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Perspectives

The importance of process intensification in undergraduate chemical engineering education

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ABSTRACT

This perspective article highlights our opinions on the imperative of incorporating Process Intensification (PI) into undergraduate chemical engineering education, recognizing its pivotal role in preparing future engineers for contemporary industrial challenges. The trajectory of PI, from historical milestones to its significance in advancing the United Nations' Sustainable Development Goals (SDGs), reflects its intrinsic alignment with sustainability, resource efficiency, and environmental stewardship. Despite its critical relevance, the absence of dedicated PI courses in numerous undergraduate chemical engineering programs presents an opportunity for educational enhancement. An exploration of global PI-related courses reveals the potential of educational platforms to fill this void. To address this gap, we advocate for the introduction of a standalone PI course as a minor elective, minimizing disruptions to established curricula while acknowledging the scarcity of PI expertise. The challenges associated with PI integration encompass faculty workload, specialized expertise, curriculum content standardization, and industry alignment. Surmounting these challenges necessitates collaborative efforts among academia, industry stakeholders, and policymakers, emphasizing the manifold benefits of PI, faculty development initiatives, and the establishment of continuous improvement mechanisms. The incorporation of PI into curricula signifies a transformative approach, cultivating a cadre of innovative engineers poised to meet the demands of the evolving industrial landscape.

1. Introduction

Process intensification (PI) in chemical processes refers to the systematic approach of optimizing chemical production through the integration of innovative technologies, methodologies, and design principles to enhance process efficiency, productivity, and sustainability (Segovia-Hernandez and Bonilla-Petriciolet, 2016). Departing from conventional practices that focused on scalability, PI emphasizes miniaturization, integration, and continuous improvement. As industrial processes face new challenges in the modern era, PI leads a paradigm shift towards optimizing processes by redesigning, integrating, and continuously enhancing them (Gómez-Castro et al., 2019). This involves the development and implementation of advanced PI techniques such as microreactors, intensified reaction systems, multifunctional reactors, and etc. to achieve higher yields, selectivity, and throughput while minimizing energy consumption, waste generation, and environmental impact. One of the key objectives of PI is to enhance efficiency across all stages of industrial processes. This involves advanced strategies targeting:

- Optimization of energy efficiency: PI designs systems to reduce energy consumption, recover residual heat, and incorporate cutting-edge technologies.
- Enhancement of product quality: Beyond efficiency, PI aims for excellence in final product quality, crucial in precision-demanding sectors like pharmaceuticals.

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- Minimization of waste and emissions: PI strives to develop cleaner, more efficient processes to reduce waste production and harmful emissions, promoting environmental sustainability.
- Increase in flexibility and agility: Compact and versatile intensified systems enable rapid adaptation to changing market demands and improved real-time decision-making.

Also, PI has demonstrated its effectiveness across various industrial applications, which include:

- Miniaturization of chemical reactors: PI facilitates the development of smaller, more efficient reactors, reducing reaction time and production costs in chemical synthesis.
- Integration of cascade processes: PI combines multiple process stages into a single unit, streamlining production, and reducing complexity and costs.
- Advanced separation technologies: PI drives the development of more efficient separation methods, saving energy and resources.
- Real-time control systems: Leveraging automation and advanced control, PI maintains processes at optimal conditions, enhancing stability, and operational efficiency.

In recent years, PI has gained unprecedented significance as a pivotal element in addressing contemporary industrial challenges and reshaping methodologies for process design and manufacturing. This surge in importance can be attributed to several contributing factors. Firstly, PI has become a linchpin in responding to global sustainability concerns, climate change, and the need to conserve resources (Segovia-Hernández et al., 2023). Recognized as a potent tool for reducing energy consumption, greenhouse gas emissions, and waste generation, PI aligns seamlessly with the growing global focus on environmental consciousness. Secondly, stringent regulatory pressures, including tightening environmental regulations and emissions targets, have driven industries to reassess their processes (Sitter et al., 2019). The inherent alignment of PI with these regulations, offering a reduced environmental footprint, has positioned it as a practical solution for achieving and maintaining compliance. Moreover, in an intensely competitive global market where operational efficiency directly correlates with economic competitiveness, PI has evolved into a strategic requirement (Stankiewicz et al., 2019). Companies are increasingly recognizing its potential to enhance cost-effectiveness by reducing resource consumption and streamlining production processes. Technological advancements have played a crucial role in translating PI concepts from theoretical idea to practical applications. Advances in materials science, microfabrication techniques, and process control systems have not only made PI more accessible but also economically viable for widespread implementation (Tula et al., 2019). Looking specifically at the recent years, the growing importance of PI can be reflected by its role in addressing global challenges. PI serves as a potent tool in the reduction of carbon emissions, the conservation of energy resources, and the minimization of industrial waste, i.e., a crucial contribution to the global effort to combat climate change and ensure a sustainable future. The advent of Industry 4.0 era and the integration of digital technologies into industrial processes have further amplified the impact of PI. Real-time data analytics, process monitoring, and advanced control systems are effortlessly integrated with PI, enabling an unprecedented level of precision and adaptability. Additionally, market dynamics and evolving consumer preferences now demand more sustainable, efficient, and high-quality products. Industries are realizing that embracing PI is not merely a matter of compliance but a strategic imperative for meeting these evolving market demands. Interdisciplinary collaboration is another noteworthy aspect of recent prominence of PI. The convergence of expertise among engineers, chemists, materials scientists, and data analysts has significantly accelerated the development and implementation of PI solutions. In summary, the historical journey of PI, marked by its evolution from the early roots to the contemporary significance, highlights its transformative potential. This journey forms the backdrop for understanding the principles, applications, and far-reaching impact of PI. Several existing review papers that offer more insights into the current deployment status of PI in industries are made available in (Kiss and Smith, 2020; Kiss et al., 2019; Shu et al., 2022; Segovia-Hernández et al., 2015; Harmsen, 2007) for interested readers.

While PI has traditionally been an advanced concept, there is a growing consensus that introducing PI principles and concepts at the undergraduate level is of paramount importance (Fernandez Rivas et al., 2020a). Historically, the chemical engineering curriculum has been rooted in fundamental principles such as fluid mechanics, heat transfer, thermodynamics, and mass transfer. While these principles provide a solid foundation, they are often taught in isolation from the practical realities of industrial processes (University of cambridge 2023; Eidgenössische technische hochschule zürich 2023; Universiti malaya 2023; Universiti teknologi malaysia 2023 ; Universiti teknologi petronas 2023; Fernandez Rivas et al., 2020b). As a result, graduates may face a significant learning curve when they enter the workforce, where they are required to optimize complex, interconnected processes. PI represents a paradigm shift in chemical engineering. It emphasizes the integration of unit operations, miniaturization, continuous processing, and sustainability, all of which are critical in addressing contemporary industrial challenges. By introducing these concepts early into the chemical engineering education, students can better prepare for the evolving demands of the field. Traditionally, chemical engineering students are exposed to large-scale, batch processing techniques. While these methods have their place, the industrial landscape is evolving towards more efficient, sustainable, and flexible processes. Early exposure to PI concepts equips students with the knowledge and mindset needed to adapt to these changes. PI also encourages a holistic approach to problem-solving. It challenges students to consider multiple factors simultaneously, such as reaction kinetics, mass transfer, and energy efficiency, when designing processes. These skills are invaluable in the real world, where complex processes demand multifaceted solutions. PI principles promote innovation and creativity in process design. By introducing these concepts early, students are encouraged to think beyond conventional boundaries and explore novel approaches to process optimization. This fosters a culture of innovation that is essential in addressing future challenges.

In academic institutions, there often exists a disparity between the curriculum taught and the practical expectations of the industry. This can leave graduates ill-prepared to navigate the complexities of real-world processes. Integrating PI education into the undergraduate curriculum can help bridge this gap, ensuring that students are better aligned with industry expectations upon graduation. In today's business landscape, there is a growing emphasis on adopting sustainable practices. PI, with its focus on resource efficiency and minimized environmental impact, directly addresses these evolving demands. While it is important to note that there might not be comprehensive statistical data supporting a universal industry demand for PI, our opinion is that graduates well-versed in PI concepts are undoubtedly better equipped to contribute to sustainable initiatives within various industries. Chemical engineering graduates often pursue careers in diverse sectors, ranging from pharmaceuticals to petrochemicals and food processing. Given the broad applicability of PI concepts across these industries, graduates with knowledge of PI can offer versatility and adaptability in their career paths.

The integration of PI concepts into the undergraduate curriculum requires careful planning and coordination. These concepts can be introduced through dedicated courses, case studies, or integrated modules within the existing courses. Hands-on laboratory experience is invaluable for students to grasp the practical aspects of PI. An example of laboratory experiments can involve intensified microreactors, membrane separations, and hybrid systems, these equipments for which has been documented to be available in specialized PI labs at some institutions (B v raju institute of technology 2024; Shiv nadar ioe 2024).

We believe these techniques can deepen students' understanding and appreciation of PI principles. Collaboration with industries that have embraced PI can provide students with real-world insights. Industry-sponsored projects, internships, and guest lectures can expose students to the practical applications of PI and the challenges and opportunities it presents. Modifying the curriculum to incorporate PI may require careful planning and approval processes. Institutions should be prepared for potential resistance to change and should engage faculty, students, and stakeholders in the decision-making process. Introducing PI concepts may necessitate investments in laboratory equipment, materials, and software. Institutions should assess the resource requirements and allocate budgets accordingly. Furthermore, faculty members tasked with teaching PI should possess a strong background in chemical engineering principles, particularly in process design, optimization, and sustainability. Expertise in advanced topics like reactor engineering, separation processes, and process control is advantageous. Given the interdisciplinary nature of PI, familiarity with fields such as chemistry, thermodynamics, and fluid mechanics enhance the teaching experience. Ideally, faculty members should also have practical experience or research background in PI methodologies and applications, potentially acquired through industrial projects, collaborative research, or publications. Professional development workshops and seminars can be explored to address any lack of specialized skills among departmental faculty. Inviting visiting scholars, industry experts, or guest lecturers to deliver lectures, seminars, or workshops enriches the educational experience and provides valuable insights. Faculty members can also leverage online resources, textbooks, journals, and educational platforms for self-study to enhance their understanding of PI principles and applications.

This paper aims to share our opinion on the significance of integrating PI education into the undergraduate curriculum for chemical engineering students. **Section 2** surveys and elaborates the current status of PI courses within undergraduate chemical engineering curricula. Addressing necessary curriculum revisions and proposing insights, **Section 3** discusses suggestions and challenges associated with incorporating PI courses. Finally, **Section 4** concludes this perspective article, encapsulating the importance of integrating PI education into the undergraduate chemical engineering curriculum.

2. Literature survey on existing education curriculum

Prior to surveying the existing PI courses within undergraduate chemical engineering curriculum, it is crucial to provide a brief background context on the historical evolution of PI and its significance in achieving the United Nations Sustainable Development Goals (UNSDGs). These initial discussions serve to contextualize the subsequent survey of literature findings concerning the current curricular landscape.

2.1. Evolution of PI

The concept of PI has a rich historical backdrop, marked by a series of transformative milestones that have led to its contemporary significance (Tian and Pistikopoulos, 2019). The seeds of PI were sown in the mid-20th century when chemists and engineers began grappling with the challenges of enhancing the efficiency of chemical reactions and industrial processes (Demirel et al., 2019). During this era, industrial processes were characterized by their large-scale, energy-intensive nature. The emphasis was primarily on increasing the production capacity to meet the growing demand (Dimian et al., 2019). Early attempts at improving process efficiency involved the refinement of conventional, large-scale reactors. Researchers sought ways to optimize reaction conditions, heat transfer mechanisms, and mass transfer within these reactors. While these endeavors yielded incremental improvements, it became evident that a more radical shift in approach was required to address the evolving industrial landscape and environmental concerns (Patrascu, 2023). The terminology PI began to gain recognition and prominence in the 1980s and 1990s (Márquez et al., 2023). This period marked a significant departure from traditional process engineering practices. Researchers and practitioners in various fields started to embrace the idea that there was untapped potential in reimagining how chemical processes were designed and executed. It was during this era that fundamental PI principles began to crystallize. Concepts such as microreactors, continuous processing, intensified heat exchange, and innovative separation techniques came to the forefront (Boodhoo and Harvey, 2013). These principles laid the foundation for a paradigm shift that would revolutionize industrial processes. As the theoretical foundations of PI were being established, practical applications started to emerge toward the latter part of the 20th century (Segovia-Hernandez et al., 2021). Industries such as petrochemicals and specialty chemicals were among the first to adopt PI principles (Becht et al., 2009). Miniaturized reactors, for example, allowed for precise control of reaction conditions and shorter residence times (Tian et al., 2018). This not only accelerated the chemical reactions but also reduced the production of unwanted byproducts. These advantages are particularly beneficial for enzyme-catalyzed reactions, photochemical reactions, and high-pressure reactions. Additionally, miniaturized reactors boast superior heat transfer capabilities and efficient temperature control, which are advantageous for highly exothermic reactions such as nitration, oxidation, hydrogenation, and polymerization processes. Additionally, innovative separation techniques, including membrane technologies and intensified distillation processes, played a pivotal role in improving efficiency and product purity (Kong et al., 2022). Altogether, the introduction of these intensified processes brought about transformative changes across the chemical process industry, yielding significant benefits and outcomes. Moreover, intensified processes promoted cleaner production methods, waste minimization, and resource conservation, thereby reducing environmental footprints and aligning with sustainability goals. Additionally, they accelerated innovation and technology adoption, driving the development of novel process intensification technologies and methodologies. In fact, the dawn of the 21st century witnessed a profound acceleration in the adoption of PI principles across diverse industries. Several factors contributed to this surge, which include sustainability concerns, regulatory pressures, economic competitiveness, and technological advancements.

2.2. PI as a catalyst for achieving UNSDGs by 2030

In recent years, PI has emerged as a significant and transformative contributor to the realization of the UNSDGs. The 2030 Agenda, a global commitment that addresses a spectrum of challenges, from poverty and inequality to climate change and environmental degradation, is structured around 17 SDGs. PI, with its innovative and sustainable approach to industrial processes, plays a pivotal role in facilitating the transition to a circular economy, i.e., an economic model that prioritizes the elimination of waste and the continuous use of resources through thoughtful product and process design with recycling and reuse in mind.

The core aspirations of the 2030 Agenda, encapsulated in UNSDGs, seek to achieve a more equitable, sustainable, and prosperous world by 2030. Notably, the challenge of transitioning to a circular economy is addressed, and PI emerges as a crucial enabler for this paradigm shift. As industries grapple with evolving global dynamics, PI aligns seamlessly with several SDGs:

SDG 6 - Clean water and sanitation: A circular economy, integral to PI principles, minimizes water consumption and pollution through the promotion of water recycling and efficient usage in industrial processes.

SDG 7 - Affordable and clean energy: Energy efficiency, a cornerstone of the circular economy, is significantly advanced by PI through the reduction of energy consumption in industrial processes.

SDG 9 - Industry, innovation, and infrastructure: PI, embodying innovative approaches, pave the way for sustainable industrialization and infrastructure development.

SDG 12 - Responsible consumption and production: PI, by playing a pivotal role in achieving resource efficiency and reducing waste, actively contributes to the objectives of responsible consumption and production.

SDG 13 - Climate action: By reducing resource consumption and emissions, PI actively contributes to the broader objective of mitigating climate change, a critical aspect of the circular economy and SDG 13.

SDG 14 - Life Below Water and **SDG 15 -** Life on Land: The resource efficiency and the reduced environmental impact associated with the circular economy, facilitated by PI, contribute to the preservation of terrestrial and marine ecosystems

The transformative principles and applications of PI are inherently rooted in sustainability, resource efficiency, and environmental stewardship. In this context, several specific contributions of PI to the UNSDGs can be highlighted:

Maximizing resource efficiency (SDG 12): PI, at its core, aligns with SDG 12's call for responsible resource management. Its principles of miniaturization, integration, and continuous processing optimize the utilization of raw materials and energy resources, minimizing waste, and enhancing material and energy flows.

Reducing environmental impact (SDG 13, SDG 14, and SDG 15): Both the circular economy and PI share the common goal of reducing the environmental footprint of industrial activities. PI's focus on reducing emissions, waste generation, and resource depletion aligns with SDG 13 to 15.

Enhancing industrial innovation (SDG 9): Synonymous with industrial innovation, PI challenges conventional processes and encourages the development of new technologies and approaches. These innovations support SDG 9's objectives of sustainable industrialization, infrastructure development, and fostering innovation.

Promoting sustainable consumption and production (SDG 12): Achieving a circular economy necessitates a shift toward sustainable consumption and production patterns. PI reduces the environmental impact of industrial processes while simultaneously enhancing their efficiency, aligning with SDG 12′s call for more responsible resource management and sustainable supply chains.

Advancing access to clean water and energy (SDG 6 and SDG 7): Resource-efficient industrial processes, characteristic of PI, minimize water and energy consumption. By optimizing these critical resources, PI supports access to clean water (SDG 6) and affordable, clean energy (SDG 7) for communities worldwide. In the water treatment community, for example, there is a well-known term known as "fit-for-purpose water treatment". This concept emphasizes tailoring water treatment processes to meet specific needs or requirements. It involves designing and implementing treatment strategies that are optimized for the intended use or application of the treated water (Jegatheesan et al., 2021). While fit-for-purpose water treatment prioritizes meeting specific water quality objectives for different applications, it is important to mention that PI techniques are employed to optimize the efficiency and sustainability of water treatment processes. Therefore, there is a significant overlap between the two concepts, as PI methods can be utilized to tailor water treatment processes according to specific needs and requirements, contributing to the overall goal of fit-for-purpose water treatment (Zhang et al., 2018). However, it is interesting to note that practitioners in the water treatment community may implement PI techniques without explicitly referring to them as such in their publications. This could be due to varying terminology preferences, disciplinary backgrounds, or focus on practical application rather than theoretical frameworks. Nonetheless, both fit-for-purpose water treatment and PI share the common goal of optimizing water treatment processes to meet diverse needs efficiently and sustainably.

The circular economy and PI are intrinsically linked, sharing common principles and objectives. In the context of PI, the circular economy refers to a systematic approach aimed at optimizing resource utilization, minimizing waste generation, and promoting sustainable production and consumption patterns within industrial processes. This framework emphasizes the design and implementation of closed-loop systems where materials, energy, and resources are continuously recycled, reused, or regenerated to maximize efficiency and minimize environmental impact (Campbell-Johnston et al., 2020; Liu et al., 2022; Kristoffersen et al., 2020). PI techniques play a crucial role in enabling circular economy principles by enhancing the efficiency, flexibility, and sustainability of manufacturing processes, thereby facilitating the transition towards more resource-efficient and environmentally friendly industrial practices. However, while the integration of PI into the circular economy framework presents myriad opportunities, it is not without its challenges and considerations. Widespread technological adoption may require substantial investments and adjustments to existing industrial processes. Overcoming regulatory hurdles and ensuring proactive resource management strategies in place are critical. Furthermore, fostering global collaboration and knowledge sharing is essential for the accelerated development and dissemination of sustainable technologies and best practices.

In essence, PI, as a transformative approach to industrial processes, holds immense promise in contributing to the UNSDGs and the transition to a circular economy. Through innovation, collaboration, and a steadfast commitment to sustainability, the integration of PI into the circular economy framework offers a tangible path forward. As industries and nations strive to address global challenges, harnessing the full potential of PI can create a more equitable, prosperous, and sustainable future for all by 2030. Fig. 1 briefly illustrates the interplay and alignment among the goals of sustainable development, the circular economy, and PI.

2.3. Coverage of PI in the existing education curriculum

In this section, we conducted a brief literature survey of the coverage of PI courses in undergraduate chemical engineering curriculum. Our investigation focused on top-ranked universities worldwide, including those in Mexico and Malaysia. The latter two countries hold particular significance as they are the authors' home countries. Our methodology involved consulting the QS World University Rankings in Chemical Engineering (Qs quacquarelli symonds limited, 2023) to compile a list of universities for survey, given by Table 1. Note that we relied primarily on publicly available information from university websites and course catalogues. Here, it is crucial to emphasize that the purpose of our literature survey here was to provide readers with insights into the current status of PI as an independent course in leading universities. We want to clarify that our survey specifically targets standalone PI courses, and while other senior design courses may incorporate aspects of PI, they are not included in our review. This decision aligns with our intention to offer a general overview of the presence of standalone PI courses in top-ranked universities, supporting our perspective on the importance of integrating PI education into undergraduate chemical engineering curriculum, rather than aiming for an exhaustive search of all universities worldwide offering PI to undergraduate students.

Our literature survey of the top 10 universities globally unearthed a concerning trend, i.e., there is a noticeable absence of explicit PI courses within their undergraduate chemical engineering programs. While foundational subjects like general chemistry, mathematics, physics, and core engineering principles are well-covered, the limited presence of dedicated PI coursework raises questions about its integration into mainstream education. Despite traditional emphasis on chemical engineering principles, PI appears notably absent as a distinct part of the curriculum. Although transport processes, separation techniques, and laboratory experiences are prominently featured, specialized PI courses are largely lacking. Some universities offer elective courses indirectly related to PI, such as specialized topics in reaction engineering (Eidgenössische technische hochschule zürich, 2023; Universiti malaya, 2023) and industrial chemical process design (Uc regents 2023; Ucsi education sdn. bhd., 2023). However, direct integration of PI concepts seems limited or absent. This gap signifies a significant opportunity for

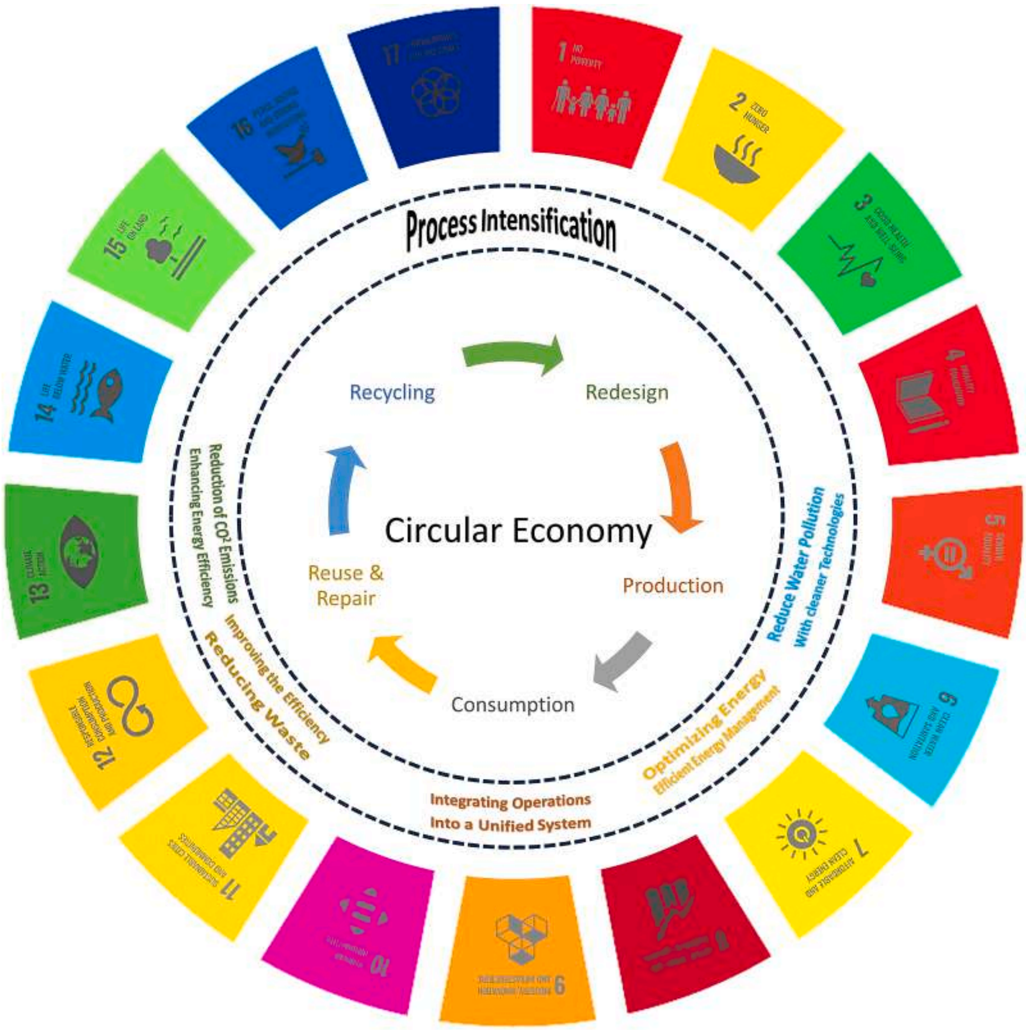

Fig. 1. Sustainable development goals and its relationship with circular economy and PI.

expansion and integration of PI as a fundamental component of undergraduate chemical engineering education. In our survey of the top 10 universities globally, our research indicates that Delft University of Technology (TU Delft) stands out by offering a dedicated PI course within their chemical engineering undergraduate program (Technische universiteit delft, 2023). Their syllabus covers an introduction to PI, sustainability-related issues in the process industry, definitions of PI, fundamental principles and approaches of PI, and how to design a sustainable, inherently safer processing plant, among other relevant topics (University of cambridge, 2023; Eidgenössische technische hochschule zürich, 2023; Universiti malaya, 2023; Universiti teknologi petronas, 2023; Uc regents, 2023). This distinct offering reflects the potential benefits of integrating PI concepts directly into the academic curriculum to better prepare future engineers for industry demands.

An extensive survey of the chemical engineering programs across the top 8 universities in Malaysia revealed a consistent trend, i.e., a conspicuous absence of dedicated PI courses. Similar to the global university landscape, the top 8 universities in Malaysia provide a thorough grounding in foundational subjects like general chemistry, mathematics, and core engineering principles. Despite the emphasis on traditional chemical engineering principles, distinct modules focusing on PI are noticeably absent from the curriculum. Notably, among these universities, our investigation identified the University of Science Malaysia (USM) as standing out by offering a dedicated PI course within their chemical engineering undergraduate program (D. School of chemical enigneering usm, 2023). This unique course provides students with an introduction to the concept and technologies of PI in chemical processes. Within this course, students probe into the fundamental principles of intensification technology and its practical applications within the contemporary chemical process industries. The overarching objective is to cultivate the ability to design a chemical plant that is not only compact enough to fit on a tabletop but also characterized by enhanced productivity, cost-effectiveness, and intrinsic safety. This approach aims to deliver improved product quality, adaptability to market dynamics, and the creation of a more sustainable environment. The course curriculum encompasses a broad spectrum of topics, including the definition and fundamentals of PI, the philosophy and opportunities inherent in PI, various techniques of PI, exploration of both active and passive intensified heat transfer, in-depth study of innovative concepts like the spinning disc reactor, the application of reactive distillation, the design principles behind compact heat exchangers, and the utilization of microreactors in chemical processes. This curriculum at USM serves as a notable exemplar of integrating PI principles into undergraduate chemical engineering education, aligning with the evolving needs of the industry. It highlights the potential for further expansion and integration of PI-related coursework into the broader academic landscape of chemical engineering programs. Such initiatives are crucial for producing graduates who are not only well-prepared but also highly adaptable in addressing the ever-changing challenges of the chemical engineering field.

As for the top 6 universities in Mexico, our extensive examination of chemical engineering programs revealed an identical trend where there

Table 1
List of universities offering chemical engineering program by QS world university rankings.

No.	2023 QS University Rankings by Subject: Chemical Engineering		
	World ranking	Malaysia ranking[a]	Mexico ranking[b]
1	Massachusetts Institute of Technology (MIT)	Universiti Malaya (UM)	Universidad Nacional Autónoma de México (UNAM)
2	Stanford University	Universiti Teknologi Malaysia	Instituto Politécnico Nacional (IPN)
3	University of Cambridge	Universiti Teknologi PETRONAS (UTP)	Tecnológico de Monterrey
4	University of California, Berkeley (UCB)	Universiti Sains Malaysia (USM)	Universidad Autónoma Metropolitana (UAM)
5	ETH Zurich	Universiti Kebangsaan Malaysia (UKM)	Universidad Autónoma de Nuevo León
6	National University of Singapore (NUS)	Universiti Putra Malaysia (UPM)	Universidad de Guadalajara (UDG)
7	Imperial College London	Universiti Malaysia Pahang	
8	Delft University of Technology	UCSI University	
9	University of Oxford		
10	Nanyang Technological University, Singapore (NTU Singapore)		

[a] Only Top 8 are available due to the QS Ranking system only provided Top 8 universities for Chemical Engineering course in Malaysia.
[b] Only Top 6 are available due to QS Ranking system only provided Top 6 universities for Chemical Engineering course in Mexico.

is also a noticeable lack of dedicated PI courses. Similar to the global and Malaysia universities, universities in Mexico also provides a strong foundation in fundamental subjects and core engineering principles. Despite this emphasis on traditional chemical engineering principles, explicit modules centered on PI are noticeably absent from their curriculum. One notable point was that our investigation revealed that, unlike the scenario observed in Malaysia, none of the top 6 universities in Mexico offer a dedicated PI course within their chemical engineering undergraduate programs, as far as our literature survey suggest. While it remains possible that aspects of PI might be integrated into courses like "Analysis of integrated separation and reaction processes" to "Application of process engineering in industrial projects" at Tecnológico de Monterrey (D. School of chemical enigneering usm, 2023) for example, detailed information about such integration is not readily available online. Hence, our emphasis remains on the overarching finding that, based on our literature survey, none of the top 6 universities in Mexico appears to offer a dedicated PI course within their chemical engineering undergraduate programs. This distinction highlights a potential gap in the Mexican chemical engineering education system, suggesting an opportunity for the integration and expansion of PI as a fundamental component within undergraduate curricula, aligning with industry demands and technological advancements.

Overall, the relatively limited incorporation of PI courses in current chemical engineering education programs presents a notable opportunity for enhancing alignment with industry needs. Again, we emphasize that while concrete statistical evidence of industry demand for PI courses may not be readily available, it is widely recognized that PI plays a crucial role in addressing contemporary engineering challenges. As such, our opinion is that there is a growing consensus among educators and industry leaders about the importance of advocating for the integration of PI concepts into the curriculum. Moving forward, it is prudent to embark on future research and collaborative endeavors aimed at exploring effective strategies for the thoughtful integration of PI into undergraduate chemical engineering education. Such efforts are essential to ensure that graduates are well-equipped to contribute effectively to the industry's ongoing progress and sustainability goals.

Apart from surveying the coverage of PI courses within undergraduate chemical engineering curriculum, our exploration was extended to the various PI-related courses offered by universities and professional institutions. Notably, the American Institute of Chemical Engineers (AIChE) provides several concise PI-based courses (American institute of chemical engineers, Aiche academy 2023). These encompass fundamentals of PI, process design for PI, modeling and simulation for PI, and PI for separation processes, among others. For instance, the "Fundamentals of PI" is a succinct 4-hour course exploration into PI deployment, fundamental engineering concepts applied to PI, practical examples, and modular plant technologies (American institute of chemical engineers, 2023). Similarly, AIChE offers a "Modeling and Simulation for PI" course, also spanning 4 h. This course introduces modeling and simulation for PI, covering steady-state reaction systems, separation processes, reactive separation, dynamic intensification, and model-based analysis of process operability, safety, and control for intensified processes. In addition to AIChE, various free open online platforms offer educational courses of PI aimed at university and college students. For instance, SWAYAM, an Indian government portal, provides such courses (Swayam, 2023). Their 12-week course includes comprehensive topics such as PI history, mechanisms, sustainable development, design techniques, stochastic optimization, PI in distillation, extraction, membrane systems, and micro process technology (Swayam, 2023). These courses aim to serve engineers and chemists keen on implementing intensified reactor and separator systems in the chemical industry, offering a fundamental understanding of chemical engineering principles and PI concepts. Moreover, universities like TU Delft provide an 84-hour PI course, mirroring their undergraduate PI syllabus, covering a wide array of PI-related subjects (Open education global 2023 ; leuven, 2023). Similarly, postgraduate course offered by Katholieke Universiteit Leuven (KU Leuven) on "PI in the Chemical Industry" addresses overarching PI concepts, focusing on structural, energy, synergy, and temporal aspects, while exploring barriers and opportunities within PI (leuven, 2023). Graduates of these courses are equipped to identify and elucidate key technical challenges faced by the chemical processing industry in the 21st century.

3. Suggestion on curriculum revision and challenges

In addressing the critical need to integrate PI within undergraduate chemical engineering education, a humble suggestion is proposed here regarding potential curriculum adjustments. Our suggestion revolves around the possibility of introducing a standalone PI course at the undergraduate level, although we acknowledge this is solely our opinion. To avoid substantial disruptions to well-established curriculum, we propose offering this as a minor elective rather than a core unit. This recommendation stems from our understanding that modifying core curriculum might be difficult or not practical. Additionally, the scarcity of expertise available to teach PI further prompts our suggestion of offering it as an elective. To assist in structuring this proposed course, we have drafted a tentative week-by-week breakdown of the course content (Table 2), aligning with the common 14-week teaching format observed in Malaysian universities. This outline is fashioned purely from our own perspective on PI education and aims to provide a potential framework for student learning. In terms of instructional time, 2 h for lectures and 1 h for tutorial sessions per week are recommended. The tutorial sessions can be transformed into consultation hours, providing students an opportunity to discuss their project progress and seek guidance from the tutor. When it comes to assessments, a focus on the practical application of skills and knowledge in solving problems (i.e., functioning knowledge) rather than emphasizing declarative knowledge is advocated. Declarative knowledge refers to the understanding of facts, concepts, principles, and theories, expressed through spoken and/or written words (Biggs, 2003). Assessments for declarative knowledge typically involve exams, quizzes, or knowledge-based evaluations, where the

Table 2
Proposed week-by-week content for PI course in undergraduate curriculum.

Week#	Content	Possibility of integration with other module
1	**Introduction to PI** • Understanding the need for PI in chemical engineering: Explore the contemporary motivations for adopting PI approaches, including increased efficiency, reduced environmental impact, and improved competitiveness in global markets. • Overview of intensified processes vs. conventional methods: We recommend providing specific examples of how intensified processes differ from traditional methods, especially in terms of reaction kinetics, equipment design, and overall process performance.	This module could be easily integrated into the curriculum that covers the fundamentals of chemical processes and engineering, since it lays the groundwork for understanding the importance of PI in modern chemical engineering practice.
2	**Fundamental principles and historical context of PI** • Efficiency, selectivity, and sustainability as key principles: Analyze each principle in-depth, considering their interplay and importance in designing and implementing intensified processes. Discuss recent advancements in process design that emphasize these principles. • Understanding the evolution and historical development of PI concepts: Trace the historical development of PI from its early beginnings to the present day, highlighting key milestones and breakthroughs in the field. Discuss how historical challenges and successes have shaped current PI methodologies. • Case studies highlighting successful PI applications: Present a range of case studies from different industries, showcasing successful implementations of PI principles. Analyze the factors that contributed to the success of each case study and extract lessons learned for future applications.	Similar to the "Introduction to PI" module, we contend that this module could seamlessly integrate into the curriculum covering the fundamentals of chemical processes and engineering. This offer students a broader understanding of the historical context of PI and its fundamental principles, thereby fostering a deeper appreciation of the evolution of chemical engineering concepts.
3	**Reaction intensification techniques** • Reactive processes and intensified reactors: Explore various reactor designs and operation modes used to intensify chemical reactions, including microreactors and packed-bed reactors. Discuss the advantages and limitations of each approach. • Advanced concepts in catalysis and kinetics for intensified reactions: Explore advanced topics in catalysis and reaction kinetics, including catalyst design, reaction mechanisms, and kinetic modeling. Discuss recent advances in these areas and their implications for PI.	This module could be integrated into courses on chemical reaction engineering or reactor design course. Students can apply their knowledge of reaction kinetics and reactor design principles to explore intensified reactor technologies in greater depth.
4	**Advanced reactor designs** • Innovative designs and applications for intensified reactors: microfluidic reactors, multifunctional catalytic reactors, fluidized bed reactors, electrochemical reactors, etc. • Exploration of emerging trends and technologies in intensified industry.	Advanced reactor designs align well with an elective course on advanced reactor engineering.
5	**Separation intensification** • Enhanced separation techniques and equipment • Membrane processes and their applications	This module could complement core courses on separation processes and unit operations. Students can further explore intensified separation techniques as part of their study of distillation, extraction, and membrane processes.
6	**Reactive separation and hybrid processes** • Innovative designs and applications for intensified reactive separation and hybrid processes: Provide a comprehensive overview of advanced reactor designs such as membrane reactors and reactive distillation.	Similar to the separation intensification, this module could complement core courses on separation processes and unit operations. Students can explore deeper into intensified separation techniques within the framework of their studies on distillation, extraction, and membrane processes. Alternatively, this course can also be integrated into chemical reaction engineering.
7	**Heat and mass transfer intensification – Part 1** • Advanced heat exchanger designs for intensified heat transfer: Investigate advanced heat exchanger designs, including compact heat exchangers, microchannel heat exchangers, and heat-integrated reactors. Discuss their advantages in terms of heat transfer efficiency and compactness. • Active and passive intensified heat transfer techniques: Compare active and passive heat transfer enhancement techniques, including surface modifications, phase-change materials, and advanced fluid dynamics. Discuss recent advancements and applications of these techniques in industrial processes.	These concepts could be integrated into courses on Heat Transfer and Mass Transfer. Students can deepen their understanding of intensified heat exchanger designs and mass transfer processes within the context of these core subjects.
8	**Heat and mass transfer intensification – Part 2** • Multi-scale heat and mass transfer phenomena: Explore heat and mass transfer phenomena at different length scales, from molecular to macroscopic. Discuss how these phenomena influence the design and operation of intensified processes. • Applications and case studies in intensified heat and mass transfer: Present case studies and examples of intensified heat and mass transfer processes in various industries, including chemical processing, food production, and energy generation. Analyze the performance and economic feasibility of these processes.	

(*continued on next page*)

Table 2 (*continued*)

Week#	Content	Possibility of integration with other module
9	**Integration and optimization in PI** • Integrating intensified units in process design: Discuss strategies for integrating intensified process units into larger process flowsheets, considering factors such as mass and energy integration, process safety, and operability. Present optimization techniques for maximizing the overall efficiency and sustainability of integrated processes. • Process optimization strategies for PI: Explore optimization techniques such as mathematical modeling (i.e., using MATLAB) and simulation (i.e., Aspen Plus). Discuss their application to PI processes and their role in improving process performance and profitability.	Integration and optimization principles align with courses on process design and optimization. Students can learn how to integrate intensified process units into larger process flowsheets and optimize overall process performance using mathematical modeling and simulation techniques.
10	**Economic and commercial aspects of PI** • Cost-benefit analysis of intensified processes: Present methodologies for conducting cost-benefit analyses of intensified processes, including capital and operating cost estimation, risk assessment, and sensitivity analysis. Discuss how these analyses inform decision-making in process design and implementation. • Market trends and economic viability of PI implementations: Analyze current market trends in PI technologies and their implications for industrial adoption. Discuss factors influencing the economic viability of PI implementations, including regulatory requirements, market demand, and technological readiness.	This could be covered in a course on engineering economics and project management where students can learn how to conduct cost-benefit analyses and assess the economic viability of process intensification projects.
11	**Sustainability in intensified processes** • Lifecycle analysis and environmental impact of intensified processes: Explore methodologies for conducting lifecycle assessments (LCA) of intensified processes, including environmental impact assessment, resource depletion analysis, and social impact assessment. Discuss how LCAs inform decision-making in process design and operation. • Developing inherently safer processing plants: Present strategies for designing inherently safer processing plants using PI principles, including process simplification, substitution, and mitigation. Discuss case studies and examples of successful implementation of inherently safer design principles.	These topics could be integrated into courses on environmental engineering and process safety. Students can explore the environmental impact of intensified processes and learn about strategies for designing inherently safer and environmentally sustainable processes.
12	**Intensified process control** • Advanced control strategies for intensified processes: Discuss advanced control strategies for PI processes, including model predictive control (MPC), adaptive control, and advanced process monitoring techniques. Explore the challenges and opportunities associated with controlling highly dynamic and nonlinear PI systems. • Challenges and solutions in controlling intensified systems: Identify common challenges in controlling intensified processes, such as limited process understanding, model uncertainty, and variability. Present solutions and best practices for addressing these challenges, including robust control design, real-time optimization, and fault detection.	Intensified process control principles could be covered in a course on process control and dynamics. Students can learn advanced control strategies for handling dynamic and nonlinear systems encountered in intensified processes.
13	**PI 4.0** • Incorporates a data approach based on the design principles of Industry 4.0: Explore the integration of data-driven approaches and advanced computing techniques into PI design and operation. Discuss the use of machine learning, artificial intelligence, and big data analytics in optimizing PI processes and enhancing process reliability. • Machine Learning/advanced computing in PI: Present applications of machine learning and advanced computing techniques in PI, including process optimization, fault detection, and anomaly detection. Discuss the potential benefits and challenges of implementing these techniques in industrial settings.	PI 4.0 concepts could be integrated into courses on data analytics and artificial intelligence in engineering. Students can learn how to utilize data-driven approaches and advanced computing techniques to optimize PI in the context of Industry 4.0.
14	**Final project presentations** Students present their final projects, applying the knowledge and skills acquired throughout the course to solve real-world PI challenges. Presentations include detailed analyses of project objectives, methodologies, results, and conclusions. Peer feedback and discussion foster collaboration and critical thinking skills.	

students demonstrate their comprehension and recall of specific content. On the other hand, functioning knowledge require the students to apply their understanding of concepts and theories in real-world scenarios (Biggs, 2003). In this case, students can be assigned a specific problem involving a non-intensified process followed by tasking them with analyzing potential intensification approaches. Students will be expected to conduct thorough literature reviews, evaluating diverse intensification methods for the given process. They should analyze the benefits of intensification from multiple perspectives, encompassing cost, feasibility, sustainability, and other relevant aspects. Ultimately, students will present their findings *via* an oral presentation as part of their assessment.

An exemplary project worth considering is the integration approach to sustainable PI in bioprocessing industries. This project entails adopting an integrated and sustainable approach to PI in bioprocessing industries, with a focus on scaling up and intensifying bioreactor systems in conjunction with downstream separation processes for biochemical production and biomanufacturing applications. Students will explore into advanced PI techniques (e.g., immobilized enzymes, cell recycling, intensified distillation columns, hybrid separation processes, and integrated membrane systems), aiming to enhance productivity, yield, and sustainability across diverse industries. Emphasis will be placed on integrating intensified bioreactor designs with downstream processing to achieve a comprehensive approach to PI, with a focus on optimizing existing process flowsheets by integrating intensified separation units and using intensified reactor geometries to maximize productivity, minimize residence times, and reduce waste generation. Another potential example could be the developing intensified reactor for sustainable petrochemical processes. In this project, the aim can be addressing the pressing need for sustainable practices in petrochemical processes by exploring intensified reactor design and the integration of renewable feedstocks. Students will explore into innovative approaches such as microchannel reactors, reactive separations, and catalytic membrane reactors to enhance reaction rates, selectivity, and energy efficiency. Additionally, the project will focus on incorporating renewable feedstocks into petrochemical processes through the aforementioned innovative approaches.

The incorporation of PI into undergraduate chemical engineering curriculum may be accompanied by a multitude of challenges and potential objections from academic institutions. Universities may express reservations about the perceived escalation in faculty workload and the demand for specialized expertise to effectively teach the intricacies of PI. The adaptation of established curriculum may encounter resistance, raising concerns about the practicability and longevity of PI as a specialized field of study amid the ever-evolving landscape of technological advancements. Additionally, uncertainties may emerge regarding the sustainability of PI education and its ability to stay relevant in the face of emerging technological shifts. The hesitancy to update teaching resources, textbooks, and learning materials specific to PI poses significant logistical and financial challenges for academic institutions. The development or acquisition of comprehensive and up-to-date educational resources that are aligned with the latest industry practices demands considerable investments of both time and capital. Standardizing the curriculum across diverse institutions to ensure a consistent quality of education in PI poses inherent difficulties. Overcoming these multifaceted challenges requires a comprehensive approach involving collaboration among academia, industry partners, and policymakers. Advocating the enduring benefits of integrating PI into curricula, sharing success stories from institutions that have successfully implemented similar specialized electives, and fostering a community of practice for educators specializing in PI are crucial steps. Furthermore, addressing the need for ongoing faculty development and training in PI, creating avenues for student exposure to industrial applications, and establishing mechanisms for continuous feedback and improvement in the curriculum are essential aspects of navigating the intricate landscape of integrating PI into undergraduate chemical engineering education. Another potential suggestion is to integrate specific PI elements into existing core courses and in this context, we also highlight in Table 2 the potential for incorporating the proposed content into other core chemical engineering courses that are likely already part of the curriculum. This approach offers flexibility, allowing the PI concepts to be seamlessly integrated with existing coursework.

4. Conclusion

This perspective article presents our viewpoint on the significance of integrating PI education into the undergraduate curriculum for chemical engineering students. Despite the importance of PI, a brief survey of existing curricula reveals a significant absence of dedicated PI standalone courses in many undergraduate chemical engineering programs, although some may cover PI in senior design courses. While certain institutions have taken pioneering steps by offering dedicated courses or modules, there remains ample room for improvement and expansion. Additionally, our exploration goes beyond curriculum observations to include various PI-related courses offered by professional institutions and universities worldwide. These offerings highlight the potential of educational platforms to fill the gaps in PI education, providing essential insights into chemical engineering principles and PI concepts. To address the critical need for integrating PI into undergraduate chemical engineering education, we propose introducing a standalone PI course at the undergraduate level, offered as an elective rather than a core unit. This approach aims to minimize disruptions to existing curricula while recognizing the shortage of expertise available to teach PI. Our proposed course content and recommended instructional time aim to establish a framework for student learning and assessment, emphasizing practical application in real-world scenarios. However, integrating PI into the curriculum may encounter various challenges and objections from academic institutions, including concerns about faculty workload, specialized expertise, sustainability of PI education, and alignment with industry demands. Therefore, several recommendations are given, which include emphasizing modular curriculum frameworks for integrating PI principles into existing courses and establishing faculty development programs focused on PI methodologies and pedagogies.

CRediT authorship contribution statement

Zong Yang Kong: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Eduardo Sánchez-Ramírez:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jia Yi Sim:** Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jaka Sunarso:** Project administration, Supervision, Writing – original draft, Writing – review & editing. **Juan Gabriel Segovia-Hernández:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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.

Data availability statement

All data generated or analyzed during this study are available from the corresponding authors on reasonable request.

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