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Sustainability – The core of responsible engineering practice and education: Reality or still just utopia? A comparative study between China and the Rest of the World

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ABSTRACT

This paper discusses the importance of sustainability in chemical engineering education, driven by global societal pressures and climate change. It considers the impact of engineering education on sustainability and explores necessary adjustments. Approaches to integrating sustainability into the curriculum are identified including: adding sustainability subjects in relation to the UN SDGs; and integrating sustainability content and values. Global examples highlight a number of strategies and challenges, in particular China's "New Engineering Education" strategy. The role of educators and access to resources, such as the IChemE "Sustainability Hub" and the "Engineering for One Planet" framework, are emphasised. The study investigates perceptions of sustainability skills development among students, academics, and industry professionals, revealing geographical differences. Respondents from institutions in China, starting from a higher knowledge baseline, showed less growth in understanding sustainability over time compared to those from the rest of the world. The study highlights the need for curriculum renewal to better integrate sustainability, with tailored emphasis on specific concepts based on regional needs. The findings highlight the importance of embedding sustainability in chemical engineering education to prepare future engineers for global challenges.

1. Introduction

Sustainability is a widely used and at times misused or even abused term. The societal pressure for more sustainable products, processes, manufacturing, services, and way of life in general is rapidly increasing; particularly as we witness the consequences of climate change in all parts of the world. This, together with recent legislative frameworks, raises the demands on engineers to develop more sustainable solutions to a range of challenges. Given that we are past the half-way point at which the UN Sustainable Development Goals, UNSDGs (UN, 2015), are supposed to be attained, it is pertinent to review the impact of decades of engineering education for sustainable development and explore if any adjustments of educational approaches are necessary. Arguably, appropriate attitudes to sustainability should be developed from an early age in all people, the critical role engineers play in developing sustainable solutions and thus the key role of higher education institutions play as 'sustainability transformers' has been highlighted by Gutiérrez-Mijares et al. (2023). This is demonstrated not only through the content of sustainability curriculum taught at universities, but also by modelling sustainable behaviours to their students through practical measures implemented in their campuses.

Whilst curriculum content criteria demanded by professional accreditation requirements of engineering higher education have included sustainability for a number of years now (AHEP, 2010; Byrne, 2023), the impact this has had on the formation of professional engineers remains a focus of debate. The recent introduction of the requirement of sustainability culture in the IChemE accreditation requirements in addition strengthens the role of modelling sustainable behaviours in a drive to increase the practical impact of these measures (Bolton, et al. 2023).

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1.1. Sustainability in (chemical) engineering education course content – literature highlights on the WHAT and the HOW

Alarcon-Pereira et al. (2023) highlight in their bibliographic review the evolution of engineering education for sustainable development since late 1980 using the Conceive-Design-Implement-Operate (CDIO, 2021) framework. They explored not only the questions of knowledge and skills engineers must master, but also how they are best developed. Their work classifies the various approaches to teaching sustainability in engineering into three distinct approaches: i) a complement or add-on strategy incorporating sustainability subjects into the existing curriculum without changing the structure; ii) an integration strategy to include content and values related to sustainability, without fundamentally changing the educational paradigm; and iii) a restructure or rebuilding strategy undertaking a major redesign of the educational curriculum/paradigms towards sustainability.

A range of reports provide various examples of applying mainly the first two strategies to sustainability (development) in engineering education across the world. For example, Alexa et al. (2020) offer a review of the empirical content analysis of curricular in technical universities in Romania with specific emphasis on sustainable development related topics, highlighting significant differences and 'siloed approach' between them. Salvatore et al. (2016) provide examples of sustainability learning opportunities in undergraduate programmes in North America and Rampasso et al. (2018) analyse in more detail specific difficulties in introducing sustainability into engineering education using Brazilian HEIs as a study sample. On the other hand, Fernandez Rivas et al. (2020) highlight enabling approaches and examples of specific intervention, helpfully mapped against the cognitive domain of Bloom's Taxonomy (Anderson and Krathwohl (Eds.), 2001), that engineering educators can use to teach process intensification providing students with practical tools for developing sustainable solutions. Other specific examples of initiatives to include sustainability in (chemical) engineering courses across various geographies include for example Rorrer et al. (2023) describing a joint Austrian and US initiation on using active methodologies of teaching demonstrating a positive impact on students' understanding of renewable energy systems in an international context. Illustrating the 'integration strategy' described above, Svanström (2016) describes a specific example of restructuring a sustainability course in chemical engineering programme at Chalmers University of Technology in Göteborg, Sweden and introducing sustainability courses supported by practitioner informed project delivery to a positive effect on students' development of 'change agency'.

In the context of the research reported in this paper, a better understanding of the sustainability context in HEIs in China was particularly useful. Zhuang and Xu (2018) discussed in detail the impact of the New Engineering Education (NEE) national development strategy, launched in 2017, upon engineering curricula across China and the development of new directions and disciplines in universities, including sustainability aspects. This follows earlier reports, for example by Yuan and Zuo (2013) exploring students' awareness and their perceptions of factors that contribute towards the sustainability education. Subsequently, Qu et al. (2020) described the development of a new curriculum at Tongling University 'to improve the knowledge and awareness of students on sustainability within social dimensions by guiding and introducing them to typical social and environmental issues. They provide a valuable insight into knowledge, attitudes and behaviours of engineering students towards sustainability concepts at this University, highlighting positive impact upon the knowledge and attitudes of students as a result, but a more mixed impact on their personal behaviours.

Across all these reports the role of the educator is either implicitly or explicitly (e.g. Rampasso et al., 2018) discussed. However, whatever the level of 'sustainability expertise' of engineering educators is on an individual level, a wider and easier access to a range of resources supporting the academics in the delivery of sustainability-related content is integral in amplifying the impact on student learning.

1.2. Spotlight on education resources

A plethora of educational resources has been developed recently specifically for the use by (chemical) engineering educators and practitioners. In the UK, the IChemE Sustainability hub (IChemE, 2021) provides a range of resources, such as training courses, webinars, sustainability success stories and information repository relating to four of the 17 UNSDGs with most extensive chemical engineering input: SDG 3: Good health and wellbeing; SDG 6: Clean water and sanitation; SDG 7: Affordable and clean energy and SDG 12: Responsible consumption and production.

The Engineering for One Planet (EOP) framework extends this to all UNSDGs, mapping specific sustainability related learning outcomes against the ABET accreditation requirements (ABET, 2024). The framework formulates 92 (46 Core and 46 Advanced) 'essential sustainability focused learning outcomes that hundreds of academics, engineering professionals, and other key stakeholders have identified as necessary for preparing all graduating engineers — regardless of subdiscipline — with the skills, knowledge, and understanding to protect and improve our planet and our lives' (EOP, 2022). These learning outcomes may be useful to the educators developing their courses by providing them clear outcomes to be incorporated into their courses.

Whilst specific learning outcomes are a useful indication of the content to be covered, the Engineering Professors Council's (EPC) Sustainability toolkit currently provides one of the most comprehensive suites of knowledge, guidance and teaching tools with specific learning activities, case studies, project materials and assessment and accreditation materials (EPC, 2023). Since these can be directly implemented in relevant classroom activities, they are particularly valuable to educators restructuring their teaching to enrich it with specific sustainability-related content and activities.

1.3. Research focus

The present research seeks to address three specific research questions in the context of sustainability teaching in HE engineering education:

RQ1: How do students, academics and practising engineers perceive the extent of sustainability skills development in current chemical engineering higher education?

RQ2:Are these perceptions supported by evidence of course delivery description available on-line?

RQ3:Are there geographical differences in these perceptions between participants in different stakeholder groups from China compared to the rest of the world?

2. Methodology

Ethical approval for this study was sought and granted by the Faculty of Science, Agriculture and Engineering ethics committee at Newcastle University.

2.1. Questionnaire development and deployment

Data was collected through questionnaires developed specifically for this research given a lack of a validated instruments published in relevant literature sources that address the specific goals of this research. Before questionnaire deployment for data collection, validity checks were carried out by educational expert members of the IChemE Education Special Interest Group. In the case of student questionnaires, the survey was piloted with a small sample of Master's students at Newcastle University to ensure that the concepts were clearly understandable by the targeted audience. The questionnaires were translated into Mandarin by a native speaking Master's student with background in chemical engineering and sustainability, independently checked by a native speaking engineer and finally blind back-translated by a professor lecturing chemical engineering at a Chinese University to ensure that the technical terms had been translated into Mandarin faithfully and in a way the stakeholders would comprehend.

The surveys were distributed by email via IChemE-accredited departments network, Heads of UK and Australian chemical engineering departments, European Federation of Chemical Engineers (EFCE) distribution list, and by QR code in regular newsletters, personal networks, social media student contacts. The questionnaires in Mandarin were distributed via WeChat social media, personal contacts of the author team both in academia and industry, as well as QR code distribution to the attendees of the Global Chinese Chemical Engineering Symposium held on 5–9 August 2023 at the Hong Kong University of Science and Technology.

The surveys invited each respondent to rate their 'past' and 'present' understanding of the links between chemical engineering and sustainability on a five-point Likert scale. The links were surfaced through four statements specifically exploring the role of chemical engineering/engineers in: (i) climate change and adaptation; (ii) delivery of the UNSDGs; (iii) application of systems thinking for sustainable outcomes; and (iv) an holistic consideration of sustainability spanning environmental, economic, and social impact. The reference point for 'past' understanding was slightly different for each stakeholder group: for students, this referred to the time when they started their degree of study; for industry respondents, the 'past' referred to the point of their graduation; and for academics, it was when they first started teaching or research practice.

2.2. Quantitative data analysis

Raw survey data was first processed in Microsoft Excel, where Likert scale responses were numerically coded to enable statistical analysis; namely 'Strongly disagree' was assigned a numerical value of 1, 'Disagree' as 2 and so on. After this treatment, the mean and standard deviation values for all the Likert scale-type questions were calculated using the 'average()' and 'stdev.s()' functions respectively. The confidence interval for the mean values based on the t-distribution was calculated using the 'confidence.t()' function.

Further statistical analysis of the survey data was then performed in a Jupyter notebook using Python code. The Pandas library was used to import survey data stored as Microsoft Excel files into the Jupyter notebook. The internal consistency of the survey questions was evaluated using the Cronbach's alpha coefficient, which was calculated using the 'cronbach_alpha()' function in the Pingouin statistical library. The function returns the Cronbach's alpha value along with a default confidence interval of 95 %.

The pairwise correlation between different survey statements was calculated using the 'corr()' method in the Pandas library. Specifically, the Pearson correlation coefficient between pairs of data columns of the numerically coded responses to each Likert-scale question was calculated. The Pearson correlation coefficient, ranging from −1–1, was used to measure the linear relationship between two data columns (Wan Abdul Aziz et al., 2020). The analysis was performed for pairs of different survey statements resulting in a matrix of correlation coefficient values, which was visualised in the form of a heatmap using the 'seaborn.heatmap()' function available in the Seaborn data visualisation library.

2.3. Qualitative data analysis

The open text responses in the questionnaires were analysed in NVivo using reflexive thematic analysis (Braun and Clarke, 2020). This method does not require prior expectations with regards to the explored concepts and was thus considered appropriate in this research. Two Master's students independently read all qualitative open text responses and coded them independently. The discrepancies in coding were discussed with the academic supervisor of the project and resolved into a unified coding framework. The open text responses of the questionnaires administered in Mandarin were independently translated by two native speaking Master's students and the coding procedure then followed the above process.

2.4. ECTS course content mapping

Information on teaching sustainability skills and concepts explored in the student survey was investigated using publicly available data provided by IChemE-accredited institutions within the UK and internationally. Due to lack of information, certain concepts were replaced by most sensible proxy concepts on which information was available. For example, the concept of 'stakeholders' was replaced by 'transferable skills' which consider professional behaviours, namely communication, professionalism, leadership and engineering practice (e.g. punctuality and organisation abilities) (Jackson, 2010). Modules named 'professional skills' or 'professional development' or modules where the above listed transferable skills were both taught and assessed, e.g. oral assessments, assessed communication skills and organisation skills were included in the analysis.

Many of the institutions indicated teaching of concepts of the three pillars of sustainability under various themes, such as 'environmental awareness', 'societal implications' and 'economic factors' which are all counted towards the ECTS credits. However, given the recent emphasis on Environmental, Social and Governance (ESG) ratings, and the move of the industrial sector to the explicit use of the term ESG, ECTS credits were counted in this category only when specifically stated as 'ESG ratings'. This was the case also for the remaining concepts in the credit allocation process. The actual calculation of ECTS credits is shown below.

Due to the large number of universities in China only those institutions ranked within the Top 300 universities in chemical engineering were investigated (QS Top Universities, 2019 and www.university-list.net, 2019). Due to the lack of detailed information on the official websites of the Chinese institutions and no access to the internal systems, assumptions had to be made when calculating ECTS credits for certain universities. For example, for Tsinghua University, a 2022 undergraduate teaching manual can be found on the official website (Tsinghua University, 2022). Within this a course "Introduction to Environmental and Earth Sciences", which is counted as 2 credits in the first semester of the year, and the expected study time of 2 hours per week is listed. The total number of credits for the whole stage of the programme for 2022 year is 47. The ECTS credits for this course are calculated as follows:

$$(2\ credits/47\ total\ credits) \times 60\ equivalent\ year\ 1\ ECTS\ credits = 2.55\ credits$$

Based on the content description of the textbook, there are 2 units related to 'life cycle analysis' and 3 units related to 'resource conservation' out of 6 units. Therefore, the ECTS credits for this course are for each of the sustainability concepts:

Life cycle analysis credit: $2\ 55 \times 2/6 = 0.S85$ credits

Resources conservation credit: $2\ 55 \times 3/6 = 1.275$ credits

It is important to note that not all universities provide sufficient information publicly. These universities were marked as 'N/A' in the ECTS credit table. Some universities provided the course name publicly without stating specific topics covered or textbooks used. In these cases, the ECTS credit was calculated by finding the past textbooks of this university through a search engine, or by finding some related textbooks that were used within the province of the institution and using the average value to estimate the ECTS credits for each concept.

3. Results and discussion

The analysis presented herein is based on survey responses from three stakeholder groups investigated in this study – students, industry employees, and academics – categorised based on geographic location as either from China or elsewhere ('rest-of-the-world'). Thereby, the usage of the terms Chinese students or Chinese industry employees in the rest of this paper refers to the respective stakeholders based at Chinese institutions (and does not refer to the respondents' nationality). Table 1 documents the number of responses received for each survey. Due to the limited number of responses from Chinese academics, this data is not included in the analysis. Although the other datasets allow for in-depth analysis, all interpretations drawn are subject to limitations imposed by sampling bias as a result of convenience sampling (Udeozor et al., 2023). The Chinese data for all stakeholder groups predominantly came from respondents in two provinces: Sichuan and Hubei. Furthermore, the rest-of-the-world (ROW) data has a skew in terms of UK respondents (>50 % for the students' survey and >25 % for the academics' survey) and is not truly representative of the global demographic as the majority of respondents outside of the UK are from Europe and Australia with very limited representation of the Global South. With respect to the student populations, there is a disproportionate representation of students studying an IChemE-accredited degree programme in the ROW data – over 80 % of respondents. On the other hand, the equivalent figure was less than 20 % in the Chinese student group. As a result of these factors, due caution would need to be exercised when extrapolating findings to formulate a national (Chinese) or global perspective.

The surveys were designed to elicit the following information: (i) past and present understanding of the links between chemical engineering and sustainability in all respondent groups (ii) student and academic perspectives on embedding sustainability in the curriculum and extra-curricular development of sustainability skills and (iii) self-evaluation of specific sustainability concepts or skills from students and industry respondents. Since a series of Likert scale questions were used to explore these aspects, Cronbach's alpha test (Cronbach, 1951) is used to measure the internal consistency of the survey questions for each theme. As evident in the statistics presented in Table 2, Cronbach's alpha values for all survey themes in the Chinese data is greater than 0.9, indicative of very high internal consistency. Although the values for the rest-of-the-world data is comparatively lower, they are still greater than the threshold value of 0.7, suggesting that the series of questions used within each survey theme are consistent in probing a common underlying construct or basis.

Fig. 1 shows the mean 'past' and 'present' rating pairs (as identified in the methodology) for four key statements exploring the links between chemical engineering and sustainability for the different stakeholder groups along with the associated error bars representing a 95 % confidence interval based on the t-distribution. For all four statements, the past and the current ratings are reasonably close to each other in the case of Chinese students and industrialists. However, in the case of all respondent groups from ROW, there is a much more pronounced increase in the current understanding relative to their past. Hence, the self-declared understanding of links between chemical engineering and sustainability appear to evolve much less over time among the Chinese respondents; although it would be incorrect to extrapolate this finding to state that university study and industrial jobs in China do not help further the understanding of chemical engineering's role in sustainability as much as in other parts of the world. Firstly, the survey respondents are not necessarily representative of the Chinese student or industrial population (*vide supra*). Secondly, the study did not include the investigation of sustainability teaching at secondary education level, as the entry point into higher education and subsequently into employment, and thus it is not possible to establish whether any significant differences exist between China and ROW in this respect. Finally, a direct comparison of self-declared levels of understanding of respondents from different parts of the world is difficult to perform as multiple research studies have highlighted the role of cultural differences on cognitive self-evaluation (Cai et al., 2007) and metacognition (Klafehn et al., 2013; van der Plas et al., 2022). Nevertheless, the data from China does demonstrate the rather flat temporal trajectory of knowledge evolution among students and industry respondents, highlighting the scope for embedding sustainability in degree programmes and job roles in ways that can further increase the self-declared levels of understanding in all areas explored in this study (see Fig. 1).

Interestingly, Qu et al. (2020) also found very high levels of sustainability awareness amongst their sample of 124 students of quality management and engineering majors at Tongling University, although their sustainability concepts were much more broadly defined, e.g. 'waste recycling, anti-air pollution, no waste of daily food, green consumption, be part of social responsibility and low carbon transport'. Despite the differences in student populations surveyed, these findings provide additional support to possible hypotheses outlined above.

The 'present' Chinese students' understanding aligns fairly reasonably to the on-graduation or 'past' level of understanding of the Chinese industrialists (Fig. 1). While these two categories of respondents are expected to analyse their level of understanding differently given their different levels of experience relating to practical implementation of sustainability, this indicates that exposure to industry does not result in a significant deflation of 'past' understanding for the Chinese industrialists. This is in contrast to ROW industrial respondents, who report a much lower 'past' understanding compared to the 'present'. While this may suggest that there is not much of a step change vis-à-vis sustainability competence in the Chinese context on transitioning from a university student to an industrial employee, it also establishes the role that companies must play in the continuous professional development of their employees, particularly recent graduates. Systematic literature reviews exploring the integration of sustainability in higher education find an increasing prominence of the topic in engineering curricula; however, such analysis is mostly based on reports from the Global North (Arefin et al., 2021; Thürer et al., 2018). Likewise, reviewing sustainability reports from process industries worldwide, skewed again in terms of representation from the Global North, reveals very similar sustainability emphasis across all sectors (Liew et al., 2014), although a more comprehensive (AllianceforCorporateTransparency, 2020) and holistic consideration of SDGs (Kim, 2021) would be warranted going forward. Nevertheless, these clear trends of the growing emphasis on sustainability in engineering education and industrial practice could be an underpinning reason for the enhanced 'present' understanding declared by ROW students and industry employees. Although the integration of the different dimensions of sustainability in corporate sustainability development reports published in China was limited until 2013 (Bai et al., 2015), more recent analysis shows larger state-owned enterprises disclosing more circular economy information in their documentation (Kuo and Chang, 2021). Sustained efforts are clearly needed for industrial employees to grow their sustainability-related competencies.

The mean self-declared 'present' understanding was largely similar for each of the four statements in the Chinese respondents. However, a larger variance is evident in the rest-of-the-world (ROW) data – the statement on 'present' understanding of how chemical engineering is involved in the delivery of the SDGs received a mean rating of 3.73 among students and 4.03 among academic respondents. Comparatively, all the other statements had a mean 'present' rating > 4 among students and > 4.38 among academics. Likewise, the SDGs-related statement received a mean rating of 4.08 among ROW industry employees. Hence, the lowest average rating in all ROW respondent groups is for the statement on the SDGs; this is particularly noteworthy given the traction that the SDGs have received since their establishment in 2015 and that they are due to expire in 2030.

The comparison of the student groups indicates Chinese students

Table 1
Number of valid survey responses.

Stakeholder group	China	Rest of the world
Students	142	80
Academics	9	39
Industry employees	318	38

Table 2
Cronbach's alpha values with 95 % confidence interval shown in square brackets for each survey theme.

Survey theme	China		Rest of the world		
	Students	Industry employees	Students	Industry employees	Academics
Past understanding of links between chemical engineering & sustainability	0.958 [0.945,0.968]	0.949 [0.939,0.957]	0.898 [0.855,0.930]	0.880 [0.802,0.932]	0.952 [0.922,0.973]
Present understanding of links between chemical engineering & sustainability	0.953 [0.939,0.964]	0.960 [0.952,0.966]	0.760 [0.661,0.836]	0.862 [0.772,.922]	0.822 [0.709,0.898]
Perspectives on sustainability in the curriculum & extra-curricular development	0.906 [0.880,0.928]	n/a	0.792 [0.713,0.856]	n/a	0.809 [0.698,0.889]
Self-evaluation of sustainability concepts/skills	0.919 [0.898,0.938]	0.963 [0.957,0.969]	0.844 [0.787,0.891]	0.806 [0.694,0.887]	n/a

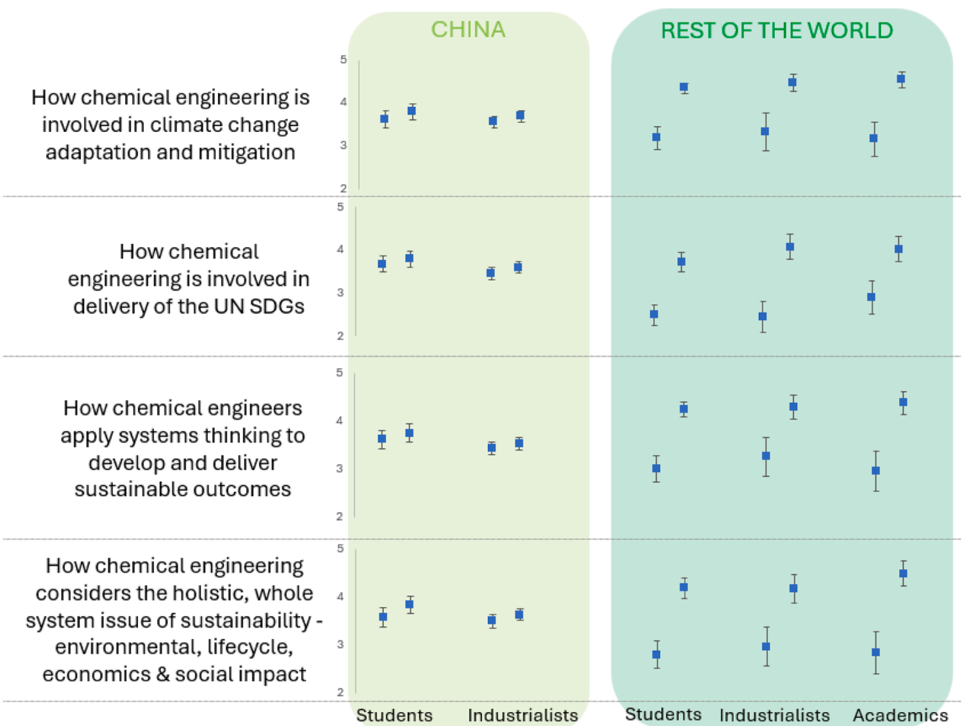

Fig. 1. Self-declared understanding of the links between chemical engineering and sustainability. Average 'past' (left blue square) and 'present' (right blue square) rating pairs are depicted for each stakeholder group. Error bars represent a 95 % confidence interval based on the t-distribution.

reporting a greater average self-declared understanding for all four statements at the start of their degree programme compared to their international counterparts (Fig. 1). In the 'present', the trend reverses, with the ROW students reporting a higher mean understanding for three off the four statements, except for that on the SDGs. The underlying heterogeneity of Chinese students, particularly in the context of recent findings of a divide in sustainability competencies in students at public and private universities in China (Wang et al., 2020) should also be noted. Despite these caveats, the results show Chinese student respondents having a wide awareness of the links between sustainability and chemical engineering from early stages in the programme, which is broadly in line with findings from other disciplines (Yuan and Zuo, 2013). However, as they progress through their degree programme, their self-reported evolution of this understanding does not change significantly, which raises the importance of analysing the curriculum for integration of sustainability and allied concepts (*vide infra*).

To further explore the evolution of these changes in student understanding from the 'past' to the 'present', Fig. 2 presents a more granular analysis of the same four statements considered in the previous figure, but factoring in level of study – ranging from their arrival at university, through to undergraduate and postgraduate years of study. Unlike in the ROW data, none of the Chinese student respondents self-identified as postgraduate/Master's-level students or as pursuing a placement year. Considering this difference in the survey sample between the ROW and Chinese students, it is important to look beyond the lumped mean figure for 'present' understanding displayed in Fig. 1. Although it would generally be expected that the rating for 'present' understanding would increase with advancement on a degree programme, the trend from the survey data is not as straightforward, because it is based on different respondents at different levels of study rather than on each respondent rating the evolution of their understanding at each level of their own studies. Nevertheless, Fig. 2 shows that the most significant increase in self-declared understanding of the four statements is seen in the first two years of undergraduate study for ROW students. This increase appears to bridge and potentially surpass the gap compared to Chinese students at the start of university (Fig. 2). Fig. 2 also helps illustrate that even in the case of ROW students, there is a tapering off in the self-declared understanding ratings beyond the third/fourth year of study. While this does not mean that undergraduate students after one or two years on the course are as competent as those at the end of their programme or Master's-level students, there could be various reasons for the tapering off observed. Anecdotally, this could be due to students becoming more aware of what they still need to learn as they go further on the degree programme; such a hypothesis and other contributing factors would

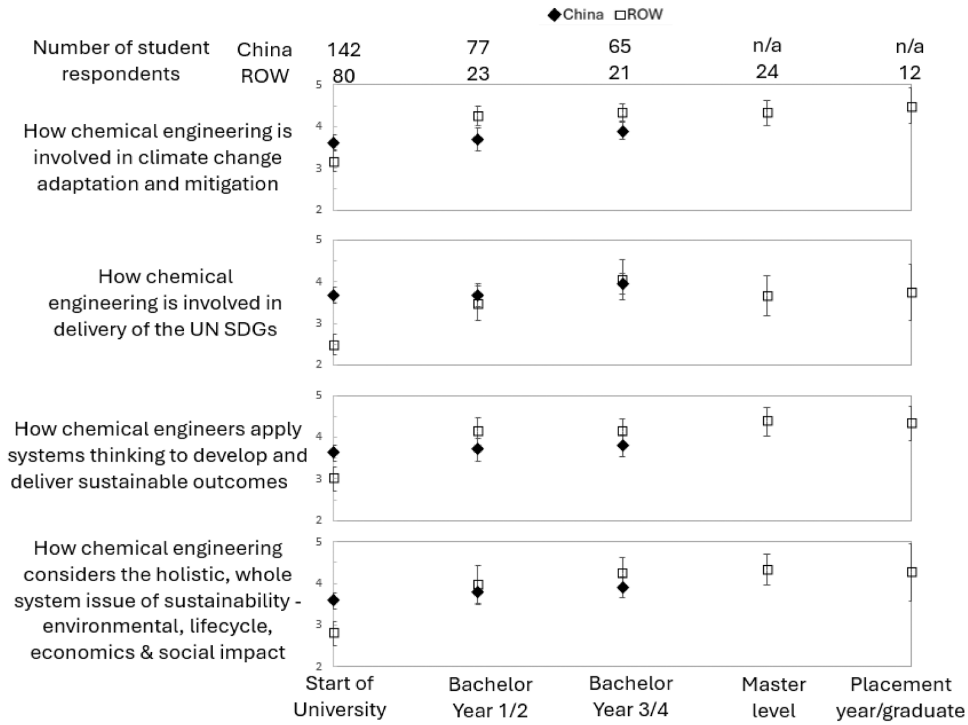

Fig. 2. Average self-declared understanding of the links between chemical engineering and sustainability for Chinese (filled black diamonds) and ROW students (empty squares) based on year or level of study. Error bars represent a 95 % confidence interval based on the t-distribution. Sample size of each year group is shown above the top panel in the figure.

need to be explored further.

The student survey also asked respondents to rate their understanding of specific sustainability skills or concepts on a four-point Likert scale, ranging from 'never heard of' to 'can use proficiently' (Fig. 3). Among the eight concepts, principles of 'safety and risk assessment' received the highest mean rating in ROW students. Comparatively, Chinese students declared a much lower level of competence on process safety and risk assessment. Likewise, the Chinese industrial respondents also express relatively low confidence on the same topic (Figure S1). Taken together, this reiterates the importance of increasing safety-related training in China, as expressed in a recently published diagnostic analysis of major chemical accidents in the country (Bai et al., 2023).

Among the Chinese student respondents, the highest ranked category was ethical responsibilities and actions. The only category where the Chinese students expressed a greater level of understanding compared to their international counterparts was 'Environmental, Social, and Governance (ESG)' ratings (Fig. 3). Interestingly, despite the average Chinese student rating being higher than the ROW students for the statement on SDGs in Fig. 1, the average self-declared competence in SDGs is higher among ROW students (Fig. 3). This should not be perceived as conflicting data since knowledge about the SDGs and knowledge about how chemical engineering plays a role in the delivery of the SDGs are not equivalent.

There is no apparent skew towards environmental sustainability concepts among either respondent group – for example, the average self-declared competence of ROW students in 'life-cycle analysis' is similar to that in 'ethical responsibilities and actions'. Among the Chinese students, average competence in 'ethical responsibilities and actions' is comparable to that in 'net-zero carbon emissions'. Interestingly, the same two categories were the highest ranked also among the Chinese industry respondents (Figure S1). However, on other aspects of sustainability, there is not much of a gap in self-declared competence between the Chinese and ROW students (Fig. 3), which is despite the challenges identified in the wider literature on embedding sustainability in the Chinese higher education curricula (Issa et al., 2017; Winter et al., 2022).

Fig. 4 presents a pairwise correlation heatmap for four statements on sustainability-related competency against the eight specific concepts/skills analysed in Fig. 3. The four statements range from a basic

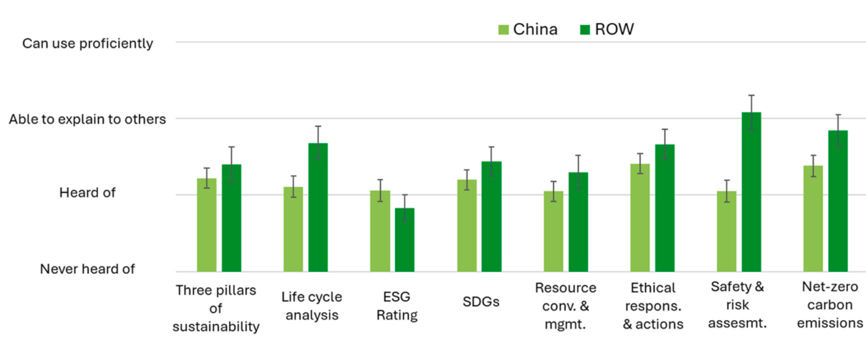

Fig. 3. Average self-declared competence of key sustainability-related concepts in Chinese and ROW students. Error bars represent a 95 % confidence interval based on the t-distribution.

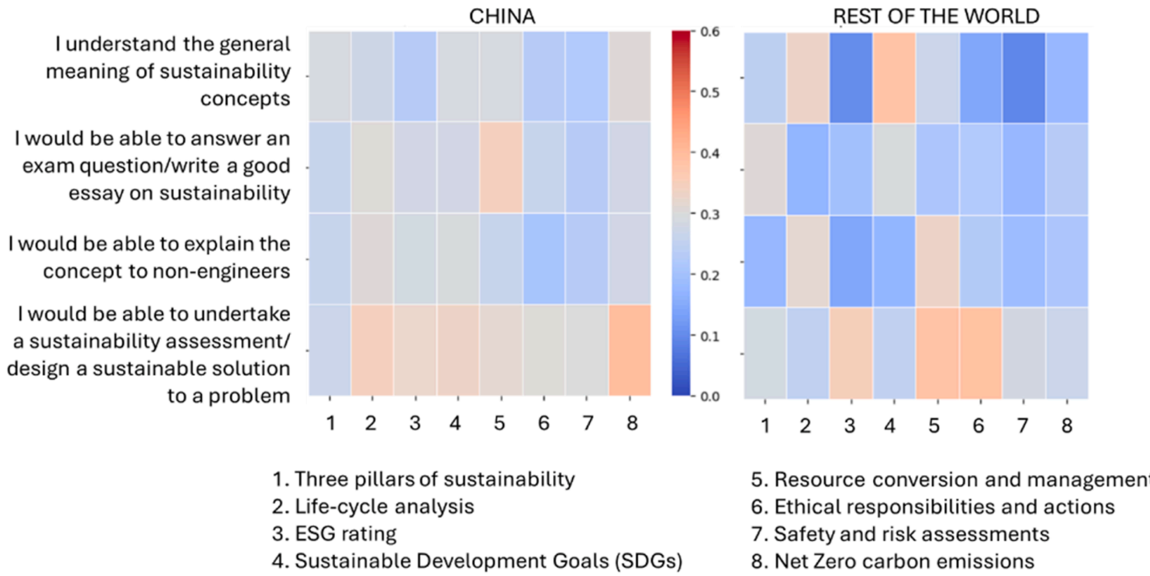

Fig. 4. Pairwise correlation heatmap between general statements on sustainability-related competence (along y-axis) and specific sustainability-related concepts (along x-axis) for Chinese and ROW student survey data.

'understanding' of the meaning of sustainability concepts to more advanced capability of 'assessing' and 'designing' sustainability solutions representing the increasing levels of cognitive skills of Bloom's taxonomy (Anderson and Krathwohl, 2001) in a more student-friendly manner. Among both groups of students, the self-declared competence in 'ESG rating', 'ethical responsibilities and actions', and 'safety and risk assessments' do not correlate strongly with the self-declared rating for the statement 'I understand the general meaning of sustainability concepts' (Fig. 4). In other words, respondents who express reasonably high confidence in the understanding of general sustainability concepts do not necessarily report high self-declared competence in 'ESG ratings', 'ethical responsibilities and actions', and 'safety and risk assessments'. This suggests that, from the perspective of the student respondents, these three concepts are less well-known or perceived as less critical for general sustainability awareness compared to the other five.

In contrast, for the statement 'I would be able to undertake a sustainability assessment/design a sustainable solution to a problem', we see a stronger positive correlation to all eight concepts/skills among both Chinese and ROW students (Fig. 4). Hence, expression of confidence in the higher-order ability of sustainability assessment and design is concomitant with a reasonably high confidence across all identified concepts/skills. However, there are noteworthy differences between the two groups of students. Among the Chinese respondents, the two skills with the highest positive correlation for the ability to answer an exam question or essay on sustainability are 'resource conversion and management' and 'life-cycle analysis' (Fig. 4). For the ROW students, it is 'the three pillars of sustainability' and 'the SDGs'. Therefore, for an ability to answer exam questions or write essays, considerations of environmental sustainability rank higher among Chinese respondents whereas a more holistic consideration of sustainability comes through in the ROW data. Nevertheless, when it comes to explaining sustainability to non-engineers, ROW students also start emphasizing environmental sustainability, since the two skills with the highest positive correlation are life-cycle analysis and resource conversion and management (Fig. 4).

Fig. 5 illustrates students' perspectives of the integration of sustainability in the taught curriculum and other co- and extra-curricular opportunities. On average, the Chinese student respondents express greater satisfaction for all survey statements compared to the ROW students. Taken together with the data in Fig. 3, the ROW students are more critical and more confident in sustainability-related competence.

In terms of most effective ways of integrating sustainability into the curriculum, in free-text responses, there were many comments from Chinese students that highlighted the value of practical engagement with industry: the "integration of sustainable development concepts and real-life experiences"; "let industry come to campus for lectures and students to go to industry for practical learning. Learning through

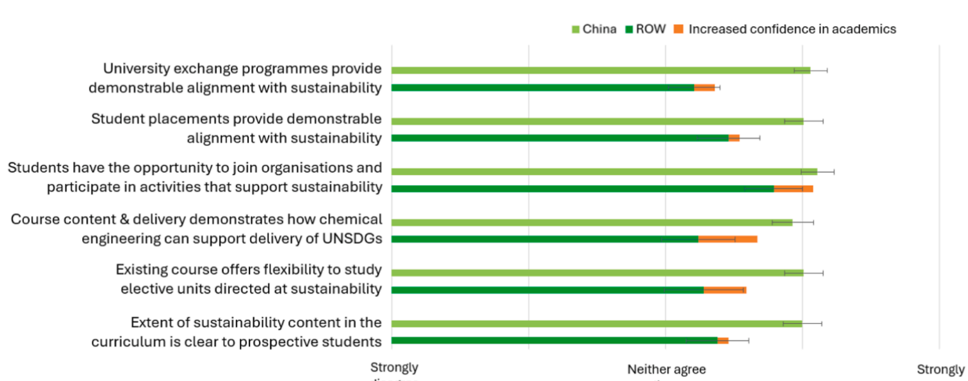

Fig. 5. Student opinion on embedding sustainability in the curriculum and other broader opportunities. Average rating for Chinese (light green) and ROW (dark green) student respondents shown along with error bars representing a 95 % confidence interval based on the t-distribution. The higher average rating expressed by ROW academics shown in orange.

practice will 'double the results with half the effort'"; "learning from books always feels superficial. It is better to show how chemical companies practice the concept of sustainable development more intuitively during an internship…chemical design competitions centred on sustainable development encourage students to apply what they have learned and deepen their understanding." This resonates with the study of Yuan and Zuo (2013) noting that student opportunities and sustainable development related research were perceived by students as important to achieve higher education for sustainable development goal.

Similar comments on industry relevance were made by ROW students: "being able to explore into an organisation and companies who emphasise sustainability will widen a student's horizon and give them the interest to learn more and help society and the environment."; "lectures should be relevant to current topics and not just theory.". It was clear from ROW academics who noted: "it is clear to me that students want to address issues around sustainability but don't know how."; another noting the caveat, "[sustainability] is easy to embed, but a barrier is the loose way that term like "sustainable" are thrown around". Both Chinese and ROW academics recorded that sustainability topics are taught through lectures, case studies, simulation and team-based project work.

The response from industrialists in China provided a different focus, with sustainability topics learned "on the job", through "CPD" and in "sharing practice". ROW industrialists had a different take on how sustainability should be taught: "I wouldn't focus on UN goals. Instead, focus on life-cycle analysis (LCAs), environmental impact assessments, and climate/sustainability innovations."; another noting that "courses on LCAs should be incorporated into process design and any courses dealing with the production of materials"; and suggesting that reaction and energy engineering "should be taught early in studies"; along with "electives that are available for students who have an interest in topics such as 'carbon capture and clean energy".

As was the case in Figs. 1 and 3, the mean rating for all statements in Fig. 5 fall in a relatively narrow range for the Chinese respondents with considerably more variability seen across the statements for the ROW student data. In addition to this difference, the student perspective on sustainability in the curriculum and other opportunities correlates very differently to self-evaluated sustainability competencies among Chinese and ROW students. As opposed to the latter, the former respondent group in general shows a stronger positive correlation between opinion on the curriculum and student opportunities and self-evaluated sustainability competencies (Fig. 6). In other words, self-evaluated competence is fairly decoupled from student perspective on sustainability in the curriculum and other opportunities in the case of ROW student responses. However, even among this group, we see that the specific ability to undertake a sustainability assessment or design (statement 4 in Fig. 6) shows a small positive correlation with several statements capturing student opinion on sustainability in course content and placement opportunities. More broadly, all four ability statements correlate positively to varying degrees with an appreciation of how the chemical engineering programme highlights the role of the discipline in the delivery of the UNSDGs (Fig. 6). With respect to statements 2, 5 and 6 in Fig. 6, these attracted the largest differences between the Chinese and RoW responses. However, these questions are really related to the flexibility in a university programme to include options such as electives, placements and exchanges. If these aren't possible, they probably attracted a low rating, which is more a criticism of the lack of flexibility in these programmes.

In line with the relatively low self-declared student understanding of how chemical engineering is involved in the delivery of the SDGs (Fig. 1), both the Chinese and ROW student data show the lowest average rating for the statement 'Course content and delivery demonstrates how chemical engineering can support delivery of UNSDGs' (Fig. 5). This reinforces the global necessity to highlight this more clearly in the taught curriculum. At the other end of the spectrum, the statement with the highest average in both student groups is on student opportunities to join organisations and participate in activities that support sustainability (Fig. 5). Given the commonality of these trends in both student groups, it is important that educators worldwide take action to close this apparent gap in sustainability emphasis between in-curriculum content and extra-curricular activities. This message is particularly important since Fig. 5 also shows ROW academics, on average, expressing a more positive outlook to all statements compared to the students. The increased confidence expressed by the academics is the greatest for the statement on chemical engineering and the SDGs. Hence, not only would the curriculum need to be reviewed for opportunities to embed sustainability, but the articulation of these concepts

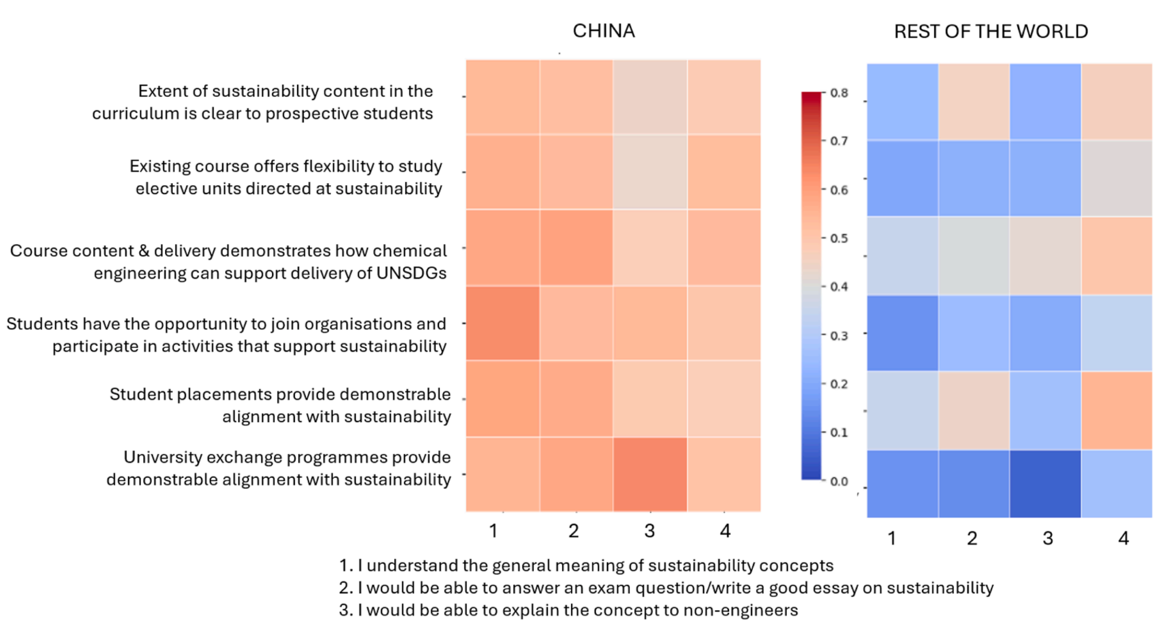

Fig. 6. Pairwise correlation heatmap between opinion on sustainability in the curriculum and other broader opportunities (along y-axis) and self-declared sustainability-related abilities (along x-axis) for Chinese and ROW student survey data.

must also be done in a manner that enables students to realize how chemical engineering helps address global sustainability challenges.

In order to further understand the similarities and differences identified in the Chinese and ROW student data, the survey findings were compared with an analysis of IChemE-accredited chemical engineering programmes offered worldwide. An ECTS credit apportioning analysis was undertaken for the eight key sustainability concepts/skills shown in Fig. 3. The institution-wise ECTS credits for each skill are listed in the supporting information (see methodology for detail on how this analysis was undertaken). Table 3 lists the descriptive statistics of this ECTS credit analysis for institutions in China and the IChemE accredited degrees in the ROW.

Although the ECTS credit apportioning exercise can be considered subjective and often challenging because of limited availability of information, and in the case of the Chinese institutions, subject to translation barriers, several key trends found in Table 3 align well with the student survey findings discussed earlier. As shown in Fig. 3, the Chinese student respondents reported a higher self-declared competence over the ROW respondents only for the concept of ESG rating. In line with this, Table 3 shows that the concept of ESG rating (as an explicit concept) is barely covered in the ROW curriculum (based on the information publicly available on institutional websites). Although the average ECTS credit value for this concept is greater at Chinese institutions, more than half the analysed Chinese chemical engineering programmes do not appear to cover this in their curriculum. Furthermore, a substantial gap between China and ROW was observed for competence in safety and risk assessment (Fig. 3), which is also borne out in the ECTS credit analysis (Table 3). Coupled with the Chinese industrial employees' data where again a low confidence was expressed in this topic (Figure S1), there is a clear necessity to increase the emphasis on principles of process safety and risk assessment at Chinese institutions (Zhao et al., 2013).

Likewise, there is a significant difference in the coverage of the concept of the three pillars of sustainability in the Chinese and ROW curriculum (Table 3). However, certain concepts related to environmental sustainability appear to be emphasized much more in the Chinese curriculum – specifically 'life-cycle analysis' and 'resource conversion and management'. This might explain why among Chinese respondents, the ability to answer an exam question on sustainability showed the highest correlation with these same two concepts: 'resource conversion and management' and 'life-cycle analysis' (Fig. 4).

Following the concept of ESG ratings, the average coverage of SDGs, as suggested by the ECTS credits analysis, is the second lowest in both the Chinese and ROW curriculum (Table 3). Strengthening the focus on SDGs and how they link to chemical engineering as proposed, for example, in IChemE's technical roadmap 'Chemical Engineering Matters' (IChemE, 2022) is vital to increase the relatively low levels of self-declared student understanding on this topic (Figs. 1 & 5). While greater coverage of ESG ratings and SDGs is needed universally on all chemical engineering programmes, the ECTS credits analysis also reveals the different paths that Chinese and ROW institutions would need to take towards curriculum renewal and revision. Reinforcing the 'three pillars of sustainability' and 'principles of safety and risk assessment' would need to be prioritised in the Chinese chemical engineering curriculum, the ROW institutions would benefit from a greater emphasis on 'life-cycle analysis' and 'net-zero carbon emissions'.

Table 3
Descriptive statistics of ECTS credits for eight sustainability-related concepts in the curriculum offered in China and at IChemE-accredited chemical engineering degree programmes in ROW.

China			Sustainability concept /skill	Rest of the World		
Mean	Median	Std. Dev.		Mean	Median	Std. Dev.
0.64	0.00	1.22	Three pillars of sustainability	5.95	5.00	4.48
2.38	2.25	2.41	Life-cycle analysis	0.73	0.00	1.54
0.28	0.00	0.58	ESG Rating	0.01	0.00	0.12
0.34	0.00	0.47	SDGs	0.28	0.00	1.82
4.82	3.00	4.82	Resource conversion & management	2.80	1.50	3.89
2.46	2.88	1.77	Ethical responsibilities & actions	1.26	0.00	2.14
3.23	3.25	2.74	Safety & risk assessment	8.31	8.00	4.64
1.38	0.00	1.94	Net-zero carbon emissions	0.43	0.00	1.20

4. Conclusions

This research highlights the need for renewal to better integrate sustainability, with tailored emphasis on specific concepts based on regional needs, into the (chemical) engineering curriculum. It finds that Chinese students show higher initial understanding but less growth in sustainability knowledge compared to their international counterparts, who show significant increases during their studies. The differences in perceptions of sustainability competence align reasonably well with the differences uncovered in course delivery descriptions (as available online) for chemical engineering programmes accredited by the IChemE and those delivered in China.

The study underscores the importance of embedding sustainability in chemical engineering education to prepare future engineers for global challenges, emphasising the role of educators and access to resources like the IChemE "Sustainability Hub" and the "Engineering for One Planet" framework. Alongside joining accreditation programmes that will drive the emphasis on integrating sustainability as a core graduate learning outcome, it is important that Universities offering chemical engineering programmes systematically engage with their students, alumni and external stakeholders to monitor and improve progress. Thereby, the findings suggest that both curriculum content and practical engagement with industry are essential for effective sustainability education.

CRediT authorship contribution statement

Hoadley Andrew: Writing – review & editing, Project administration, Investigation. **Glassey Jarka:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **Ravi Manoj:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Russell-Sewell Nigel:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The co-author Jarka Glassey is Editor-in-Chief of Education for Chemical Engineers, but has not had editorial access to the peer review process for this article at any point.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ece.2025.02.002.

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