Exploring Sustainable Development in Chemical Engineering Practice: A Scoping Review and Keyword Co-occurrence Network

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ABSTRACT

CONTEXT

Future engineers must have the capabilities to address critical sustainable development challenges and contribute to sustainable societies. The education to gain these capabilities requires both generalist and discipline-specific knowledge. Like all engineering disciplines, chemical engineering (ChE) practice has a unique relationship to sustainable development. Understanding this relationship is vital to teaching sustainable development in chemical engineering education.

PURPOSE

In this paper, we aim to answer the research question, “In Australia in the 2020s, what is the interaction between sustainable development and chemical engineering practice?”. We aim to articulate the relationship between current, acceptable Australian chemical engineering practice and sustainable development. This articulation will allow educators to teach sustainable development more effectively.

APPROACH

We performed a Scoping Review to explore the black and grey literature discussing the interaction between ChE practice and sustainable development. 4,031 records were initially identified, and 381 sources were included in the review. A network of the keyword co-occurrences was generated, the network was analysed and the keywords qualitatively analysed.

OUTCOMES

The network contained 118 keywords automatically sorted into five clusters. The main sustainable development challenges discussed in the literature were water/ wastewater, energy, waste, the environment, and lifecycles / circular economy. SDGs 4, 6, 7, 9, 12, and 13 were directly addressed in the network. This preliminary analysis forms the foundation for future research and provides inspiration for project-based learning and capstone subjects.

CONCLUSIONS

This is the first Scoping Review of chemical engineering practice and sustainable development. Articulating this sustainable development – chemical engineering practice relationship will allow sustainable development to be meaningfully taught within chemical engineering education. This will enable future chemical engineers to better contribute to solving sustainable development challenges.

KEYWORDS

Sustainable development, chemical engineering, engineering practice

Introduction

Sustainable Development (SD) asks us, as a society, to meet the needs of our generation without compromising the ability of future generations to meet their own needs (Brundtland, 1987). Currently, 2.2 billion people lack access to safe drinking water: engineering is crucial to delivering this safe water and meeting our generation's need (UNESCO, 2021; United Nations, 2021).

Education is part of the foundation for a sustainable society (Dempsey *et al*., 2011). And engineering education is the foundation for developing the capabilities of engineers to create a more sustainable society. This education requires both generalist competencies and discipline-specific knowledge to be meaningful. To best prepare chemical engineering graduates for solving sustainable development challenges, we must first understand how chemical engineers solve sustainable development challenges. Engineering educators cannot be expected to teach something without first understanding it.

Chemical engineering is a wide-reaching discipline focused on manipulating material and energy. The field encompasses many industries and the sub-disciplines of biochemical and process engineering. Little formal work has been done to synthesise the broad and developing relationship between chemical engineering practice and sustainable development. In this study, we aim to articulate the current, current Australian chemical engineering practice-sustainable development relationship.

We undertook a Scoping Review to answer the Research Question: "In Australia in the 2020s, what is the relationship between sustainable development and chemical engineering practice?". In this paper, we focus on the foundational data analysis: keyword analysis. Analysing keywords can be helpful in the first stage of data analysis in extensive literature reviews: this analysis can reveal patterns that can guide further analysis *(Radhakrishnan et al*., 2017). We generated a Keyword Co-occurrence Network and present the subsequent network and qualitative keyword analysis.

Method

The first author performed a Scoping Review (ScR) on chemical engineering practice and sustainable development. A ScR is similar to a Systematic Review but includes grey literature, which captures chemical engineering practice not published in research journals. A ScR represents a synthesis of available knowledge on a topic (Sutton *et al*., 2019): this synthesis will describe the relationship between current, acceptable Australian chemical engineering practice and sustainable development. As seen in Figure 1, a ScR generally has five sections: 1- preparation; 2- search strategy; 3- search and screen; 4- chart data; 5- collate, summarise and report data (Mak & Thomas, 2022).

Preparation

The preparation stage of a Scoping Review involves setting the research question and articulating the purpose of the review. The research question can be found above in the Introduction. The purpose of this review is to synthesise the relationship between sustainable development and current, acceptable chemical engineering practice to enable meaningful teaching of sustainable development in chemical engineering.

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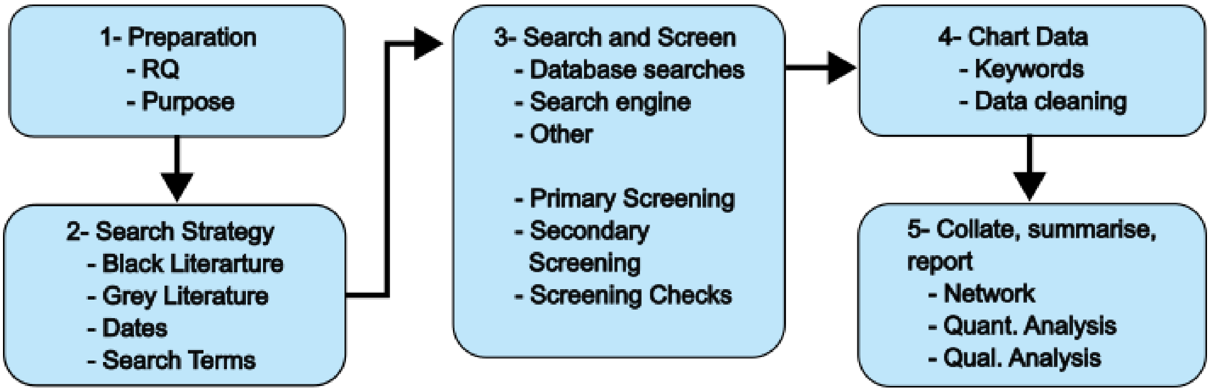

Figure 1: Flowchart of Scoping Review Stages , RQ: Research Question

Search Strategy

The following search strategy was written with the University's Science Librarian. The same search terms were used for database searches and search engines.

- Databases: SCOPUS, Inspec, Informit
- Grey literature
  - Search Engines: DuckDuckGo, Google
  - Web sites: Institution of Chemical Engineers, American Institute of Chemical Engineers
  - Professional Publications: *The Chemical Engineer*, *Chemical Engineering Progress*
- Publication Dates: 1/1/2013 – 5/2/2024
- Search terms: discipline term AND sustainable development term
  - Discipline terms: chemical engineer*, chemical engineer* practice, biochemical engineer*, biochemical engineer* practice, process engineer*, process engineer* practice
  - Sustainable development terms: sustainable development, sustainability, sustainable development goals
  - Example search terms: "chemical engineer*" AND "sustainability"

Search and Screen

Search: The first author used the above search terms to construct 18 search strings, and each string was entered into three databases and two search engines, giving a total of 90 searches. These search results, along with other grey literature, gave 4031 records. All records were stored in Zotero reference management software (Corporation for Digital Scholarship, 2024), Figure 2. All duplicates (1602 records) were removed, leaving 2429 sources to be screened. All papers, reports, and other materials found through the Scoping Review will be referred to as 'sources' in this paper.

Screen: Five criteria outlined below were used to screen sources for inclusion in the ScR. Two rounds of screening were used: primary (title-abstract screening) and secondary (full-text screening). All three authors independently screened, or rated, the material, and are referred to as raters 1, 2 and 3. Figure 2 shows how many sources were retained and rejected in each stage of the Scoping Review.

The inclusion criteria for screening were constructed to retain sources that provided meaningful data for the review's purpose: articulating the ChE-SD relationship. If a source did not meet all the inclusion criteria, it was rejected from the ScR. Sources without the full text available to the researchers were also rejected from the ScR.

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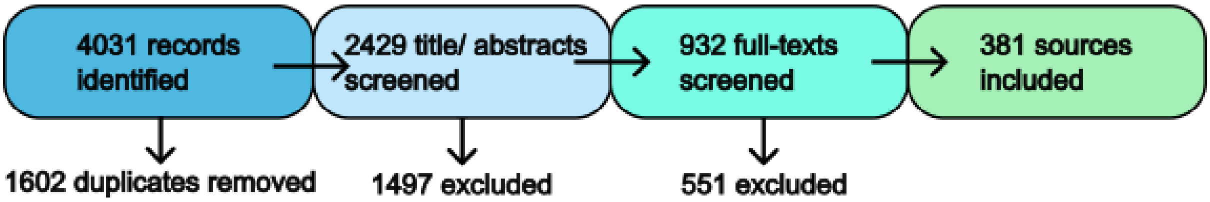

Figure 2: Number of sources retained in each stage of Scoping Review

- Criterion 1: the source must discuss chemical engineering practice.
- Criterion 2: the source must discuss sustainable development and its relationship to chemical engineering.
- Criterion 3: the source must discuss chemical engineering practice relevant to Australia.
- Criterion 4: the source must not be purely marketing material.
- Criterion 5: the source must be readable and contain no demonstrable factual errors.

It is important to have a high level of agreements between raters for the screening results to be consistent. Cohen's κ is a measure of inter-rater reliability and was calculated for each round of screening between each pair of raters. κ for the 1-2, 1-3 and 2-3 rater pairs for primary screening were 0.72, 0.72 and 0.69 respectively. κ for secondary screening was 1.00 for all pairs. A value of $\kappa \geq 0.6$ is considered "substantial" and an acceptable level of inter-rater reliability (Landis & Koch, 1977).

Chart Data

'Charting' data in a Scoping Review is the process of extracting data from the sources included in the study (Mak & Thomas, 2022). As the keyword analysis is the focus of this paper, only the charting of the keyword data is discussed. Most sources (~85%) retained their keywords from database exports. The first author manually added appropriate keywords to the remaining sources (~15%) where no keywords were originally present. The keyword data were cleaned to merge duplicates, alternative spellings, and smaller keywords into broader concepts (e.g., enzyme → biocatalyst).

Collate, summarise, and report the data

The data extracted during the charting stage was then synthesised to draw findings and conclusions from the review. In this case, the keyword data were exported from Zotero into VOSViewer (*VOSViewer*, 2024), a software that generates Keyword Co-occurrence Networks (KCNs) from bibliographic data. 118 keywords from 381 sources were used to generate a KCN for chemical engineering practice and sustainable development (Figure 3). Keywords with ≥5 occurrences were included. VOSViewer automatically categorised these 118 keywords into 5 'clusters', based on keyword association. Each node in the network is a different keyword, so there are 118 nodes.

The first author employed qualitative content analysis to thematically analyse the keywords, and frequency analysis of keywords was used for quantitative analysis.

Findings and Discussion

Keyword Network

Figure 3 shows the chemical engineering – sustainable development KCN generated by VOSViewer. 5 'clusters' were generated by VOSViewer, shown in red, green, yellow, blue, and purple in the network. These clusters do not have a central node or keyword, but the following patterns can be seen in the types of words present in each cluster:

- Cluster 1 (red): process engineering;
- Cluster 2 (green): recent ChE advances, e.g., pharmaceuticals;

- Cluster 3 (blue): water treatment technologies;
- Cluster 4 (yellow): chemical engineering technologies;
- Cluster 5 (purple): biotechnologies.

Relationships between nodes can be explored to show patterns in the chemical engineering practice-sustainable development relationship. An important concept in sustainable development is the ‘food-energy-water’ (FEW) nexus; this is the concept that food, energy, and water are all essential for life, but burden on these resources is rapidly increasing (United Nations, n.d.). Figure 4 shows the nodes of “food”, “energy” and “water” in the KCN. All three nodes are present and connected within this network. This demonstrates that chemical engineering supports and improves quality of life through the FEW nexus.

Additionally, all three nodes are connected to the SDGs, economics, environmental impact, education, circular economy, biofuels, and water treatment nodes. The presence of these connections demonstrates the FEW nexus’ inherent interconnected nature. This interconnectedness demonstrates the importance of systems thinking and holistic thinking in sustainable development; considering how different parts of a system impact the system as a whole.

The analysis of the KCN are the hundreds of relationships it represents begins to answer the research question on the interaction between chemical engineering practice and sustainable development The visualisation of this network demonstrates that the interaction between chemical engineering practice and sustainable development is complex and multi-dimensional. This interaction is spread across the broad discipline of chemical engineering because the work that chemical engineers are doing in sustainable development is essential and interconnected: complex sustainable development challenges require collaboration.

Qualitative Analysis

The first author used qualitative content analysis to analyse the keywords in the network (Figure 5) into categories that were more meaningful than the clusters produced by VOSViewer, which were based only on quantitative association. Figure 5 shows five categories of keywords: sustainable development concepts, sustainable development issues, engineering technology, chemical engineering principles, and aspects of engineering practice.

Five sustainable development challenges are represented in this figure, demonstrating that chemical engineering practice is actively working on solving the challenges of water/ wastewater, energy, waste, environment, and lifecycles/ circular economy. Table 1 compares Figure 5's items with the UN Sustainable Development Goals. This comparison illustrates that chemical engineering is contributing to many SDGs. Further mapping of chemical engineering’s contributions to the SDGs is important but outside the scope of this paper.

Solving these sustainable development challenges requires the application of chemical engineering principles. Eight chemical engineering principles are referenced in this network, with the principles of design, systems thinking, separation processes, and thermodynamics being well-represented. The presence of these principles shows that while the application of chemical engineering principles is evolving with new sustainable development challenges, the core principles of chemical engineering remain steady. Beyond the principles, aspects of chemical engineering practice such as interdisciplinarity, education, ethics, research, and innovation are also present in the network.

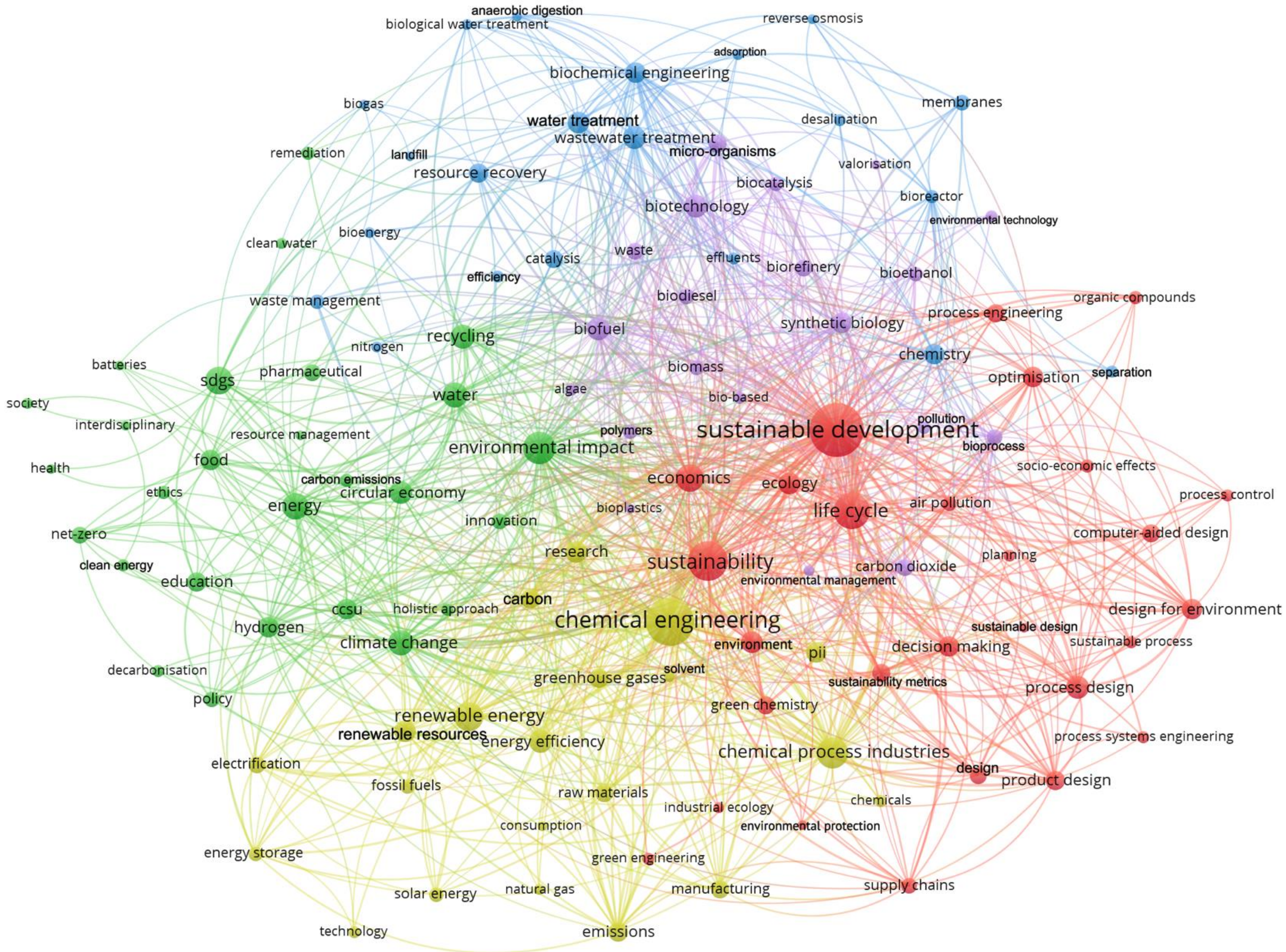

Figure 3: Network of Keyword Co-Occurrences for Chemical Engineering Practice and Sustainable Development Literature, generated by VOSViewer

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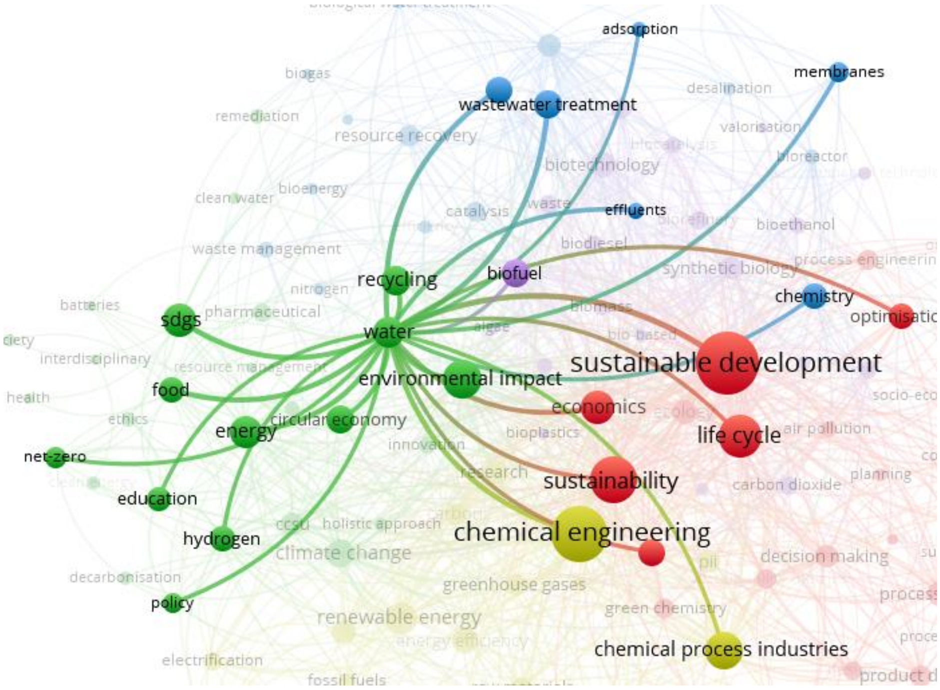

Figure 4: Water 'node' in KCN generated by VOSViewer (representative of 'energy' and 'food' nodes)

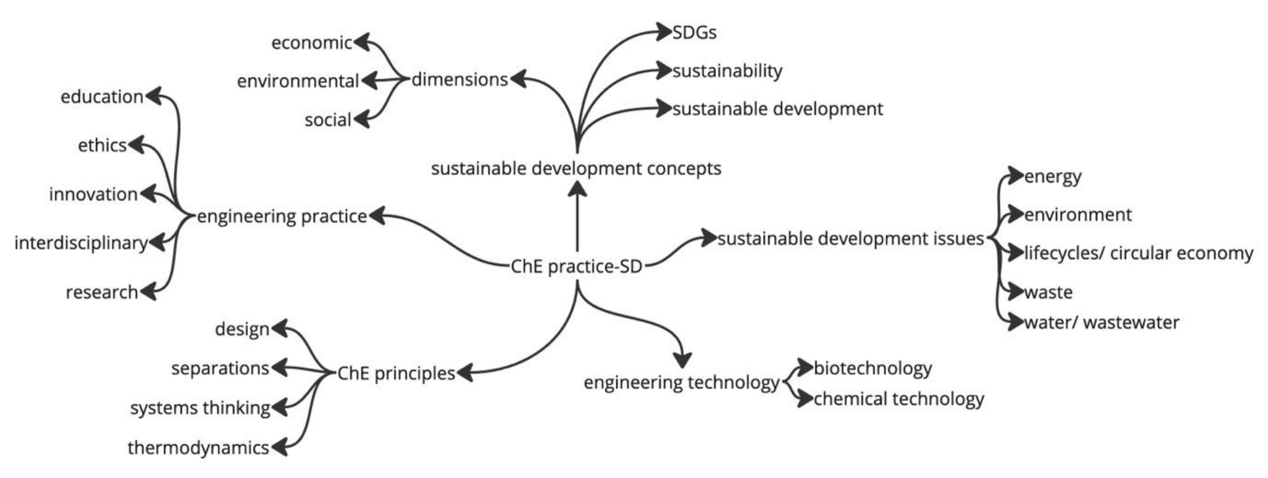

Figure 5: Mind map of categories from qualitative content analysis

The qualitative analysis of the keywords also begins to answer the research question. The categories present in Figure 5 demonstrate that chemical engineering's contributions to sustainable development are focused on specific topics (e.g., energy), require the application of chemical engineering principles (e.g., separations), and require the application of professional practice (e.g., ethics). Detailed analysis of these contributions requires coding and thematic analysis of the sources in the review. This analysis is part of the Scoping Review, but outside the scope of this paper.

Implementation

This primary purpose of this project is to inform future research around what discipline-specific sustainable development knowledge, skills and competencies should be integrated into chemical engineering curricula. But several takeaways from this preliminary research can be implemented in current chemical engineering education. Firstly, the list of sustainable development issues presented in Figure 5, and the SDGs in Table 1 can inspire project-based learning and capstone subjects. Secondly, the size and complexity of the network reminds students of the need for collaboration in their engineering practice: no single engineer can work on the entire network.

Table 1: Comparison of United Nations' Sustainable Development Goals and categories from qualitative content analysis

SDGs	Relevant Keywords from Figure 3
SDG 3 (Good Health and Wellbeing)	Water/ Wastewater
SDG 4 (Education)	Education
SDG 6 (Clean Water and Sanitation)	Water/ Wastewater
SDG 7 (Clean Energy)	Energy
SDG 9 (Innovation)	Waste, Chemical Technology, Biotechnology
SDG 12 (Responsible Consumption and Production)	Chemical Technology, Biotechnology
SDG 13 (Climate Change)	Environment
SDG 14 (Life Below Water)	Environment
SDG 15 (Life on Land)	Environment
SDG 17 (Partnerships)	Interdisciplinarity

Limitations

As a literature review, this research is inherently limited by the data available via black and grey literature. A substantial amount of engineering practice solving sustainable development challenges is not published and is thus missing from the review. Cataloguing this unpublished work is important but outside the scope of this study. The published chemical engineering practice, as opposed to chemical engineering science, is often published in grey rather than black literature. A Scoping Review, compared to a Systematic Review was chosen so this grey literature could be included and thus overcome some limitations inherent in a systematic review.

Concluding Remarks

This paper presents the keyword analysis for a Scoping Review to articulate the relationship between sustainable development and chemical engineering practice. This is the first Scoping Review of chemical engineering practice and sustainable development, and synthesises published data across the discipline and sub-disciplines of chemical engineering. The keyword networks and analysis presented in this study begin to demonstrate the interaction between sustainable development and chemical engineering practice. The breadth and complexity of the KCNs signify that chemical engineering is doing substantial work in the sustainable development space. The most notable topics in the literature are circularity, energy, the environment, waste and water/ wastewater. These topics provide engineering educators with the opportunity to begin including sustainable development in chemical engineering education.

The next stage of this study is to complete the data charting and analysis, including detailed coding and thematic analysis. With this data, we will aim to fully articulate the relationship between chemical engineering practice and sustainable development. By understanding this relationship, we, as engineering educators, can more meaningfully and effectively teach sustainable development. This will help develop chemical engineering graduates who can solve sustainable development challenges in their engineering careers and contribute to a sustainable society.

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