high-value pedagogical solution in alignment with a Collaborative Online International Learning (COIL) model.[6] Such initiatives can function as a "pre-Erasmus+" experience, preparing students for future mobility, or as a robust and enriching alternative for those unable to participate in in-person exchange programs. These initiatives align directly with the United Nations' Sustainable Development Goals (SDGs), particularly those related to ensuring quality education, promoting decent work, reducing inequalities, and fostering strategic alliances.[7]

The core of this pedagogical approach is the promotion of direct experience exchange and the enhancement of language competencies through active collaboration. By working in international teams, students are immersed in a peer learning process.[8] Non-native speakers have the opportunity to refine their communication skills in a foreign language within a real-world professional context, while native speakers learn to adapt their language to be more inclusive and effective in an intercultural dialogue. Furthermore, the collaboration highlights the intrinsic differences in working methodologies and academic cultures, such as how meetings are arranged, tasks are divided, or project materials are designed, thereby compelling students to negotiate, adapt, and develop a greater sociocultural awareness.

Sustainability issues are particularly appropriate for COIL-type experiences, given the holistic and lateral approach to problem-solving that often requires diverse teams working across disciplines to solve.[9] Within the chemistry and chemical engineering space, green chemistry is well aligned with facilitating the chemical and allied industries in transitioning toward a more sustainable future through embracing circular principles. To achieve this, training students to adopt systems thinking-based approaches to learning, such that they are aware of and can respond to the interdependence of components within a system to optimize desired outcomes, perhaps in response to system perturbations or time-dependent behavior, is desirable for facilitating scientists to practice green chemistry.[10] Within this domain, biorefining as a means of generating bioenergy products from various biomass feedstocks via conversion technologies, is a key platform for enabling the transition from a linear to a circular bioeconomy through green chemistry.[11]

Given this background, this work presents the outcomes of two pioneering experiences conducted between the University of York (UK) and the University of Zaragoza (Spain), connecting students majoring in chemistry and chemical engineering to work jointly on the design and development of novel biorefinery concepts. Through these collaborations, students created scientific posters, flash presentations, and educational videos, utilizing digital tools and social media to manage their projects and disseminate their findings. This article analyzes how this COIL-based pedagogical model not only helped students transition from a reductionist understanding of their discipline to a holistic, integrated view of complex systems, but also served as a catalyst for the development of multicultural, communicative, and collaborative skills indispensable for future professionals.

2 Methodology

2.1 Study Design and Participants

This study synthesizes the results from two pedagogical interventions conducted in cooperation between the University of York (UK) and the University of Zaragoza (Spain) over two academic years. Ethical approval was obtained accordingly. The initiatives were designed to foster multicultural and interdisciplinary collaboration among students from diverse nationalities, educational backgrounds, and geographic locations.

Across the two iterations, 18 students participated. The first iteration involved 8 students. The cohort included four Chemistry undergraduates from the University of York and four Chemical Engineering Master's students from the University of Zaragoza.

The participants were equally divided between males (50%) and females (50%). All students worked remotely in four international pairs ("e-pairs"), with each pair consisting of one student from each of the two universities. The second iteration included 10 students (40% male and 60% female) with British, Portuguese, and Spanish nationalities. Akin to the first cohort, participants were Chemistry students from the University of York and Chemical Engineering students from the University of Zaragoza. This cohort was organized into five international pairs under two distinct collaborative models: two pairs worked remotely ("e-pairs") as their members were based in different countries. In comparison, three pairs consisted of members based at the same institution ("in-place pairs"). In both iterations, students were able to choose the research topic they were most interested in from a provided list of biorefining topics. Upon selecting a topic, students with mutual interests were paired and connected via their institutional email addresses to initiate their collaboration. **Table 1** shows the distribution of students across both pedagogical experiences.

2.2 Pedagogical Framework and Collaborative Tasks

The collaborations were structured as 6-week projects centered on developing new biorefinery concepts. A systems-thinking educational framework was consistently employed to encourage students to move toward a holistic, integrated perspective on the selected topic. The collaborative tasks differed slightly between the two project iterations. For the first pedagogical experience, students worked in pairs with their international counterparts to produce a scientific poster and two corresponding flash presentations (one in English and one in Spanish). The topics focused on areas such as citric waste valorization, crude glycerol upgrading, marine plastic pollution remediation, and the valorization of spent cooking/automotive oil. In the second pedagogical experience, the primary output for this cohort was the creation of educational videos covering various biorefinery topics, including the chemistry of Cyrene,[12] spent coffee valorization, and biopolymer production.

Throughout both pedagogical projects, students were responsible for managing their own workflow, including distributing tasks and arranging meetings. Communication was facilitated through a variety of channels; students exchanged emails, conducted virtual meetings via platforms such as Skype (formerly Microsoft Teams),[13] Zoom,[14] and Google Meet,[15] and, in the case of "in-place pairs," also held face-to-face meetings. A key component of the pedagogical experiences was the use of social media, particularly X,[16] to post updates, promote their work, and request feedback from a wider audience. The integration of social media into chemistry education to develop students' communication skills has been consistently demonstrated to be an effective intervention across a variety of software platforms, empowering students to become educators in their own right.[17–20] In the second iteration, students also utilized platforms such as YouTube[21] and TikTok[22] to disseminate their videos. **Table 2** summarizes the work plan provided to students to organize their work throughout the pedagogical process in both experiences.

2.3 Data Collection and Analysis

To evaluate the effectiveness of the interventions and gather students' perceptions, an anonymous open-ended questionnaire was administered at the end of each 6-week collaborative project. This qualitative data provided insights into the students' experiences with their international partners, the challenges they faced, and the skills they perceived they had gained. The quality of the students' work was also assessed through their final outputs (posters, flash presentations, and videos) and their responses to questions during examination periods. The surveys were designed to address the following domains: Participant Demographics, Project Context & Logistics, Communication Language, Communication Volume (Email), Communication Clarity (Email), Meeting Volume, Meeting Modality & Quality, Collaborative Dynamics (Participation), Collaborative Dynamics (Decision-Making), Perception of Sociocultural Differences, Perception of Interdisciplinary Differences, Perception of Learning Outcome (Systems Thinking), Perception of Social Media Use, Perception of Project Output, Overall Project Usefulness, Open-ended Feedback. **Table 3** lists the questions and possible answers used in both surveys.

Table 1 Student demographic details (type of pair, members' sociocultural characteristics) and research topics.

Cohort	Type	Member 1				Member 2				Research topic
		Gender	Nationality	Background	University	Gender	Nationality	Background	University	
1	e-pair	Female	British	Chemistry	York	Male	Spanish	Chem. Eng.	Zaragoza	Citric wastes
	e-pair	Female	British	Chemistry	York	Male	Spanish	Chem. Eng.	Zaragoza	Crude glycerol from bio-diesel
	e-pair	Female	British	Chemistry	York	Female	Spanish	Chem. Eng.	Zaragoza	Marine plastic wastes
	e-pair	Male	British	Chemistry	York	Female	Spanish	Chem. Eng.	Zaragoza	Spent cooking/automotive oil
2	e-pair	Male	British	Chemistry	York	Male	Spanish	Chem. Eng.	Zaragoza	The chemistry of Cyrene
	e-pair	Female	British	Chemistry	York	Female	Portuguese	Chem. Eng.	Zaragoza	Spent coffee valorization
	in-place	Male	Spanish	Chem. Eng.	Zaragoza	Female	Portuguese	Chem. Eng.	Zaragoza	Biofuels and hydrogen
	in-place	Male	Spanish	Chem. Eng.	Zaragoza	Female	Portuguese	Chem. Eng.	Zaragoza	Biopolymers production
	in-place	Female	Spanish	Chem. Eng.	Zaragoza	Female	Portuguese	Chem. Eng.	Zaragoza	Recycling LEDs

Table 2 Project working plan: Relation of tasks given to the students to organize their work in both pedagogical experiences.

Week	Tasks
1	1. Exchange emails to introduce yourself and talk about your nationality, education, and skills 2. Talk about your project. Why do you think some efforts have to be put into the valorization of your feedstock? Are the media talking about your feedstock? etc. 3. Use your X account/open a new X account and post about the work you are doing. Check whether people are aware of the scientific work being done in your feedstock or research area 4. Distribute the work and provide your ideas about how to organize the work 5. Find relevant information for the project and share it. You can send papers by email and/or create a shared folder on the cloud
2	1. Arrange a/some online meeting/s to discuss and share all the information you have found regarding your project. When arranging a meeting, make it clear whether you mean UK or Spain time 2. Discuss the options addressed to date for the valorization of your feedstock. Talk about the pros and cons of all the different valorization routes. Find alternatives to produce fine chemicals, bio-materials, bio-fuels, etc. 3. Among all the potential alternatives, choose the best/most promising one or two options under your own criteria 4. Use social media to promote your project and ask people about the best option. Post your thoughts on X and look for a more specialized audience; open an account in Research Gate and/or in any specialized scientific forum and talk to researchers from all around the world
3	1. Start working on your poster/video. Decide the title, sections, and format. Draft and think about how to complete all the sections together 2. Exchange emails and arrange online meetings 3. Post your progress on social media. Engage people in your project
4	1. Post a preliminary version of your poster/video on social media and ask for feedback 2. Share your poster/video with classmates and friends and ask them for feedback
5	1. Finish your poster and prepare two flash presentations, one in English and the other in Spanish. A flash presentation is a small talk of around 3-4 minutes about your poster./Finish your videos 2. Both flash presentations must talk about the poster and give the same information using two different languages (English and Spanish)
6	1. Submit the final version of your poster/video 2. Post the final version of the poster/video on social media

Table 3 Unified survey instrument (interventions 1 and 2) with full question and answer text.

Domain	Intervention 1: Posters Project	Intervention 2: Videos Project
Participant Demographics	Q1. Select your nationality (A and B) and the languages you speak (C-F). (You can select several options) Options: (A) I am British, (B) I am Spanish, (C) English, (D) Spanish, (E) French, (F) German, (G) Others (Italian, Portuguese, Chinese ...)	Q1. Select your nationality (A–C) and the languages you speak (D-I). (You can select several options) Options: (A) I am British, (B) I am Spanish, (C) I am Portuguese, (D) English, (E) Spanish, (F) French, (G) German, (H) Portuguese, (I) Others (Italian, Chinese ...)
Project Context & Logistics	Not explicitly asked (all were remote e-pairs)	Q2. Were you and your partner based in the same country over the course of the project? Options: (A) Yes, (B) No Q6. What type of meetings did you arrange? Options: (A) Only virtual. We were in different countries. (B) Only virtual despite being in the same country. (C) Only in-person. We were in the same country. (D) Virtual and in-person. We were in the same country.
Communication Language	Not explicitly asked	Q3. Which language/s did you and your partner use over the course of the project? Please, give any details you consider relevant. Options: (Open-ended)
Communication Volume (Email)	Q6. How many emails did you exchange over the course of the project? Options: A) 5 or fewer. B) Between 5 and 10. C) Between 10 and 15. D) More than 15.	Q4. How many e-mails did you exchange over the course of the project? Options: (A) 5 or fewer. (B) Between 5 and 10. (C) Between 10 and 15. (D) More than 15.
Communication Clarity (Email)	Q7. Was the information clear from the e-mail exchanges? Options: (A) Yes. I understand... (B) No. I did not understand... their English was not very good. (C) No. I did not understand... their English was too colloquial and/or too technical...	Q5. Was the information clear from the emails exchanged? Options: (A) Yes. I understood... (B) No. I did not understand... (C) No. My partner did not understand...
Meeting Volume	Q8. How many virtual meetings did you have over the course of the project? Options: (A) None. (B) One. (C) 2 or 3. (D) More than 3.	Q7. How many virtual meetings did you have over the course of the project? Options: (A) None. (B) One. (C) 2 or 3. (D) More than 3. Q8. How many face-to-face meetings did you have over the course of the project? Options: (A) None. (B) One. (C) 2 or 3. (D) More than 3.

(*Continued*)

Table 3 (Continued)

Domain	Intervention 1: Posters Project	Intervention 2: Videos Project
Meeting Modality & Quality	Q9. Did you use audio and video in the virtual meetings? Options: (A) Yes, both audio and video, (B) Only audio. I did not want to use my camera. (C) Only audio. My camera did not work/ I do not have a camera. Q10. How was the communication in the virtual meetings? Options: (A) Very good… (B) Good… (C) OK. Communication was difficult… (D) Bad. We did not have any virtual meetings.	Q9. How was the communication in the meetings? Options: (A) Very good… (B) Good… (C) OK. Communication was difficult… I was not a native speaker… (D) My partner was a native speaker and their accent was strong… (E) None of the above.
Collaborative Dynamics (Participation)	Q11. Describe your participation in the project. Options: (A) Both… contributed equally… (B) I mostly led… (C) My partner largely led… (D) I was responsible for the vast majority… (E) My partner was responsible for the vast majority…	Q10. Describe your participation in the project. Options: (A) Both… contributed equally… (B) I mostly led… (C) My partner largely led… (D) I was responsible for the vast majority… (E) My partner was responsible for the vast majority…
Collaborative Dynamics (Decision-Making)	Q12. How were all the decisions taken? Options: (A) By mutual agreement… (B) I took most of the decisions… (C) My partner took most of the decisions… (D) I had to take most of the decisions… (E) My partner had to take most of the decisions…	Q11. How were all the decisions taken? Options: (A) By mutual agreement… (B) I took most of the decisions… (C) My partner took most of the decisions… (D) I had to take most of the decisions… (E) My partner had to take most of the decisions…
Perception of Sociocultural Differences	Q13. Have you noticed differences when it came to developing this project? Options: (A) Yes… We work differently in Spain and the UK… perspectives… splitting the labor. (B) Yes… We work differently in Spain and the UK… work is organized… (C) No. Apart from working with a partner from another University… (D) Others…	Q12. Have you noticed cultural differences when it came to developing this project? Options: (A) Yes. I have noticed that we work differently. Different perspectives… (B) No. Apart from working with a partner from another nationality… (C) Others…
Perception of Interdisciplinary Differences	Q15. Have you noticed differences related to education (Chemistry vs. Chemical Engineering)…? Options: (A) Yes… different but complementary ideas… (B) Yes… different ideas… I do not find multidisciplinary projects good… (C) No. I have not noticed such differences.	Q14. Have you noticed differences related to education (Chemistry vs. Chemical Engineering, vs. other)…? Options: (A) Yes… different but complementary ideas… (B) Yes… different ideas… I DO NOT find multidisciplinary projects good… (C) No. I have not noticed such differences.
Perception of Learning Outcome (Systems Thinking)	Q16. Do you think that developing a bio-refinery concept… is good for your education? Options: (A) Yes. It has helped me… to a holistic deep understanding… (B) No. I have used the skills and knowledge I already had. (C) Others…	Q18. Do you think that developing a bio-refinery concept… is good for your education? Options: (A) Yes. It has helped me… to a holistic… understanding… (B) No. I have used the skills and knowledge I already had. (C) Others…
Perception of Social Media Use	Q2. Select the type of X account used in the project: Options: (A) We created a bespoke… did not want to share my identity. (B) We created a bespoke… better to create a dedicated account… (C) We created a bespoke… I did not have a X account… (D) We used our personal… I did not mind using it… (E) We used our personal… We did not think about creating a bespoke account… (F) We created a new personal… We did not have a X account… (G) We created a new personal… we did not want to use our personal accounts. Q3. What do you think about using X to promote your work? Options: (A) I think it is a good idea… (B) I think using X is a good idea, but other social media are better… (C) Other…	Q15. What do you think about using social media to promote your work? Options: (A) I think it is a good idea, and I used them. (B) I think it is a good idea, but we did not use them. (C) I do not think it is a good idea, although I used them. (D) I do not think it is a good idea, and I did not use them. Q16. What social media did you use? (You can select several options) Options: (A) None, (B) X, (C) Instagram, (D) Tik-Tok, (E) You-Tube, (F) Other…
Perception of Project Output	Q5. Did you post your flash presentation on X? Write Yes or No and give reasons. Options: (Open-ended)	Q20. Have you ever shot a divulgation video as part of your training? Options: (A) No, this has been the first time. (B) Yes, but only a few. (C) Yes, many of them. Q21. What do you think about making videos in comparison with traditional assignments…? Options: (A) I think it is a good idea, and I liked the experience. (B) I do not think it is a good idea. (C) I found it similar to traditional assignments. Q22. In comparison with traditional assignments, videos are Options: (A) More challenging… useful… (B) More challenging, but I do not think this activity has contributed… (C) Equally challenging, but I found it useful… (D) Equally challenging and I do not think this activity has contributed… (E) Less challenging

(Continued)

Table 3 (Continued)

Domain	Intervention 1: Posters Project	Intervention 2: Videos Project
Overall Project Usefulness	Q18. Have you found this experience useful? Options: (A) Yes. I think it has been a good experience… to be prepared for the real world… (B) No. I do not think I will be working in multicultural… environments. (C) No. Because …. (give details in question 19)	Q23. Have you found useful the experience of working in a multicultural and multidisciplinary environment useful? Options: (A) Yes. I think it has been a good experience… to be prepared for the real world… (B) No. I do not think I will be working in multicultural… environments. (C) No. Because …. (give details in question 24)
Open-ended Feedback	Q4. If you selected B or C in question 3, please complete here… Q14. If selected D in Question 13 please give details… Q17. If you selected C in question 16, please give details… Q19. If you selected C in question 18, please give details… Q20. Please share your experience and suggest how you would improve this activity	Q13. If selected C in Question 12 please give details… Q17. If selected F in question 16, please give details… Q19. If you selected C in question 18, please give details… Q24. If you selected C in question 23, please give details… Q25. Please share your experience and suggest how you would improve this activity

3 Results and Discussion

The combined analysis of the two pedagogical interventions provides a comprehensive view of the effectiveness of the pedagogical activity. The results are discussed below, synthesizing quantitative data from questionnaires, qualitative assessment of student-generated artefacts, and direct feedback on the collaborative process. Examples of the students' work (posters, videos, social media accounts) are available elsewhere.[23]

3.1 Quality and Technical Depth of Collaborative Outputs

Across both cohorts, student engagement was exceptionally high, with participants consistently describing the experience as both "challenging and exciting." This enthusiasm translated directly into the high quality of the final outputs. In the first iteration (Cohort 1), the four international "e-pairs" produced scientific posters and accompanying flash presentations. A formal assessment concluded that "most of the students did great work." The posters were not merely functional; they were lauded as "extraordinarily well written, but also innovative and eye-catching," successfully integrating complex technical information from both chemical and engineering perspectives. The second iteration (Cohort 2), the primary output shifted to educational videos. The assessment was similarly high, with the videos described as "excellent work" and as "informative, eye-catching, accurate, and timely" across the board. The topics covered also demonstrate a significant grasp of contemporary biorefinery challenges in the second interaction, ranging from the valorization of everyday waste products, such as spent coffee, to the sustainable chemistry of emerging platform molecules, such as Cyrene. The high standard of these outputs confirms that, working collaboratively, the students gained substantial insights into their biorefinery topics.

3.2 Analysis of Communication Dynamics and Workflow

The collaborative projects were underpinned by intensive and persistent digital communication across both cohorts, with English employed as the lingua franca for all interactions. The technological

Table 4 Unified comparative analysis of communication dynamics and modality (cohorts 1 and 2).

Metric	Cohort	Cohort 2
(Email Volume)		
<5 emails	20% (1/5)	40% (4/10)
5–10 emails	40% (2/5)	10% (1/10)
10–15 emails	20% (1/5)	10% (1/10)
>15 emails	20% (1/5)	40% (4/10)
Collaboration Modality		
Remote "e-pair" (Virtual Only)	100% (8/8)	40% (4/10)
"In-place" pair (Virtual Only)	Not applicable	10% (1/10)
"In-place" pair (Hybrid)	Not applicable	50% (5/10)
Perceived Effectiveness		
Communication Clarity	100% "Very Effective"	100% "Very Effective"

framework comprised a suite of informatics technologies widely used in both academia and business, including email exchanges, shared electronic diaries (e.g., Google Calendar), and various virtual meeting platforms (e.g., X, Google Meets, and Zoom). A comparative analysis of the communication data from both cohorts reveals a high level of engagement and a clear evolution in working practices. **Table 4** synthesizes the quantitative survey data from both iterations. Cohort 1 data are based on project reports (N=8) and the valid responses from its survey file. Cohort 2 data are drawn directly from the 10 individual student survey responses provided, offering a precise and granular view of that cohort.

The data from both iterations confirm that communication was not only functional but highly successful. In Cohort 1, 100% of the surveyed participants found the communication "effective" and reported experiencing "no idiomatic barriers." This sentiment was strengthened in Cohort 2, where 100% of students rated the communication as "Very Effective." The quantitative data in **Table 4**, however, illustrate a significant evolution in

workflow. While Cohort 1's email communication ranged from 5 to 15 emails (60% of respondents), Cohort 2 showed a clear bifurcation: 40% of students were hyper-communicators (exchanging 15+ emails), while an equal 40% exchanged five or fewer. This suggests that the latter group, comfortable with the available tools, likely pivoted more quickly to synchronous meetings or used other unmonitored communication channels.

The most telling finding relates to the normalization of virtual meetings. In Cohort 1, all participants were remote "e-pairs," making virtual collaboration a necessity. The innovation in Cohort 2 was the inclusion of three "in-place" pairs (six students) who were physically co-located at the same university. Despite having the ability to meet face-to-face, the analysis of the raw survey data reveals that one of these "in-place" students (10% of the total cohort) chose to meet exclusively online. The other five "in-place" students (50% of the cohort) adopted a hybrid model, conducting both virtual and in-person meetings. This strongly indicates that digital collaboration tools are no longer merely a substitute for in-person contact. These tools have become an embedded and preferred component of students' working practices, actively used to "conduct team work more efficiently and with more flexibility," irrespective of physical proximity.

3.3 Development of Technical Understanding via Systems Thinking

A primary pedagogical objective was to employ a systems thinking approach to "facilitate students to transition from a reductionist understanding to a holistic understanding of integrated biorefinery concepts." The project's interdisciplinary design, pairing Chemistry undergraduates with Chemical Engineering Master's students, was central to this achievement. Qualitative feedback from both cohorts overwhelmingly indicated that this integration helped students be mindful of how a problem can be solved from different, yet complementary, perspectives. This process directly promoted peer-learning and increased students' motivation. Students moved beyond viewing their topic as a simple chemical conversion (the Chemistry perspective) or a unit operation (the Chemical Engineering perspective) and began to appreciate the entire system, from feedstock logistics and social impact to process economics and circularity as evidenced from the work produced.

3.4 Cultivation of Sociocultural and Intercultural Competencies

The most profound outcomes were observed in the development of transversal skills. The international nature of the pairings acted as a powerful catalyst for sociocultural awareness.

3.4.1 Language and Communication Adaptation

The collaboration served as a real-world linguistic test. For Spanish students, it meant overcoming a language barrier, moving from passive academic English to active professional negotiation. Simultaneously, this created a critical learning opportunity for the native British speakers. They realized that they had to adapt/moderate their language when talking to non-native English speakers. This adaptation was specific and practical:

students reported consciously "avoiding the use of dialect and slowing down their speech during virtual meetings." This two-way adaptation improved fluency for non-native speakers and fostered inclusive communication among native speakers, which, together, constitute a high-level competence that is exceptionally difficult to simulate in a traditional classroom.

3.4.2 Awareness of Divergent Working Cultures

Beyond language, students were confronted with fundamental differences in academic and professional norms. Feedback from the surveys showed that students realized that collaborative work is not done the same way everywhere. This abstract awareness was grounded in concrete project management challenges. Students detected differences in approaches to "the division of labor," "arranging meetings," and even the aesthetic design of posters. Successfully navigating these differences required students to develop empathy, flexibility, and cross-cultural negotiation skills.

3.5 Impact of Collaboration Modality: "e-pairs" versus "in-place"

The unique design of Cohort 2, featuring both remote "e-pairs" and co-located "in-place" pairs, helped us to detect one of the most telling findings of our study. While communicative and multicultural skills were enhanced across all pairs, significant differences emerged in social media use.

3.5.1 Digital Literacy and Dissemination

A striking behavioral divergence emerged regarding project dissemination. Despite all students in both cohorts being encouraged to use social media, only the remote "e-pairs" (all Cohort 1 and some in Cohort 2) fully embraced these tools to promote their work. The "e-pairs" created bespoke X (formerly Twitter) accounts, as well as YouTube and TikTok channels, to host their videos and engage a wider audience. The students' social media accounts demonstrate their initiative in building a public-facing identity for their projects. Conversely, the "in-place" pairs did not use social media for dissemination. This suggests that international cooperative activities among students from different universities increase their interest in promoting their work, likely because they are already operating in a wholly digital environment and are more attuned to the value of online promotion.

3.5.2 Inclusivity as a Function of Virtuality

The most critical difference between in-place and e-pair was the design of the outputs. The remote "e-pairs" in Cohort 2 "created more inclusive videos with audios and subtitles in different languages" (e.g., English, Spanish, Portuguese). This was a proactive step, not explicitly required by the project brief. This behavior was absent in the "in-place" pairs. This finding indicates that international cooperative activities among students from different universities increase their awareness of the importance of creating inclusive materials. Forced to mediate their entire relationship through digital tools across linguistic and national boundaries, the "e-pairs" appeared to develop a deeper, more intuitive understanding of accessibility and inclusion. This suggests that

the fully remote COIL model, while seemingly a compromise, may in fact be a superior pedagogical tool for cultivating the specific digital and intercultural competencies required for a globalized, virtual workforce.

4 Conclusions

This study validates that the deployed COIL model, which bridged the disciplines of Chemistry (UK) and Chemical Engineering (Spain), was highly effective in cultivating both technical and transversal skills. The interdisciplinary, systems-thinking framework was pivotal, successfully assisting in transitioning students from a reductionist view to a holistic understanding of complex biorefinery concepts. The high quality and technical depth of the posters and videos produced evidenced this cognitive shift. Furthermore, the collaboration provided an authentic professional environment that fostered critical sociocultural competencies: non-native English speakers enhanced their professional fluency, while native speakers developed the vital, high-level skill of moderating their language to be more inclusive. The most profound finding emerged from the comparison between remote "e-pairs" and co-located "in-place" pairs. The fully remote "e-pairs" demonstrated superior outcomes in digital-age competencies. They were the only participants to utilize social media for broader dissemination and, most significantly, to proactively create more inclusive outputs, such as adding multilanguage subtitles. This strongly suggests that the constraints of a fully remote model, far from being a compromise, may actually be a superior pedagogical tool for fostering the specific digital and global inclusion skills required by today's virtual workforce. In summary, this work provides a validated pedagogical template that functions as both a "pre-Erasmus+" experience and a robust alternative to physical mobility. It demonstrates that international virtual collaboration, when anchored in complex interdisciplinary challenges, is a powerful method for cultivating the holistic, digitally adept, and interculturally aware scientists and engineers that the 21st century demands.

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