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Social Sustainability in Chemical Engineering: Concepts, Methodologies, Challenges, and Integration Strategies

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ABSTRACT

Chemical engineering faces an increasing imperative to integrate sustainability principles beyond traditional economic and environmental considerations. The social dimension—encompassing impacts on human well-being, equity, community health, labor practices, and ethical governance—represents a critical yet often underdeveloped pillar within the field. To tackle this research gap, this study employs a systematic literature review. Its unique contribution is the synthesis of a fragmented, multidisciplinary body of literature into a coherent conceptual framework specifically for chemical engineering. Social sustainability is conceptualized, examining its key elements and its place within the broader triple bottom line framework, while critically analyzing the inherent complexities and frequent hierarchy observed among the triple bottom line pillars, particularly, the dominance of economic drivers. The review narrows its focus to three critical themes: the persistent challenges in conceptualizing social sustainability for engineering contexts; a critical evaluation of assessment methodologies, particularly qualitative and stakeholder-based approaches; and actionable strategies for integrating these concepts into chemical engineering practice and education. Strategies for advancing social sustainability are explored, including robust stakeholder engagement, integration into corporate policy and project management, supply chain responsibility, green engineering principles, industrial symbiosis, responsible innovation, and educational reform. The evolving role and ethical responsibilities of chemical engineers as agents of social change are emphasized.

1 | Introduction

Chemical engineering stands as a cornerstone of modern civilization, providing the essential processes and technologies that transform raw materials into the vast array of products underpinning energy, materials, food, agriculture, transportation, healthcare, and countless other sectors vital to contemporary life (Chang et al. 2021; Stahl et al. 2019). The discipline's ability to manipulate matter and energy at various scales has driven unprecedented industrial progress and improvements in living standards globally. However, this transformative power is inextricably linked with significant responsibilities. The chemical and process industries are major consumers of global energy and material resources, often relying heavily on finite fossil fuels, and are substantial contributors to emissions, waste streams, and the generation of potentially hazardous substances (Arastoopour 2019; Chang et al. 2021; Iles and Mulvihill 2012). These activities inevitably exert profound impacts, not only on the natural environment but also critically on human health, occupational safety, community well-being, labor practices, resource access, social equity, and the overall fabric of society (Das and Cabezas 2018; Vallance et al. 2011).

In response to the escalating global challenges associated with industrial activity, population growth, resource depletion, climate change, environmental degradation, and persistent social inequalities, the concept of sustainable development has emerged as the defining paradigm for the 21st century (Valsaraj 2013). Famously articulated by the World Commission on Environment and Development in their report "Our Common Future," sustainable development aims to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (Bond et al. 2012). This definition intrinsically demands a balanced consideration of economic, environmental, and social objectives (Clift 2006). The operationalization of this concept is frequently captured by the "Triple Bottom Line" (TBL) framework, advocating for the simultaneous pursuit of economic viability ("profit"), environmental protection or integrity ("planet"), and social equity ("people") (Azapagic and Perdan 2005; García-Serna et al. 2007; Sikdar 2003).

Within chemical engineering, the journey toward sustainability has seen notable advancements, particularly concerning the economic and environmental pillars. Driven by regulatory pressures (García-Serna et al. 2007), opportunities for cost reduction through efficiency gains, and a growing societal awareness of environmental degradation, the field has increasingly embraced concepts such as green chemistry, green engineering, cleaner production, industrial ecology, process intensification, and pollution prevention (Allen and Shonnard 2001; Jin et al. 2004). Chemical engineers are routinely tasked with optimizing resource utilization (water, energy, materials), minimizing waste generation and emissions, developing processes based on renewable feedstocks and energy sources, designing inherently safer operations, and improving overall process efficiency. Indeed, the capacity to develop environmentally superior technologies that are simultaneously economically advantageous is often presented as the primary pathway for chemical engineering contributions to sustainable development (Sikdar 2003).

However, the third pillar—social sustainability—has historically received less attention and rigorous analysis within the chemical engineering field, presenting persistent and unique challenges for the discipline (Mitchell 2000). While its importance is increasingly acknowledged as integral to the holistic vision of sustainable (Azapagic and Perdan 2005; García-Serna et al. 2007), its practical integration into the core functions of chemical engineering design, assessment, operation, and education remains significantly less mature and often peripheral (Azapagic and Perdan 2005; García-Serna et al. 2007; Popovic and Kraslawski 2015; Van Schoubroeck et al. 2018). The definition of social sustainability itself is complex, multifaceted, context-dependent, and lacks a single, universally accepted conceptualization (Littig and Grießler 2005; Vallance et al. 2011), making it difficult to translate into the quantitative, standardized metrics typically favored in engineering disciplines (Kloepffer 2008). Research and practical observation suggest that a "clear hierarchy" often prevails in sustainability assessments, particularly within the chemical sector, where economic and environmental considerations frequently overshadow social aspects (Van Schoubroeck et al. 2018). Furthermore, the sustainability challenges encountered by engineers are often characterized more profoundly by their social complexity than their technical difficulty, demanding approaches that transcend traditional engineering methodologies (Azapagic and Perdan 2014). Issues involving stakeholder values, community acceptance, ethical dilemmas, equitable distribution of risks and benefits, and fair labor practices in global supply chains (Bullard 2018; Cole and Foster 2001; Locke 2013; Lopes de Sousa Jabbour et al. 2024) require interdisciplinary perspectives and engagement beyond the typical scope of chemical engineering training.

A central barrier to the integration of social sustainability into routine engineering practice is the fundamental challenge of measurement and quantification. Unlike environmental impacts, such as emissions, which are often "much more easily standardized and quantified," social and socioeconomic concerns present a far greater complexity (UNEP/SETAC 2009). Key questions remain on how to "assess and measure the social effects" of a product or process and how to "assign a result or a number" to qualitative issues such as working conditions or community impacts. This difficulty arises because social impacts are often captured through qualitative data, which is frequently subjective and requires interpretation by capable experts. For example, numeric data on wages may not fully capture social impact, as compliance with minimum wage laws does not always mean the wage is livable.

However, the abstract principles of social sustainability translate into concrete and increasingly urgent challenges with direct implications for chemical engineering practice. The choices made in process and product design, for instance, are not socially neutral. A clear example is the development of biofuels, an engineering solution to the environmental challenge of climate change that has, in turn, raised significant social concerns about land-use change and food security (Azapagic and Perdan 2014). To address this challenge, frameworks such as Social Life Cycle Assessment (S-LCA) have been developed, aligning with the ISO 14040 and 14044 standards for Life Cycle Assessment (Jørgensen et al. 2008). However, even the foundational guidelines for S-LCA acknowledge that the methodology is not yet mature. They describe the technique as a "skeleton" that provides a basic structure but needs to be fleshed out with further research and development (UNEP/SETAC 2009). The guidelines explicitly state that impact assessment methodologies are still under development, making S-LCA an open field for future research. The scarcity of comprehensive social databases, the lack of standardized data quality requirements, and the difficulty in aggregating disparate social indicators into a coherent assessment remain significant hurdles. This methodological immaturity and lack of standardized quantification make it difficult for engineers, who are trained in quantitative analysis, to incorporate social criteria into their design, optimization, and decision-making processes.

Also, the implementation of engineering projects now increasingly depends on a "Social License to Operate," which is granted not by regulators alone, but by the communities and stakeholders affected by a project (Vanclay et al. 2015). This shifts the engineer's working environment into the realm of "postnormal science," where high stakes and systemic uncertainty demand inclusive deliberation with an "extended peer community" that includes the lay public (Clift 2006).

Consequently, the role of the engineer is expanding beyond that of a purely technical problem-solver to that of a normative agent of social and technological change, who must help frame societal problems, not just devise solutions (Clift 2006; Narodoslawsky 2013).

This new operational reality for engineering practice creates an unavoidable imperative for a paradigm shift in engineering education. Traditional curricula focusing primarily on technical and economic optimization are no longer sufficient to prepare graduates for these complex sociotechnical challenges (Harris et al. 2019). Integrating sustainability cannot be a superficial "add-on" but requires its incorporation as a core principle woven throughout the curriculum (Batterham 2006). This means teaching not only the technical fundamentals but also systems thinking and life cycle methodologies to equip students to analyze and manage trade-offs across the economic, environmental, and social pillars (Azapagic and Perdan 2014; Narodoslawsky 2013). Educational programs must cultivate new competencies in interdisciplinary collaboration, stakeholder engagement, and ethical reasoning, preparing engineers to work effectively with social scientists and the public to navigate value-laden 'wicked' problems (Azapagic and Perdan 2014; Mehlich et al. 2024). Ultimately, the goal is to foster a professional "state of mind" (Jin et al. 2004) that embraces a broader sense of social responsibility and prepares chemical engineers to contribute constructively to a more equitable and sustainable society (Mehlich et al. 2024).

The literature describes social sustainability as a "messy conceptual field" (Vallance et al. 2011) and notes a scarcity of research covering this dimension in engineering projects, often due to the qualitative nature and difficulty of evaluating social indicators (Miret et al. 2016; Schöggl et al. 2017; Van Schoubroeck et al. 2018). This systematic literature review (SLR) advances beyond existing work by providing the first comprehensive synthesis aimed at structuring this fragmented knowledge specifically for the chemical engineering discipline. Unlike general reviews on sustainability, this study addresses the distinct need for a conceptual framework that translates abstract social principles into the actionable language of chemical engineering practice and education (Harris et al. 2019). The novelty of this research lies in addressing specific research questions that bridge the gap between social science concepts and engineering application:

"What is the current state of conceptualizing social sustainability within, and for, the chemical engineering context, moving beyond the general triple bottom line?"

"What are the primary methodologies and assessment tools available for social sustainability, and what are their specific limitations and opportunities when applied to chemical engineering systems?"

"How can social sustainability principles be effectively integrated into core chemical engineering practices such as process design, product development, and sustainable supply chain management."

"What is the role of education in fostering social sustainability, and what pedagogical strategies and curricular changes are needed to prepare future chemical engineers for these challenges?"

By systematically answering these questions, this review moves beyond generic discussions to provide a targeted, discipline-specific synthesis. It aims to illuminate critical knowledge gaps and propose concrete pathways for embedding social equity, justice, and community well-being more deeply into the theory and practice of responsible chemical engineering (Harris et al. 2019).

2 | Materials and Methods

Guided by a pragmatist research philosophy, this study prioritizes the research problem and the real-world impact of the knowledge generated. It values research methods that effectively answer the research questions (Saunders et al. 2009). This pragmatist philosophy directly informs the selection of an SLR as the core methodology because it represents the most effective and workable approach to address the research questions posed. Being often described as a "messy conceptual field" or a "concept in chaos," characterized by a fragmented, multidisciplinary body of literature (Vallance et al. 2011), social sustainability constitutes a "wicked" problem that cannot be neatly resolved within a single, reductionist scientific paradigm (Azapagic and Perdan 2014; Van Steen 2012). A pragmatist approach, therefore, values a methodology that can systematically collate, analyze, and synthesize heterogeneous sources to build a coherent and actionable understanding. An SLR provides the necessary structure for this task (Neri et al. 2025). Furthermore, given that the corpus of documents includes a mix of qualitative and quantitative data, a statistical meta-analysis would be infeasible (Eizenberg and Jabareen 2017). Consequently, the choice of thematic analysis and narrative synthesis is a pragmatic one. Thematic analysis is a practical tool for identifying recurring concepts and patterns across diverse sources (Thakuri et al. 2025), while narrative synthesis provides a structured method to integrate these themes into a cohesive conceptual framework that directly answers the research questions (Seuring and Müller 2008). This research design is therefore not intended to test a discrete hypothesis but to pragmatically build an integrated framework from a complex and varied knowledge base, prioritizing the usefulness and relevance of the findings for engineering practice and education.

The SLR followed the three-step approach advocated by Tranfield et al. (2003): (1) planning, (2) conducting, and (3) reporting the review.

2.1 | Planning the Review and Database Search

The article selection process, shown in Figure 1, followed the PRISMA guidelines (Moher et al. 2009). It involved identifying relevant publications from the Scopus, OpenAlex and ScienceDirect databases. A systematic search using Boolean combinations of the keywords "social sustainability" and "chemical engineering" was conducted. The search, conducted in January 2025 focused on English language publications, emphasizing the most recent 5 years and foundational papers. Included were peer-reviewed journal articles, relevant

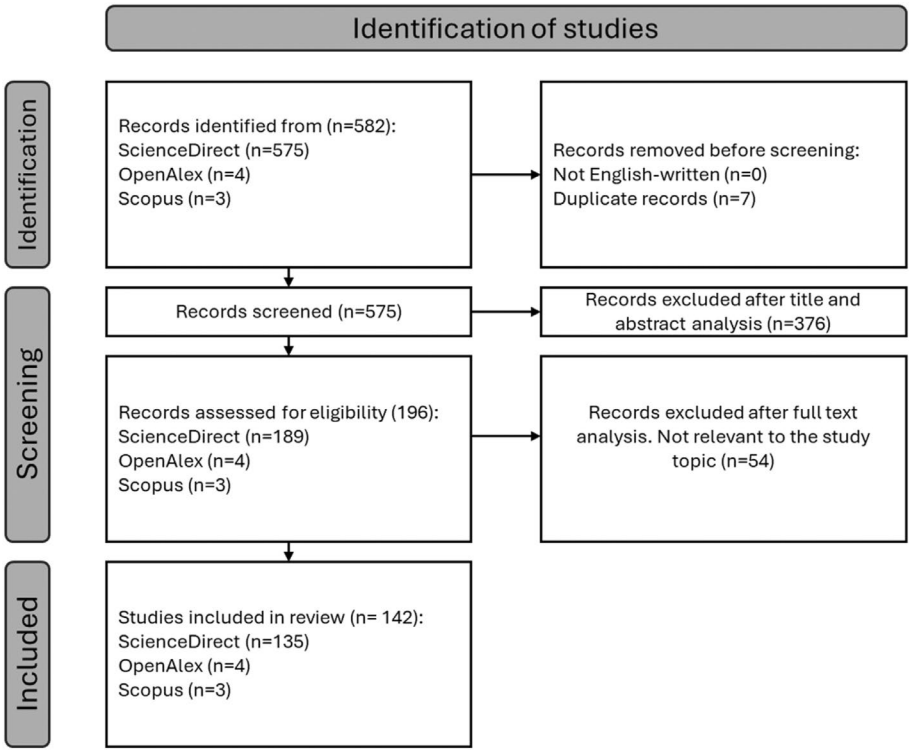

FIGURE 1 | Flow diagram for the selection of documents based on PRISMA.

conference papers, book chapters, and key reports. Excluded were non-English articles, and publications lacking full-text access.

2.2 | Conducting the Review

During the screening phase, 196 articles were selected and analyzed to assess the quality of the sources and the relevance to the research topic. The distribution by source of the resulting 142 documents is shown in Table 1.

As shown in Table 1, leading journals in the field, such as *Journal of Cleaner Production*, *Chemical Engineering Science, Sustainability (Switzerland)*, and *International Journal of Life Cycle Assessment* have shown a relevant interest in this subject.

Figure 2 shows that conceptualizing and integrating social sustainability in chemical engineering are the most represented themes in the document corpus, followed by methodologies and assessment tools, and lastly, by the role of education. This distribution suggests a logical progression in how the field of chemical engineering is addressing social sustainability: the primary focus has been on defining the problem and finding practical applications. The strong emphasis on integration reflects the urgent need to translate these abstract principles into the day-to-day practices of chemical engineers, which is identified as a core challenge. Once the concepts are broadly defined, the next logical step is to develop tools to measure and assess them. However, the lower number of documents compared to conceptualization and integration reflects the acknowledged immaturity of these tools (discussed in the next sections). The evidence presented in Figure 2 also suggests that educational reform can be seen as a subsequent step that logically follows the establishment of concepts, practices, and assessment tools.

TABLE 1 | Papers' distribution by source.

Journal	No of papers for final analysis
Journal of Cleaner Production	14
Chemical Engineering Science	4
Sustainability (Switzerland)	4
International Journal of Life Cycle Assessment	4
Environmental Science and Technology	3
AIChE Journal	3
Industrial and Engineering Chemistry Research	3
Current Opinion in Green and Sustainable Chemistry	2
Chemical Engineering Research and Design	2
Chemical Engineering Transactions	2
R&D Management	2
Computers and Chemical Engineering	2
Other	97
Total	142

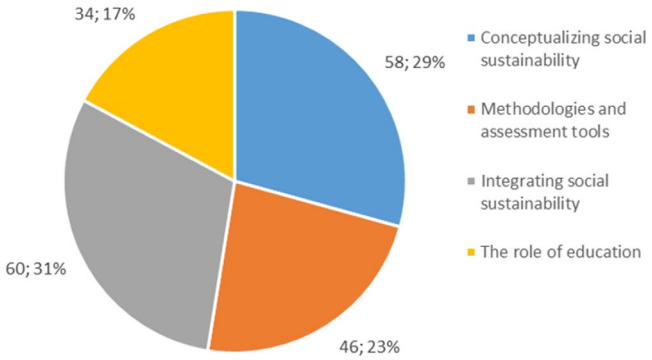

FIGURE 2 | Proportion of documents per theme.

2.3 | Reporting and Disseminating the Review

In our analysis of the data, we used a combined technique of inductive and deductive thematic analysis (Braun and Clarke 2012; Fereday and Muir-Cochrane 2006). In addition to an inductive approach, we employed a template in the form of codes from a codebook, based on the research questions and a preliminary review of the foundational papers, to organize the text for subsequent interpretation. The following key themes formed the basis of the template: conceptualizing social sustainability in chemical engineering; methodologies and assessment tools for social sustainability; integrating social sustainability into chemical engineering practice; and the role of education in fostering social sustainability. The overall process was composed of the following stages: developing the code manual (Stage 1); testing the reliability of codes by coding test documents by different researchers to ensure reliability (Stage 2); summarizing data and identifying initial themes (Stage 3); applying the template of codes and additional inductive coding of segments of data that described a new theme (Stage 4); connecting the codes and identifying themes (Stage 5); and corroborating and legitimating coded themes, to ensure that the clustered themes were representative of the initial data analysis and assigned codes (Stage 6). Although presented as a linear, step-by-step procedure, the research analysis was an iterative and reflexive process implemented using the ATLAS.ti software. Extracted data were then narratively synthesized for each theme (Thorley et al. 2019). This process generated an analytical description of the current knowledge on social sustainability in chemical engineering, identifying patterns and gaps in the literature. The synthesis focused on triangulating information across multiple sources where possible and noting differing perspectives or specific details related to each of the above-mentioned themes. Consistent with SLR practices, the focus remained on content addressing the core research questions within the specified research context.

3 | Conceptualizing Social Sustainability in Chemical Engineering

While the TBL provides a foundational framework (Azapagic and Perdan 2005; García-Serna et al. 2007; Sikdar 2003), translating the broad concept of social sustainability into specific, actionable terms relevant to chemical engineering practice is a significant challenge (García-Serna et al. 2007). Unlike

FIGURE 3 | Core principles and dimensions of social sustainability particularly pertinent to chemical engineering.

environmental impacts (e.g., greenhouse gas emissions measured in CO_2 equivalents, water consumption in cubic meters) or economic performance (e.g., profit margins, return on investment), social aspects are often characterized by their qualitative nature, context-dependency, intangibility, and resistance to quantification using universally accepted, standardized metrics (Azapagic and Perdan 2014; Kloepffer 2008; Popovic and Kraslawski 2015). Definitions vary across disciplines, but common themes revolve around social equity, justice, well-being, community cohesion, and the capacity of social systems to function effectively over the long term, ensuring that both present and future generations can thrive (Colantonio 2011; Dempsey et al. 2011; Eizenberg and Jabareen 2017).

The Global Reporting Initiative (GRI), widely used for corporate sustainability reporting, defines the social dimension in terms of an organization's impacts on the social systems within which it operates, encompassing issues such as labor practices, human rights, society, and product responsibility (Global Reporting Initiative 2011). For chemical engineering, translating these broad concepts into actionable principles requires careful consideration of the specific interfaces between chemical processes, products, industries, and the societies they affect.

Based on the synthesis of the literature (detailed next), the core principles and dimensions of social sustainability, particularly pertinent to chemical engineering, can be articulated as illustrated in Figure 3. Understanding these interconnected dimensions provides a necessary foundation for chemical engineers to systematically identify, assess, and integrate social sustainability considerations into their professional activities. It shifts the focus from purely technical problem-solving to a sociotechnical systems perspective, acknowledging the profound ways engineering shapes, and is shaped by, society. As noted by Azapagic and Perdan (2014), the social complexity often inherent in

sustainability problems presents a greater challenge for engineers than the technical aspects, underscoring the need for a broader skillset and perspective.

Figure 3 is grounded in a comprehensive review of a multidisciplinary literature corpus, aiming to bring structure to what has been described as a "concept in chaos" or a "messy conceptual field" (Vallance et al. 2011). The dimensions are aligned with the foundational principles of sustainable development outlined in reports such as the Brundtland Report, which emphasizes meeting human needs and ensuring equity (Aarseth et al. 2017; Vallance et al. 2011). More specifically, the framework draws on established methodologies such as S-LCA, whose impact subcategories are explicitly defined based on international agreements, treaties, corporate social responsibility (CSR) initiatives, and foundational stakeholder theory (Reed 2008; UNEP/SETAC 2009; Vallance et al. 2011; Van Hattum-Janssen et al. 2012). For example, the Health and Well-being and Labor Practices dimension corresponds directly to the stakeholder categories (e.g., Workers, Local Community, Society) and impact subcategories (e.g., Health and Safety, Working Conditions) that form the basis of the internationally recognized UNEP/SETAC S-LCA Guidelines (Miret et al. 2016; UNEP/SETAC 2009).

The fundamental principle of equity and social justice demands the fair distribution of resources, opportunities, benefits, and burdens across all societal groups, irrespective of race, ethnicity, gender, socioeconomic status, age, or geographical location (Rawls 2005). In chemical engineering, this translates to ensuring that the positive impacts of chemical industries (e.g., job creation, essential products) are shared equitably, while the negative impacts (e.g., pollution, health risks, displacement) do not disproportionately fall on vulnerable or marginalized populations (Bullard 2018). It involves actively challenging and addressing systemic inequalities and power imbalances that perpetuate social exclusion and environmental injustice (Cole and Foster 2001; Valizadeh et al. 2024).

Health, safety, and well-being encompass protecting and promoting the physical, mental, and social health of all individuals affected by chemical engineering activities. This includes stringent occupational health and safety protocols to protect workers from hazardous materials, accidents, and harmful working conditions (Li et al. 2011; OSHA 2016). It also extends to safeguarding the health and well-being of communities adjacent to chemical facilities by minimizing pollution (air, water, noise), preventing catastrophic incidents, and ensuring the safety of chemical products for consumers throughout their lifecycle (West et al. 2016). The proactive reduction of chemical hazards through green chemistry and engineering directly contributes to this dimension (Anastas and Zimmerman 2007). Promoting overall well-being also involves considering access to essential services such as healthcare and clean living conditions, which can be impacted by industrial activities (Putnam 2000).

Community engagement and empowerment emphasize the importance of fostering meaningful, two-way communication and collaboration with local communities and other stakeholders affected by chemical engineering projects or operations (Apel et al. 2024; Waddock 2008). It involves transparently sharing information, actively listening to concerns, valuing local knowledge, and ensuring communities have a genuine voice in decision-making processes that impact their lives (Azapagic and Perdan 2014; Matthies et al. 2024; Vanclay et al. 2015). Empowerment enables communities to participate actively in shaping their own development and holding industries accountable (Demuijnck and Fasterling 2016).

Respect for human rights and fair labor practices requires respecting and upholding the fundamental human rights of all individuals throughout the value chain, as outlined in international declarations (United Nations 1948). This includes the right to a safe working environment, freedom of association and collective bargaining, nondiscrimination, the elimination of forced and child labor, and fair wages and working hours (Pérez-López et al. 2025). Chemical engineers and companies have a responsibility to ensure these rights are respected not only within their direct operations but also within their global supply chains (Locke 2013; Lopes de Sousa Jabbour et al. 2024).

Chemical engineering plays a vital role in producing goods and services fundamental to human well-being, such as clean water, sanitation, affordable energy, pharmaceuticals, fertilizers, and materials (Hussam and Munir 2007; Pipil et al. 2024). Social sustainability demands consideration of equitable access to these essential products and services, particularly, for underserved populations, ensuring that technological advancements contribute to meeting basic human needs globally (Cornel and Schaum 2009; Echeverry et al. 2024).

Social cohesion and cultural preservation involve recognizing and respecting the social fabric and cultural heritage of communities affected by chemical industry activities. Projects should aim to minimize social disruption, avoid forced displacement where possible, support local economies and traditions, and foster a sense of community identity and solidarity rather than division (Putnam 2000; Vallance et al. 2011).

Consistent with the original Brundtland definition, intergenerational equity requires considering the long-term consequences of current actions and ensuring that the pursuit of present benefits does not compromise the ability of future generations to meet their own social, environmental, and economic needs (WCED 1987). This involves responsible resource management, preventing long-term environmental damage with social repercussions, and investing in education and infrastructure for the future.

Underlying all these dimensions is the need for strong ethical governance and conduct. This involves adherence to professional codes of ethics, transparency in operations and decision-making, accountability for impacts, and a commitment to responsible innovation that anticipates and mitigates potential negative social consequences (Iordache 2024; Martens and Carvalho 2016; Owen et al. 2012).

Translating these dimensions into measurable indicators involves using a combination of quantitative, semi-quantitative, and qualitative data, reflecting the reality that not all social impacts can be easily captured by numbers (Miret et al. 2016). Quantitative indicators are the most directly applicable in engineering models. A key example is job creation, which can be

quantitatively measured as the total number of direct, indirect, and induced jobs created by a project or supply chain (Miret et al. 2016). Another critical quantitative metric is related to health and safety. For instance, the Fire and Explosion Index, widely used in the chemical industry, can serve as a measurable indicator for social sustainability by quantifying process hazards that impact workers and the surrounding community (Isella and Manca 2025). Other metrics include tracking the number of accidents or lost workdays (Miret et al. 2016). Semiquantitative indicators are often based on scoring systems or checklists. For example, a company's performance on "fair salary" can be rated on a scale based on compliance with living wage benchmarks versus minimum wage laws (UNEP/SETAC 2009). Such scoring can also be applied to assess compliance with labor rights based on international standards (Kloepffer 2008). These indicators are particularly useful in the early design phases of a project, where detailed quantitative data may be unavailable (Schöggl et al. 2017). Many crucial social aspects, such as "community engagement" or "social acceptance" are best captured through qualitative data gathered via surveys, interviews, and participatory stakeholder workshops (Gehlot and Shrivastava 2024; Neves et al. 2020; Reed 2008; Vanclay et al. 2015). While not easily integrated into optimization models, this information is vital for a holistic assessment and for securing a "social license to operate." By adopting a structured approach and utilizing a mix of quantitative, semiquantitative, and qualitative indicators, chemical engineering can move beyond purely descriptive principles toward a more rigorous and actionable integration of social sustainability, detailed next.

4 | Methodologies and Assessment Tools for Social Sustainability

To effectively integrate social sustainability into decision-making, chemical engineers need robust methodologies and tools to identify, measure, and evaluate the social impacts of their projects, processes, and products. While assessment remains challenging due to the qualitative and context-specific nature of many social factors (Branch et al. 2019), several approaches have emerged, though their application in chemical engineering requires careful consideration of inherent limitations.

Analogous to the more established environmental impact assessment (EIA), social impact assessment (SIA) is a process for identifying, predicting, evaluating, and mitigating the potential social consequences of planned interventions (e.g., new chemical plants, major process modifications, infrastructure projects) before decisions are made (Silva et al. 2022; Vanclay 2002; Vanclay et al. 2015). SIA typically involves: (a) defining the project's area of influence, identifying affected stakeholders, and determining key social issues (e.g., health, employment, culture, community cohesion); (b) gathering information on existing social conditions; (c) analyzing potential positive and negative social changes; (d) assessing the significance of predicted impacts; (e) developing measures to manage impacts, often through stakeholder consultation; and (f) tracking actual impacts and adapting strategies. Integrating SIA rigorously into the project planning cycle is a key strategy for proactive social risk management and benefit enhancement (Aarseth et al. 2017). While often mandated for large projects, its deeper integration into the chemical engineering design process itself holds significant potential for anticipating and mitigating social risks early on.

S-LCA aims to extend the life cycle thinking paradigm, well-established in environmental LCA, to the social domain, assessing impacts across the entire value chain from raw material extraction to end-of-life (Margni and Curran 2012; Tokede and Traverso 2020). The UNEP/SETAC Guidelines provide a framework (Ramos 2024). S-LCA methodologies typically define stakeholder categories (workers, local communities, consumers, society, value chain actors) and impact subcategories within each (e.g., occupational health and safety, fair wages, child labor, human rights, community health, consumer safety, corruption) (Ramos 2024). Similar to Environmental LCA (E-LCA), it involves goal and scope definition, life cycle inventory data collection (quantitative and qualitative), life cycle impact assessment, and interpretation. For example, Pérez-López et al. (2025) explored using life cycle costing (LCC) outcomes to inform screening S-LCAs. S-LCA methodological development is ongoing, particularly regarding impact pathway definition, indicator selection/weighting, data availability and quality (especially for global supply chains), and interpreting results. Relating diverse social indicators (often qualitative) to the functional unit is a particular challenge (Kloepffer 2008). Despite limitations, S-LCA offers a valuable framework for mapping potential social hotspots across a value chain.

Recognizing the interconnectedness of the TBL pillars, Life Cycle Sustainability Assessment (LCSA) aims to integrate E-LCA, S-LCA, and LCC into a single, comprehensive framework (Guinée et al. 2011; Kloepffer 2008). The goal is to provide a holistic view of trade-offs and synergies. However, integrating these distinct assessments with their different metrics and maturity levels remains a major research challenge (Chang et al. 2021). Multiobjective optimization techniques are being explored to handle these trade-offs explicitly in process design (Isella and Manca 2025).

Social return on investment (SROI) is an outcomes-based framework that attempts to quantify the social, environmental, and economic value created relative to the investment cost (Guinée et al. 2011; Nicholls et al. 2012). It assigns monetary values (using financial proxies) to social/environmental outcomes to calculate a value-to-investment ratio. The process involves scoping, mapping outcomes via stakeholder engagement, evidencing and valuing outcomes, establishing impact (accounting for deadweight, etc.), calculating the ratio, and reporting. While complex and potentially controversial due to monetization, SROI can demonstrate broader societal contributions beyond financial metrics. Similar principles are seen in social cost–benefit evaluations (Alao and Popoola 2025; Fatima et al. 2024).

While these assessment methodologies provide valuable frameworks, their applicability and limitations for chemical engineering practice are highly context-dependent. The choice of tool is contingent on the specific engineering task, whether it is a site-specific project, a product's life cycle design, or a strategic investment decision. The core challenge for the discipline remains the integration of often qualitative and context-specific social data into the quantitative, model-driven decision-making typical of engineering. A critical comparison reveals distinct scopes and

levels of maturity. SIA is a project-level, site-specific tool primarily applicable to chemical engineers involved in the planning, construction, and operation of facilities such as new chemical plants or biorefineries (Stadler 2020). Its main strength lies in managing local community impacts—such as health, employment, and cultural heritage—and is often essential for securing a "social license to operate" (Asada et al. 2020; Vanclay et al. 2015). However, its limitation for a chemical engineering context is its narrow scope; it focuses on the impacts of a facility, not the full life cycle of the products manufactured within it. In contrast, S-LCA is a product- and process-level tool that is conceptually well-aligned with the "cradle-to-grave" systems thinking fundamental to chemical engineering (UNEP/SETAC 2009). It is the most appropriate framework for engineers engaged in process design and product development, as it aims to identify and mitigate social risks across complex global supply chains, thereby avoiding the unintentional shifting of burdens (Clift 2006). However, its practical application in engineering is severely constrained by significant limitations: the foundational UNEP/SETAC guidelines describe S-LCA as a "skeleton" that is not yet mature and requires substantial future research, particularly in the life cycle impact assessment phase; S-LCA relies heavily on qualitative, subjective, and context-dependent data, which is difficult to integrate into the quantitative optimization models and process simulations that engineers typically use (Miret et al. 2016). Data collection is often expensive, and comprehensive databases for social impacts are scarce; relating diverse social indicators (e.g., child labor, community engagement) to a technical functional unit (e.g., 1 kg of product) remains a central problem, hindering direct comparison and trade-off analysis in process design (Kloepffer 2008). While LCSA aligns with the ultimate goal of sustainable chemical engineering, its applicability is largely limited to academic research and high-level strategic assessments. For routine engineering practice, it is currently impractical as it inherits all the methodological and data limitations of S-LCA while adding the complexity of integrating three distinct assessment types (Arastoopour 2019; Bakshi 2019; Isella and Manca 2025; Sharno and Hiloidhari 2024). SROI, on the other hand, is a valuable tool for project justification and strategic communication. By monetizing social outcomes, it creates a compelling narrative for engineering managers seeking investment in projects with social benefits (Nicholls et al. 2012). Its main limitation for chemical engineers is its reduced utility in technical design and optimization, where the subjectivity of financial proxies for non-market goods is less useful than physical or process-based metrics (Nicholls et al. 2012). The overarching limitation across these tools is the challenge of bridging the gap between qualitative social science data and the quantitative, model-centric world of chemical engineering. In summary, for chemical engineers: SIA is the most practical and often mandatory tool for new facility projects; S-LCA provides the essential conceptual framework for sustainable product and process design, though its current implementation is best suited for qualitative hotspot analysis rather than quantitative optimization; SROI is most useful for making the business case for sustainable projects to management and investors; and LCSA remains an aspirational but largely impractical goal for routine design.

Using Key Performance Indicators (KPIs) is essential for tracking social sustainability progress (Azapagic and Perdan 2014). Indicators should cover relevant dimensions (e.g., safety rates, community health, local employment, supplier diversity, stakeholder satisfaction). Organizations such as GRI provide standardized reporting frameworks (Global Reporting Initiative 2011), enhancing transparency. Sector-specific initiatives such as the AIChE Sustainability Index and the IChemE sustainability metrics (which have a separate section on metrics for social sustainability) also exist (Dimian et al. 2014; Sikdar 2003). Selecting relevant, robust social indicators remains crucial (Batterham 2006). Company-specific methods such as BASF's Eco-Efficiency Analysis also aim to integrate multiple dimensions (Saling et al. 2002).

Given the limitations of quantitative methods, direct engagement with stakeholders (employees, communities, customers, NGOs) is vital not just as a principle but as an assessment method (Azapagic and Perdan 2014; Elias et al. 2002; Reed 2008). Surveys, interviews, focus groups, and workshops provide invaluable qualitative data on perceived impacts, concerns, and priorities that metrics alone cannot capture (Iles and Mulvihill 2012; Matthies et al. 2024). Significant challenges persist across these methodologies: (a) reliable social data, especially local or deep supply chain data, is often scarce (Branch et al. 2019; Pérez-López et al. 2025); (b) assigning numerical or monetary values to qualitative aspects is complex and potentially ethically problematic (Kloepffer 2008; Pérez-López et al. 2025); (c) establishing clear causal links and defining appropriate system boundaries is difficult; (d) social impacts are highly context-dependent, hindering standardization; and (e) assessments can be influenced by assessor and stakeholder values. Addressing these requires ongoing methodological development, data transparency efforts, interdisciplinary collaboration (especially with social scientists), and acceptance of qualitative assessment's vital role.

While the limitations of data scarcity, quantification, and subjectivity are persistent, the reviewed literature also highlights several practical and forward-looking strategies for addressing these challenges. Rather than being paralyzed by them, practitioners are developing pragmatic approaches to make social sustainability assessment more manageable and meaningful. To overcome the significant challenge of data scarcity, the literature suggest a multi-pronged approach that moves beyond reliance on non-existent databases (UNEP/SETAC 2009). A key strategy is to conduct a "hotspot assessment" as a preliminary step. This involves a desktop screening that uses readily available information from web searches, literature surveys, and interviews with NGOs or unions to identify which unit processes or supply chain stages are most likely to present social risks (e.g., child labor, poor working conditions). This pragmatic approach allows practitioners to prioritize and focus more resource-intensive, on-site data collection efforts where they are most needed. For areas identified as hotspots, the literature advocates for direct, on-the-spot data collection, acknowledging that comprehensive databases are often minimal. Recommended methods include social audits, directed and semi-directed interviews, focus groups, and surveys with relevant stakeholders. To improve data quality and overcome bias in reporting (e.g., a company is unlikely to report child labor), a strategy of data triangulation is proposed. This involves using and comparing information from multiple sources. For example, practitioners can complement their

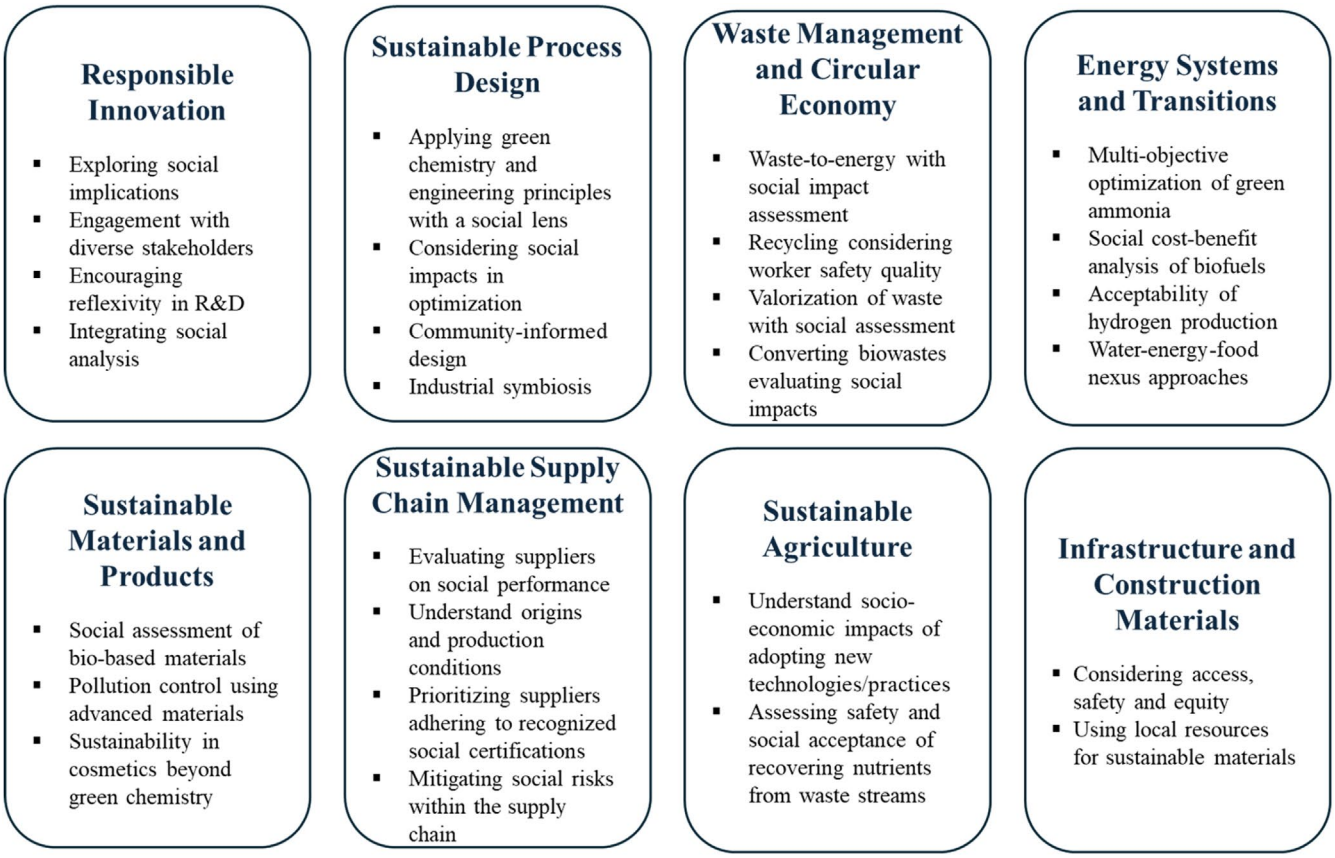

FIGURE 4 | How to integrate social sustainability in the chemical engineering practice (examples).

primary data by integrating information from other social assessment tools and reporting frameworks, such as GRI-based reports or SA8000 certifications, directly into an S-LCA study. To manage the inherent subjectivity and qualitative nature of social impacts, the literature proposes moving away from a purely quantitative mindset and embracing mixed-method approaches. A central strategy is to actively involve and engage stakeholders throughout the assessment process. This is crucial to counteract the risk of developing "top-down" indicators that may not represent the views and priorities of the impacted communities. Engaging with an "extended peer community," including the lay public, helps define relevant criteria and ensures that the assessment reflects lived experiences, which is, particularly, important when dealing with the complexity of social issues (Clift 2006). Instead of forcing all impacts into a quantitative framework, the recommended strategy is to use a mix of quantitative, semi-quantitative, and qualitative indicators. Quantitative indicators can be used for metrics such as the number of accidents, while semi-quantitative scales (e.g., scoring systems, yes/no checklists) can be applied to aspects like the presence of a stress management program. Qualitative descriptions are essential for capturing nuances that numbers cannot, such as the details of community engagement measures. To bring structure to the characterization phase and reduce pure subjectivity, the UNEP/SETAC guidelines propose using "performance reference points." These are thresholds or goals derived from international conventions, scientific consensus, or best practices that provide a transparent basis for scoring and weighting different social indicators.

The literature acknowledges that social assessment methodologies are still maturing and highlights several areas for future research and development to improve rigor and usability. There is an urgent call for the development of better databases for social information and software tools to speed up the process and make S-LCA more mainstream. A proposed research direction is to adapt robust techniques from environmental LCA, such as the "pedigree matrix," to social assessment. This would allow the conversion of qualitative data quality criteria (e.g., reliability, completeness) into quantitative scores, making the assessment process more transparent and rigorous. The reviewed literature notes that effective S-LCA requires practitioners to have a strong background in LCA, CSR, and SIA. Therefore, a long-term strategy is to build knowledge through conducting more case studies and developing educational materials to foster the necessary interdisciplinary skills.

5 | Integrating Social Sustainability into Chemical Engineering Practice

Moving beyond assessment, the core challenge lies in embedding social sustainability principles into the day-to-day practices and decision-making processes of chemical engineers across various domains (illustrated in Figure 4 and detailed next). This requires a shift in mindset and the application of specific strategies and tools, leveraging opportunities identified in green engineering, industrial ecology, and responsible innovation. Moreover, chemical engineers need to broaden their skillset

beyond technical expertise, embracing interdisciplinary collaboration, stakeholder engagement, and ethical reflection as core competencies.

Developing new materials, products, and technologies requires a proactive approach to anticipate social and ethical implications early (Owen et al. 2012; Stilgoe et al. 2013). Key elements include (a) systematically considering potential future impacts of emerging technologies (e.g., nanotechnology, synthetic biology, artificial intelligence) (Guston 2014); (b) involving diverse groups in discussions about technology development (Fisher et al. 2006; Matthies et al. 2024); (c) integrating ethical analysis alongside technical and economic assessments; (d) encouraging critical reflection on assumptions and values influencing research and development (Stilgoe et al. 2013); (e) designing flexible technologies and governance frameworks (West et al. 2016); and (f) proactively integrating safety and sustainability (including social aspects) from the earliest design stages (Apel et al. 2024; Bidart et al. 2024; Deng et al. 2024).

Process design is a cornerstone of chemical engineering, offering significant leverage for incorporating sustainability from the outset (Allen and Shonnard 2001; López-Flores et al. 2025). Integrating social considerations involves: (1) prioritizing less hazardous substances, energy efficiency, waste minimization, and renewable feedstocks inherently reduces risks to workers, communities, and consumers (Alviri et al. 2025; Anastas and Zimmerman 2007; García-Serna et al. 2007; Zimmerman et al. 2020); (2) building safety into the fundamental design minimizes the potential for catastrophic failures with severe social consequences (Li et al. 2011); (3) smaller, more efficient units can reduce footprint, resource consumption, and hazards (Stankiewicz and Moulijn 2000); (4) utilizing multiobjective optimization including social indicators (e.g., worker exposure, community risk, job creation) alongside economic and environmental metrics (Isella and Manca 2025; Kittichotsatsawat et al. 2024); (5) designing processes that utilize waste streams or produce usable byproducts fosters local economic linkages and reduces overall resource/waste burden (Chertow 2000; Han et al. 2025; Neves et al. 2020); (6) incorporating feedback from potential host communities regarding concerns such as noise, traffic, visual impact, and safety (Waddock 2008); and 7 Considering designs appropriate for low-resource settings when developing technologies for essential goods (e.g., water purification, pharmaceuticals) (Hussam and Munir 2007).

Chemical supply chains present significant social risks related to labor practices, human rights, and community impacts (Seuring and Müller 2008). Integration strategies include: (a) evaluating suppliers on social performance and verifying compliance (Locke 2013; Quan et al. 2024); (b) utilizing technologies and demanding transparency to understand origins and production conditions (Hejazi 2024; O'Rourke 2003); (c) prioritizing suppliers adhering to recognized social certifications (e.g., Fair Trade, SA8000) (Han et al. 2025); (d) collaborating to help suppliers improve social performance; (e) implementing clear corporate policies addressing human rights, labor standards, and so forth; (f) identifying and mitigating social risks within the supply chain (Lopes de Sousa Jabbour et al. 2024); and (g) utilizing tools such as social media marketing to enhance communication and transparency, especially for SMEs (Ayokunmi et al. 2025; Orji et al. 2020). To substantiate the acknowledgment of risks to labor and human rights, the reviewed literature offers several concrete examples from chemical and related supply chains that illustrate these challenges in practice. A foundational issue in global supply chains is the potential for companies to shift not only environmental but also social burdens to regions with less stringent regulations or enforcement (Seuring and Müller 2008; Silva et al. 2022). This phenomenon, sometimes termed the "export of unsustainability," can be seen where energy-intensive industries, such as primary metal production, migrate to countries with lower operational costs, effectively transferring environmental impacts and often exposing local labor forces to different standards of occupational health and safety (Clift 2006). A stark historical example is the 1984 Bhopal disaster, where a plant producing the insecticide "Sevin" operated with different safety standards, less rigorous training, and poorer management than a similar facility in the United States, leading to catastrophic consequences for workers and the surrounding community (Mehlich et al. 2024; Vanclay et al. 2015). More contemporary examples emerge from the transition to a bioeconomy. The use of bio-based feedstocks, such as lignin from the wood-pulping industry for producing bio-based chemicals, reconfigures supply chains, creating potential social risks such as job displacement and "labor declines for conventional suppliers" in the fossil-based sector (Asada et al. 2020; Lettner et al. 2020). These examples underscore that managing social sustainability in chemical supply chains requires a proactive approach to identifying and mitigating a range of risks, from immediate health and safety hazards to broader socioeconomic disruptions (Lopes de Sousa Jabbour et al. 2024).

Waste-to-Energy requires careful SIA and community engagement regarding emissions, siting, and traffic (Ramos 2024). Recycling technologies are key to developing efficient and safe processes (e.g., for plastics) considering worker safety and recycled material quality (Han et al. 2025). The valorization of waste streams creates value from waste (e.g., granite waste, urine nutrients, locust bean pods) can create economic opportunities but needs social assessment (Gehlot and Shrivastava 2024; Vordoagu and Adams 2024). Converting biomass/food waste needs consideration of land use and food security impacts (Martinelli et al. 2024; Peccia and Westerhoff 2015). The development of sustainable materials and products requires social assessment. Bio-based materials need evaluation regarding land use competition and lifecycle impacts (Gruter 2025; Quan et al. 2024). Using advanced materials for pollution control offers indirect social health benefits (Pipil et al. 2024). Integrating sustainability beyond green chemistry in cosmetics requires assessing sourcing, labor, and safety (Alviri et al. 2025). In this context, chemical engineers are pivotal, requiring social considerations. For example, the production of green ammonia requires multiobjective optimization considering economic, environmental, and social factors (land use, safety, community acceptance) (Isella and Manca 2025). In the case of Biofuels/Bio-CNG, this requires evaluating environmental sustainability and social cost–benefits (food prices, land rights) (Alao and Popoola 2025; Sharno and Hiloidhari 2024). Hydrogen production requires considering safety, infrastructure costs, and public acceptance (Tcharkhtchi et al. 2024). Designing campus/urban energy systems must include "Scope 3" emissions and social ramifications (energy poverty, job transition) (Özkan and Crowl 2024; Tian

and You 2024). Geothermal/underground storage requires careful assessment of subsurface impacts and community concerns (Yang et al. 2024). Implementing water-energy-food nexus requires integrated approaches considering social equity in resource allocation and access (Echeverry et al. 2024; Mirza and Qurat-ul-Ann 2025). Valuing the role of chemical engineers in the context of social sustainability requires understanding socioeconomic impacts of adopting new technologies/practices and assessing safety and social acceptance of recovering nutrients from waste streams (Liu et al. 2024; Valizadeh et al. 2024). This area also requires considering social implications, such as decisions on access, safety, and equity (Boakye and Okte 2025). Developing sustainable materials using local resources offers potential social benefits (e.g., durability, cost-effectiveness) (Quan et al. 2024; Vordoagu and Adams 2024).

While the principles of social sustainability are applicable across a vast spectrum of chemical engineering activities, the reviewed literature provides the strongest evidence and greatest relevance for integration within three priority domains: (1) sustainable process and product design, (2) sustainable supply chain management, and (3) waste management and the circular economy. These areas represent the core functions where chemical engineers can exert the most significant and direct influence on social outcomes, moving beyond theoretical principles to actionable, current practice (Arastoopour 2019; García-Serna et al. 2007; Huppes and Ishikawa 2007; Silva et al. 2022). Prioritizing these domains allows for a focused application of chemical engineering skills to address pressing social challenges (Azapagic and Perdan 2014).

6 | The Role of Education in Fostering Social Sustainability

Integrating social sustainability principles effectively into chemical engineering practice hinges critically on how future generations of engineers are educated and trained (Fitzpatrick and Byrne 2024; Glassey and Haile 2012). Traditional curricula have often marginalized societal context, ethical dimensions, and social impacts (Chen and Pfluger 2024; Mitchell 2000). A paradigm shift in chemical engineering education is necessary to equip graduates for the complex sociotechnical challenges ahead (Azapagic and Perdan 2014).

Embedding social sustainability requires integration across the curriculum, not just isolated courses (Chen and Pfluger 2024; Walker and Clausen 2024). Sustainable development (TBL), social dimensions, and ethics, should be introduced early (e.g., introductory engineering courses). Social considerations must be woven into technical subjects: (a) include SIA/S-LCA, ethical dilemmas, community engagement, inherent safety linked to social risk in process design (López-Flores et al. 2025); (b) discuss energy poverty, equitable access, social ramifications of energy transitions in thermodynamics/energy subjects (Özkan and Crowl 2024); (c) examine lifecycle social impacts, ethical sourcing, end-of-life management in materials science (Han et al. 2025); (d) discuss process safety implications for workers/communities in kinetics/reactor design; and (e) incorporate SROI, social cost–benefit analysis, ecological economics in economics disciplines (Fitzpatrick and Byrne 2024). Specialized courses on sustainable engineering, green chemistry, industrial ecology, environmental policy, and engineering ethics with significant social content should be offered (Walker and Clausen 2024). Explicit incorporation of social sustainability criteria (SIA, community impact, ethics, stakeholders) beyond technical/economic optimization should be required in design projects.

Effective pedagogy involves active learning and real-world relevance. Real-world cases (successes and failures) should be used to illustrate complex sociotechnical interactions and prompt critical thinking/ethical deliberation (Hussam and Munir 2007; Freckleton 2013). Structured training in engineering ethics, codes, decision frameworks, and dilemmas (Iordache 2024; Mehlich et al. 2024) should be provided. Methodologies and tools such as SIA/S-LCA should be the subject of dedicated training (Pérez-López et al. 2025; Vanclay 2002). Students should engage in projects addressing real-world problems with community partners. Collaboration with students/faculty from other disciplines (social sciences, policy, etc.) should be encouraged/required (Avelino et al. 2024; Iles and Mulvihill 2012; Matthies et al. 2024). Scenarios to navigate ethical dilemmas or stakeholder interests and invite practitioners to share experiences should be used.

Beyond technical knowledge, education must cultivate crucial skills and attitudes such as: (a) understanding complex systems and interconnectedness (Bakshi 2019); (b) identifying, analyzing, and making justified ethical decisions (Harris et al. 2019); (c) communicating effectively with diverse audiences, active listening; (d) identifying stakeholders, understanding perspectives, incorporating them into decisions (Elias et al. 2002); (e) awareness and sensitivity to diverse cultural norms (Awan et al. 2018); (f) recognizing sustainability as an evolving field; and (g) instilling professional responsibility toward society and the environment (Karjanto 2022). Integrating these elements is essential for preparing graduates who are technically proficient, ethically grounded, socially aware, and equipped for a sustainable future (Hübscher et al. 2024). Educational reform is fundamental to shifting the mindset and skillset of the profession (Azapagic and Perdan 2014).

While curricular recommendations for social sustainability can appear broad, the literature provides several documented educational experiences and measurable outcomes that can ground these proposals in practice. A foundational approach involves integrating sustainability not as an "add-on," but as a core principle throughout the engineering curriculum, a paradigm shift now supported by accreditation bodies that assess programs on outcomes rather than inputs (Karjanto 2022). Documented pedagogical experiences include long-standing courses such as the "Sustainable Entrepreneurship and Technology" subject at Delft University of Technology, which since 1996 has required chemical engineering students to develop business plans for sustainable products (Bonnet et al. 2006). The outcomes of this course are measured through project appraisals and student focus groups, which have shown an enhanced student understanding of sustainability's complexity and its integration into business (Bonnet et al. 2006). Similarly, a five-lecture series on ecological economics at University College Cork for chemical engineering students produced measurable outcomes via student

surveys, with 95% of respondents finding the material useful for understanding concepts such as ecological limits and the social dimensions often overlooked in traditional engineering (Fitzpatrick and Byrne 2024). More specific and measurable outcomes are also documented through project-based learning. For example, Barcelona Tech requires a mandatory "Sustainability Report" for all final degree projects in Informatics Engineering, which is assessed using a "sustainability matrix," providing a concrete evaluation of students' ability to apply sustainability principles (Rubio et al. 2019). Service-learning projects also offer documented outcomes by developing skills in "sustainability awareness, cultural sensitivity, [and] empathy" and helping communities "ensure individuals' human rights via sustainable, culturally appropriate, technology-based solutions" (Harris et al. 2019). Furthermore, studies focusing on specific sustainability topics have measured educational results; for example, a study on bioeconomic innovations measured "learning effects" through case studies (Asada et al. 2020), while another on farming systems used surveys to measure social outcomes such as "labor practices, job satisfaction, and the broader community impact" (Wang et al. 2024). These examples demonstrate that educational initiatives in social sustainability can be documented and their outcomes, both qualitative and quantitative, can be measured, providing an evidence-based foundation for new curricular proposals.

7 | Future Research Directions

To address the need for a more focused research agenda, future work can be prioritized into urgent, transitional, and long-term directions that are directly actionable for chemical engineering. This structured approach helps translate the broad imperatives of social sustainability into a focused research and innovation agenda.

The most urgent priorities address immediate methodological and technological gaps. Methodologically, there is a pressing need for robust assessment tools suited for the early stages of research and development to overcome the "design paradox," where design freedom is highest but data is scarcest (Chebaeva et al. 2021; Gasafi and Weil 2011; Schöggl et al. 2017). Key among these is advancing S-LCA by creating better socioeconomic databases, software tools, and impact assessment methods, which remain an "open field for future research" (Tokede and Traverso 2020). Technologically, chemical engineers are positioned to lead immediate decarbonization efforts through process intensification—creating smaller, cleaner, and more energy-efficient technologies (Arastoopour 2019)—and advancing carbon capture, utilization, and sequestration, from novel sorbent development to process-level integration using advanced computational models (Arastoopour 2019).

For the medium-term transition, a key area for chemical engineering research is the development of sustainable biorefineries that convert underutilized resources and waste streams into value-added products, thereby generalizing the traditional refinery concept (Asada et al. 2020; Narodoslawsky 2013). This includes innovating unit operations, such as membrane and chromatographic separations, tailored for biogenic feedstocks (Narodoslawsky 2013). Concurrently, research into the cleaner production and conversion of natural gas from sources like shale and hydrates is vital as it serves as a critical transitional fuel, requiring chemical engineering expertise to address environmental challenges and develop new conversion pathways (Arastoopour 2019).

Long-term actionable directions require a fundamental paradigm shift. This involves expanding the boundaries of Process Systems Engineering to holistically integrate ecosystem capacities and human behavior (e.g., the "rebound effect"), moving from a paradigm of dominating nature to one of learning from and respecting its limits (Bakshi 2019). Concrete research areas include the direct integration of renewable energy (e.g., concentrated solar power) into chemical processes, developing large-scale energy storage solutions like green hydrogen, and creating novel chemical recycling technologies for a true circular economy (Arastoopour 2019; Han et al. 2025). Achieving these goals will require chemical engineers to engage in deeper interdisciplinary collaboration, particularly, with social sciences, to tackle "wicked" sustainability problems (Azapagic and Perdan 2014; Clift 2006).

8 | Conclusion

This review's specific findings collectively lead to the conclusion that integrating social sustainability into chemical engineering requires a fundamental paradigm shift, moving the discipline beyond its traditional technoeconomic boundaries (Bakshi 2019). A central finding, synthesized from the literature, is that while the traditional three pillars of sustainability are theoretically equal, a clear hierarchy persists in practice where social aspects are often marginalized due to their complexity and the immaturity of assessment methodologies (Seuring and Müller 2008; Van Schoubroeck et al. 2018).

The review of assessment tools concludes that while frameworks such as S-LCA offer a structured approach for evaluating impacts on stakeholders such as workers, consumers, and local communities across the value chain (Gehlot and Shrivastava 2024; Ramos 2024; UNEP/SETAC 2009), their practical application is consistently hampered by challenges in data availability, indicator selection, and quantifying qualitative social values (Jørgensen et al. 2008; Tokede and Traverso 2020). This methodological gap directly connects to findings from specific practice areas; for instance, the analysis of supply chain management revealed that a lack of robust social metrics contributes to reactive rather than proactive management of labor and human rights. Similarly, in education, the evidence showed that while innovative pedagogical experiences exist, the lack of standardized, measurable outcomes for social sustainability competencies impedes their systematic integration into engineering curricula (Fitzpatrick and Byrne 2024).

Ultimately, this review concludes that addressing these interconnected findings requires chemical engineering to embrace its role in solving complex "wicked" problems (Azapagic and Perdan 2014; Bakshi 2019) by actively developing social assessment tools, fostering deeper interdisciplinary collaboration with the social sciences (Azapagic and Perdan 2014; Matthies et al. 2024), and fundamentally reframing engineering

education to equip future professionals with the necessary ethical and practical skills.

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References

Aarseth, W., T. Ahola, K. Aaltonen, A. Økland, and B. Andersen. 2017. "Project Sustainability Strategies: A Systematic Literature Review." *International Journal of Project Management* 35, no. 6: 1071–1083. https://doi.org/10.1016/j.ijproman.2016.11.006.

Alao, M. A., and O. M. Popoola. 2025. "Environmental Sustainability and Social Cost-Benefit Evaluations of bioCNG as a Fuel for Transportation in the Context of South African Provinces." *Sustainable Futures* 9: 100589. https://doi.org/10.1016/j.sftr.2025.100589.

Allen, D. T., and D. R. Shonnard. 2001. "Green Engineering: Environmentally Conscious Design of Chemical Processes and Products." *AICHE Journal* 47, no. 9: 1906–1910. https://doi.org/10.1002/aic.690470902.

Alviri, H., J. Lynes, and K. Habib. 2025. "Beyond Green Chemistry: A Comprehensive Review of How Sustainability Has Been Integrated Into Cosmetic Research." *Global Sustainability* 8: e16. https://doi.org/10.1017/sus.2025.5.

Anastas, P. T., and J. B. Zimmerman. 2007. "Design Through the 12 Principles of Green Engineering." *IEEE Engineering Management Review* 35, no. 3: 16. https://doi.org/10.1109/EMR.2007.4296421.

Apel, C., K. Kümmerer, A. Sudheshwar, et al. 2024. "Safe-and-Sustainable-By-Design: State of the Art Approaches and Lessons Learned From Value Chain Perspectives." *Current Opinion in Green and Sustainable Chemistry* 45: 100876. https://doi.org/10.1016/j.cogsc.2023.100876.

Arastoopour, H. 2019. "The Critical Contribution of Chemical Engineering to a Pathway to Sustainability." *Chemical Engineering Science* 203: 247–258. https://doi.org/10.1016/j.ces.2019.03.069.

Asada, R., G. Cardellini, C. Mair-Bauernfeind, et al. 2020. "Effective Bioeconomy? A MRIO-Based Socioeconomic and Environmental Impact Assessment of Generic Sectoral Innovations." *Technological Forecasting and Social Change* 153: 119946. https://doi.org/10.1016/j.techfore.2020.119946.

Avelino, F., K. Wijsman, F. van Steenbergen, et al. 2024. "Just Sustainability Transitions: Politics, Power, and Prefiguration in Transformative Change Toward Justice and Sustainability." *Annual Review of Environment and Resources* 49: 519–547. https://doi.org/10.1146/annurev-environ-112321-081722.

Awan, U., A. Kraslawski, and J. Huiskonen. 2018. "Governing Interfirm Relationships for Social Sustainability: The Relationship Between Governance Mechanisms, Sustainable Collaboration, and Cultural Intelligence." *Sustainability* 10, no. 12: 4473. https://doi.org/10.3390/su10124473.

Ayokunmi, L. A., N. A. Abu Seman, U. K. Rashid, and A. Mohamad. 2025. "The Role of Social Media Marketing as an ICT Tool in Improving Supply Chain Sustainability of SMEs: A Systematic Literature Review." *Procedia Computer Science* 253: 1392–1401. https://doi.org/10.1016/j.procs.2025.01.201.

Azapagic, A., and S. Perdan. 2005. "An Integrated Sustainability Decision-Support Framework Part I: Problem Structuring." *International Journal of Sustainable Development and World Ecology* 12, no. 2: 98–111. https://doi.org/10.1080/13504500509469622.

Azapagic, A., and S. Perdan. 2014. "Sustainable Chemical Engineering: Dealing With "Wicked" Sustainability Problems." *AICHE Journal* 60, no. 12: 3998–4007. https://doi.org/10.1002/aic.14650.

Bakshi, B. R. 2019. "Toward Sustainable Chemical Engineering: The Role of Process Systems Engineering." *Annual Review of Chemical and Biomolecular Engineering* 10: 265–288. https://doi.org/10.1146/annurev-chembioeng-060718-030332.

Batterham, R. J. 2006. "Sustainability-The Next Chapter." *Chemical Engineering Science* 61, no. 13: 4188–4193. https://doi.org/10.1016/j.ces.2005.10.016.

Bidart, G. N., D. Teze, C. U. Jansen, et al. 2024. "Chemoenzymatic Indican for Light-Driven Denim Dyeing." *Nature Communications* 15, no. 1: 1489. https://doi.org/10.1038/s41467-024-45749-3.

Boakye, J., and E. Okte. 2025. "Which Impacts Matter for Pavement Management Decisions? Quantifying Social Sustainability Based on a Capability Approach." *Transportation Research Interdisciplinary Perspectives* 29: 101312. https://doi.org/10.1016/j.trip.2024.101312.

Bond, A., A. Morrison-Saunders, and J. Pope. 2012. "Sustainability Assessment: The State of the Art." *Impact Assessment and Project Appraisal* 30, no. 1: 53–62. https://doi.org/10.1080/14615517.2012.661974.

Bonnet, H., J. Quist, D. Hoogwater, J. Spaans, and C. Wehrmann. 2006. "Teaching Sustainable Entrepreneurship to Engineering Students: The Case of Delft University of Technology." *International Journal of Phytoremediation* 31, no. 2: 155–167. https://doi.org/10.1080/03043790600566979.

Branch, K., D. A. Hooper, J. Thompson, and J. Creighton. 2019. *Guide to Social Assessment*. Routledge. https://doi.org/10.4324/9780429045400.

Braun, V., and V. Clarke. 2012. "Thematic Analysis." In *APA Handbook of Research Methods in Psychology, Vol. 2. Research Designs: Quantitative, Qualitative, Neuropsychological, and Biological*, edited by H. Cooper, P. M. Camic, D. L. Long, A. T. Panter, D. Rindskopf, and K. J. Sher, 57–71. American Psychological Association.

Bullard, R. D. 2018. *Dumping in Dixie*. Routledge. https://doi.org/10.4324/9780429495274.

Chang, F., X. Zhang, G. Zhan, Y. Duan, and S. Zhang. 2021. "Review of Methods for Sustainability Assessment of Chemical Engineering Processes." *Industrial and Engineering Chemistry Research* 60, no. 1: 52–66. https://doi.org/10.1021/acs.iecr.0c04720.

Chebaeva, N., M. Lettner, J. Wenger, et al. 2021. "Dealing With the Eco-Design Paradox in Research and Development Projects: The Concept of Sustainability Assessment Levels." *Journal of Cleaner Production* 281: 125232. https://doi.org/10.1016/j.jclepro.2020.125232.

Chen, C. V., and C. Pfluger. 2024. "Work-In-Progress: Integrating Sustainability Across the Chemical Engineering Curriculum Paper Presented at 2024 ASEE Annual Conference & Exposition." https://doi.org/10.18260/1-2—48546.

Chertow, M. R. 2000. "Industrial Symbiosis: Literature and Taxonomy." *Annual Review of Energy and the Environment* 25: 313–337. https://doi.org/10.1146/annurev.energy.25.1.313.

Clift, R. 2006. "Sustainable Development and Its Implications for Chemical Engineering." *Chemical Engineering Science* 61, no. 13: 4179–4187. https://doi.org/10.1016/j.ces.2005.10.017.

Colantonio, A. 2011. "Social Sustainability: Exploring the Linkages Between Research, Policy and Practice." In *European Research on Sustainable Development*, edited by C. Jaeger, J. Tàbara, and J. Jaeger. Springer. https://doi.org/10.1007/978-3-642-19202-9_5.

Cole, L. W., and S. R. Foster. 2001. *From the Ground Up: Environmental Racism and the Rise of the Environmental Justice Movement*. Vol. 34. NYU Press.

Cornel, P., and C. Schaum. 2009. "Phosphorus Recovery From Wastewater: Needs, Technologies and Costs." *Water Science and Technology* 59, no. 6: 1069–1076. https://doi.org/10.2166/wst.2009.045.

Das, T., and H. Cabezas. 2018. "Tools and Concepts for Environmental Sustainability in the Food-Energy-Water Nexus: Chemical Engineering Perspective." *Environmental Progress & Sustainable Energy* 37, no. 1: 73–81. https://doi.org/10.1002/ep.12763.

Dempsey, N., G. Bramley, S. Power, and C. Brown. 2011. "The Social Dimension of Sustainable Development: Defining Urban Social Sustainability." *Sustainable Development* 19, no. 5: 289–300. https://doi.org/10.1002/sd.417.

Demuijnck, G., and B. Fasterling. 2016. "The Social License to Operate." *Journal of Business Ethics* 136, no. 4: 675–685. https://doi.org/10.1007/s10551-015-2976-7.

Deng, Y., Q. Zhang, and B. L. Feringa. 2024. "Dynamic Chemistry Toolbox for Advanced Sustainable Materials." *Advanced Science* 11, no. 14: 1–22. https://doi.org/10.1002/advs.202308666.

Dimian, A. C., C. S. Bildea, and A. A. Kiss. 2014. "Chapter 17-Sustainability Analysis." In *Integrated Design and Simulation of Chemical Processes*, edited by A. C. Dimian, C. S. Bildea, and A. A. Kiss, vol. 35, 679–702. Elsevier. https://doi.org/10.1016/B978-0-444-62700-1.00017-6.

Echeverry, S. M. V., A. Marques, and S. Yoshinaga Pereira. 2024. "Sustainability and Groundwater in the Context of Water-Energy-Food Nexus: A Review of the Literature." *Derbyana* 45: 1–14. https://doi.org/10.69469/derb.v45.833.

Eizenberg, E., and Y. Jabareen. 2017. "Social Sustainability: A New Conceptual Framework." *Sustainability* 9, no. 1: 68. https://doi.org/10.3390/su9010068.

Elias, A. A., R. Y. Cavana, and L. S. Jackson. 2002. "Stakeholder Analysis for R&D Project Management." *R&D Management* 32, no. 4: 301–310. https://doi.org/10.1111/1467-9310.00262.

Fatima, S., S. Abbas, A. Rebi, and Z. Ying. 2024. "Sustainable Forestry and Environmental Impacts: Assessing the Economic, Environmental, and Social Benefits of Adopting Sustainable Agricultural Practices." *Ecological Frontiers* 44, no. 6: 1119–1127. https://doi.org/10.1016/j.ecofro.2024.05.009.

Fereday, J., and E. Muir-Cochrane. 2006. "Demonstrating Rigor Using Thematic Analysis: A Hybrid Approach of Inductive and Deductive Coding and Theme Development." *International Journal of Qualitative Methods* 5, no. 1: 80–92. https://doi.org/10.1177/160940690600500107.

Fisher, E., R. L. Mahajan, and C. Mitcham. 2006. "Midstream Modulation of Technology: Governance From Within." *Bulletin of Science, Technology & Society* 26, no. 6: 485–496. https://doi.org/10.1177/0270467606295402.

Fitzpatrick, J. J., and E. P. Byrne. 2024. "Incorporating Ecological Economics Into Engineering Education." *Education for Chemical Engineers* 48: 53–62. https://doi.org/10.1016/j.ece.2024.05.003.

Freckleton, J. E. 2013. "Case of Studies in Engineering Ethics." *Journal of Institute of Technology Rochester* 53, no. 9: 1689–1699.

García-Serna, J., L. Pérez-Barrigón, and M. J. Cocero. 2007. "New Trends for Design Towards Sustainability in Chemical Engineering: Green Engineering." *Chemical Engineering Journal* 133, no. 1–3: 7–30. https://doi.org/10.1016/j.cej.2007.02.028.

Gasafi, E., and M. Weil. 2011. "Approach and Application of Life Cycle Screening in Early Phases of Process Design: Case Study of Supercritical Water Gasification." *Journal of Cleaner Production* 19, no. 14: 1590–1600. https://doi.org/10.1016/j.jclepro.2011.05.021.

Gehlot, M. R., and S. Shrivastava. 2024. "Sustainability Assessment of Granite Cutting Waste Incorporated Cement Sand Rendering Mortar: Technical, Environmental, Cost, and Social Parameters." *Journal of Cleaner Production* 480: 144108. https://doi.org/10.1016/j.jclepro.2024.144108.

Glassey, J., and S. Haile. 2012. "Sustainability in Chemical Engineering Curriculum." *International Journal of Sustainability in Higher Education* 13, no. 4: 354–364. https://doi.org/10.1108/14676371211262308.

Global Reporting Initiative. 2011. *Sustainability Reporting Guidelines*. Global Reporting Initiative.

Gruter, G. J. M. 2025. "Recent Developments in Sustainable High Tg (Co)polyesters From 2,5-Furandicarboxylic Acid, Isosorbide, and Oxalic Acid. Performance and Social Perspectives." *Current Opinion in Green and Sustainable Chemistry* 53: 101013. https://doi.org/10.1016/j.cogsc.2025.101013.

Guinée, J. B., R. Heijungs, G. Huppes, et al. 2011. "Life Cycle Assessment: Past, Present, and Future." *Environmental Science & Technology* 45, no. 1: 90–96. https://doi.org/10.1021/es101316v.

Guston, D. H. 2014. "Understanding "Anticipatory Governance"." *Social Studies of Science* 44, no. 2: 218–242. https://doi.org/10.1177/0306312713508669.

Han, J., J. Zuo, G. Zillante, R. Chang, and L. Du. 2025. "A Systematic Review of PET Circularity Technologies and Management Strategies: Challenges and Future Directions." *Resources, Conservation and Recycling* 219: 108280. https://doi.org/10.1016/j.resconrec.2025.108280.

Harris, C. E., M. S. Pritchard, R. W. James, E. E. Englehardt, and M. J. Rabins. 2019. *Engineering Ethics: Concepts and Cases*. Cengage Learning.

Hejazi, M. T. 2024. "The Impact of Digitalization Practices on Supply Chain Sustainability and Organizational Sustainability." *WSEAS Transactions on Business and Economics* 21: 35–43. https://doi.org/10.37394/23207.2024.21.4.

Hübscher, C., S. Hensel-Börner, and J. Henseler. 2024. "Marketing Education for Sustainable Development." *Spanish Journal of Marketing—ESIC* 28, no. 3: 310–333. https://doi.org/10.1108/SJME-06-2022-0131.

Huppes, G., and M. Ishikawa. 2007. "Sustainability Evaluation: Diverging Routes Recombined? Tasks for a New Working Group on Modelling and Evaluation for Sustainability." *Journal of Cleaner Production* 15, no. 11–12: 1183–1184. https://doi.org/10.1016/j.jclepro.2007.01.001.

Hussam, A., and A. K. M. Munir. 2007. "A Simple and Effective Arsenic Filter Based on Composite Iron Matrix: Development and Deployment Studies for Groundwater of Bangladesh." *Journal of Environmental Science and Health—Part A Toxic/Hazardous Substances and Environmental Engineering* 42, no. 12: 1869–1878. https://doi.org/10.1080/10934520701567122.

Iles, A., and M. J. Mulvihill. 2012. "Collaboration Across Disciplines for Sustainability: Green Chemistry as an Emerging Multistakeholder Community." *Environmental Science and Technology* 46, no. 11: 5643–5649. https://doi.org/10.1021/es300803t.

Iordache, O. 2024. *General Reference Architecture Frameworks*. Vol. 73. Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-70718-6.

Isella, A., and D. Manca. 2025. "Integrating Economic, Environmental, and Social Sustainability in Power-To-Ammonia Plants: A Multi-Objective Optimization Methodology." *Computers & Chemical Engineering* 198: 109082. https://doi.org/10.1016/j.compchemeng.2025.109082.

Jin, Y., D. Wang, and F. Wei. 2004. "The Ecological Perspective in Chemical Engineering." *Chemical Engineering Science* 59, no. 8–9: 1885–1895. https://doi.org/10.1016/j.ces.2004.01.042.

Jørgensen, A., A. Le Bocq, L. Nazarkina, and M. Hauschild. 2008. "Methodologies for Social Life Cycle Assessment." *International Journal of Life Cycle Assessment* 13, no. 2: 96–103. https://doi.org/10.1065/lca2007.11.367.

Karjanto, N. 2022. "Seeking Genuine Vocations Through Sustainability in Chemical Engineering." *Sustainability* 14, no. 12: 6980. https://doi.org/10.3390/su14126980.

Kittichotsatsawat, Y., E. Rauch, and K. Y. Tippayawong. 2024. "Designing Sustainability Measurement of a Thai Coffee Supply Chain Using Axiomatic Design and Business Model Canvas." *Results in Engineering* 24: 103443. https://doi.org/10.1016/j.rineng.2024.103443.

Kloepffer, W. 2008. "Life Cycle Sustainability Assessment of Products (With Comments by Helias A. Udo de Haes, p. 95)." *International Journal of Life Cycle Assessment* 13, no. 2: 89–95. https://doi.org/10.1065/lca2008.02.376.

Lettner, M., F. Hesser, B. Hedeler, P. Schwarzbauer, and T. Stern. 2020. "Barriers and Incentives for the Use of Lignin-Based Resins: Results of a Comparative Importance Performance Analysis." *Journal of Cleaner Production* 256: 120520. https://doi.org/10.1016/j.jclepro.2020.120520.

Li, X., A. Zanwar, A. Jayswal, H. H. Lou, and Y. Huang. 2011. "Incorporating Exergy Analysis and Inherent Safety Analysis for Sustainability Assessment of Biofuels." *Industrial and Engineering Chemistry Research* 50, no. 5: 2981–2993. https://doi.org/10.1021/ie101660q.

Littig, B., and E. Grießler. 2005. "Social Sustainability: A Catchword Between Political Pragmatism and Social Theory." *International Journal of Sustainable Development* 8, no. 1–2: 65–79. https://doi.org/10.1504/ijsd.2005.007375.

Liu, Y., M. R. Razman, S. Z. Syed Zakaria, K. E. Lee, S. U. Khan, and A. Albanyan. 2024. "Personalized Context-Aware Systems for Sustainable Agriculture Development Using Ubiquitous Devices and Adaptive Learning." *Computers in Human Behavior* 160: 108375. https://doi.org/10.1016/j.chb.2024.108375.

Locke, R. M. 2013. *The Promise and Limits of Private Power*. Cambridge University Press. https://doi.org/10.1017/CBO9781139381840.

Lopes de Sousa Jabbour, A. B., P. D. C. Fiorini, H. Latan, I. Laguir, and C. J. Chiappetta Jabbour. 2024. "Supply Chain Risk Identification: Signaling Companies' Social Sustainability Reputation." *Journal of Cleaner Production* 478: 143817. https://doi.org/10.1016/j.jclepro.2024.143817.

López-Flores, F. J., A. Y. Raya-Tapia, C. Ramírez-Márquez, and J. M. Ponce-Ortega. 2025. "Exploring Clustering Tools in Process Systems Engineering: Innovations, Applications, and Future Directions." *Chemical Engineering Research and Design* 217: 13–23. https://doi.org/10.1016/j.cherd.2025.03.018.

Margni, M., and M. A. Curran. 2012. "Life Cycle Impact Assessment." In *Life Cycle Assessment Handbook*, edited by M. A. Curran. Wiley. https://doi.org/10.1002/9781118528372.ch4.

Martens, M. L., and M. M. Carvalho. 2016. "The Challenge of Introducing Sustainability Into Project Management Function: Multiple-Case Studies." *Journal of Cleaner Production* 117: 29–40. https://doi.org/10.1016/j.jclepro.2015.12.039.

Martinelli, F. R. B., M. G. Pariz, R. de Andrade, et al. 2024. "Influence of Drying Temperature on Coconut-Fibers." *Scientific Reports* 14, no. 1: 1–14. https://doi.org/10.1038/s41598-024-56596-z.

Matthies, E., K. Beer, M. Böcher, et al. 2024. "Framework Conditions for the Transformation Toward a Sustainable Carbon-Based Chemical Industry – A Critical Review of Existing and Potential Contributions From the Social Sciences." *Journal of Cleaner Production* 470, no. November 2022: 143279. https://doi.org/10.1016/j.jclepro.2024.143279.

Mehlich, J., T. Børsen, and D. Kim. 2024. "Ethics in Chemical Engineering." In *The Routledge International Handbook of Engineering Ethics Education*, edited by S. Chance, T. Børsen, D. A. Martin, R. Tormey, T. T. Lennerfors, and G. Bombaerts, 1st ed., 304–320. Routledge.

Miret, C., P. Chazara, L. Montastruc, S. Negny, and S. Domenech. 2016. "Design of Bioethanol Green Supply Chain: Comparison Between First and Second Generation Biomass Concerning Economic, Environmental and Social Criteria." *Computers and Chemical Engineering* 85: 16–35. https://doi.org/10.1016/j.compchemeng.2015.10.008.

Mirza, F. M., and A. Qurat-ul-Ann. 2025. "Bibliometric Assessment of Energy Research in Pakistan: Mapping of Past and Prospects for the Future." In *Geopolitical Landscapes of Renewable Energy and Urban Growth*, edited by F. Özsungur, M. Chaychi Semsari, and H. Küçük Bayraktar, 125–184. IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-8814-3.ch005.

Mitchell, C. 2000. "Integrating Sustainability in Chemical Engineering Practice and Education: Concentricity and Its Consequences." *Process Safety and Environmental Protection* 78, no. 4: 237–242. https://doi.org/10.1205/095758200530754.

Moher, D., A. Liberati, J. Tetzlaff, D. G. Altman, and The PRISMA Group. 2009. "Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement." *PLoS Medicine* 6, no. 7: e1000097. https://doi.org/10.1371/journal.pmed.1000097.

Narodoslawsky, M. 2013. "Chemical Engineering in a Sustainable Economy." *Chemical Engineering Research and Design* 91, no. 10: 2021–2028. https://doi.org/10.1016/j.cherd.2013.06.022.

Neri, A., E. Cagno, E. Susur, et al. 2025. "The Relationship Between Digital Technologies and the Circular Economy: A Systematic Literature Review and a Research Agenda." *R&D Management* 55: 617–713. https://doi.org/10.1111/radm.12715.

Neves, A., R. Godina, S. G. Azevedo, and J. C. O. Matias. 2020. "A Comprehensive Review of Industrial Symbiosis." *Journal of Cleaner Production* 247: 119113. https://doi.org/10.1016/j.jclepro.2019.119113.

Nicholls, J., E. Lawlor, E. Neitzert, and T. Goodspeed. 2012. *A Guide to Social Return on Investment*. SROI Network. https://socialvalueselfassessmenttool.org/wp-content/uploads/intranet/758/pdf-guide.pdf.

Orji, I. J., S. Kusi-Sarpong, and H. Gupta. 2020. "The Critical Success Factors of Using Social Media for Supply Chain Social Sustainability in the Freight Logistics Industry." *International Journal of Production Research* 58, no. 5: 1522–1539. https://doi.org/10.1080/00207543.2019.1660829.

O'Rourke, D. 2003. "Outsourcing Regulation: Analyzing Nongovernmental Systems of Labor Standards and Monitoring." *Policy Studies Journal* 31, no. 1: 1–29. https://doi.org/10.1111/1541-0072.00001.

OSHA. 2016. *Occupational Safety and Health Administration Standards*. U.S. Department of Labor.

Owen, R., P. Macnaghten, and J. Stilgoe. 2012. "Responsible Research and Innovation: From Science in Society to Science for Society, With Society." *Science and Public Policy* 39, no. 6: 751–760. https://doi.org/10.1093/scipol/scs093.

Özkan, D. S., and M. Crowl. 2024. "Board 27: Work in Progress: Where We Live: The Process of Building an Experiential-Energy Design Course for Undergraduate Chemical Engineering Paper Presented at 2024 ASEE Annual Conference & Exposition." https://doi.org/10.18260/1-2--46843.

Peccia, J., and P. Westerhoff. 2015. "We Should Expect More out of Our Sewage Sludge." *Environmental Science and Technology* 49, no. 14: 8271–8276. https://doi.org/10.1021/acs.est.5b01931.

Pérez-López, P., A. Rajaonison, B. Zebian, et al. 2025. "Exploiting Outcomes of Life Cycle Costing to Conduct Coherent Screening Social Life Cycle Assessments of Emerging Systems: A Case Study of Microalgae Biorefineries." *International Journal of Life Cycle Assessment* 30, no. 4: 770–791. https://doi.org/10.1007/s11367-024-02427-2.

Pipil, P., T. Tomer, and R. Payal. 2024. "Ceramics as Potential Materials in Pollution Prevention and Control." *International Journal of Applied Ceramic Technology* 21, no. 6: 3812–3828. https://doi.org/10.1111/ijac.14902.

Popovic, T., and A. Kraslawski. 2015. "Chapter 24 - Social Sustainability of Complex Systems." In *Sustainability of Products, Processes and Supply Chains*, edited by F. You, vol. 36, 605–614. Elsevier. https://doi.org/10.1016/B978-0-444-63472-6.00024-0.

Putnam, R. D. 2000. "Bowling Alone: The Collapse and Revival of American Community." In *Proceedings of the 2000 ACM Conference on Computer Supported Cooperative Work*, 357. https://doi.org/10.1145/358916.361990.

Quan, X., C. Chen, X. Wang, T. Ma, C. Ge, and Y. Zhang. 2024. "Mechanism Exploration of the Modified Asphalt Binders With Sustainable Rapeseed-Based Derivatives Using Multi-Scale Evaluation Method." *Construction and Building Materials* 439, no. June: 137342. https://doi.org/10.1016/j.conbuildmat.2024.137342.

Ramos, A. 2024. "Sustainability Assessment in Waste Management: An Exploratory Study of the Social Perspective in Waste-To-Energy Cases." *Journal of Cleaner Production* 475: 143693. https://doi.org/10.1016/j.jclepro.2024.143693.

Rawls, J. 2005. *A Theory of Justice*. Harvard University Press. https://doi.org/10.2307/j.ctvjf9z6v.

Reed, M. S. 2008. "Stakeholder Participation for Environmental Management: A Literature Review." *Biological Conservation* 141, no. 10: 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014.

Rubio, R. M., D. Uribe, A. Moreno-Romero, and S. Yáñez. 2019. "Embedding Sustainability Competences Into Engineering Education. The Case of Informatics Engineering and Industrial Engineering Degree Programs at Spanish Universities." *Sustainability* 11, no. 20: 5832–5842. https://doi.org/10.3390/su11205832.

Saling, P., A. Kicherer, B. Dittrich-Krämer, et al. 2002. "Eco-Efficiency Analysis by BASF: The Method." *International Journal of Life Cycle Assessment* 7, no. 4: 203–218.

Saunders, M., P. Lewis, and A. Thornhill. 2009. *Research Methods for Business Students*. 5th ed. Pearson.

Schöggl, J. P., R. J. Baumgartner, and D. Hofer. 2017. "Improving Sustainability Performance in Early Phases of Product Design: A Checklist for Sustainable Product Development Tested in the Automotive Industry." *Journal of Cleaner Production* 140: 1602–1617. https://doi.org/10.1016/j.jclepro.2016.09.195.

Seuring, S., and M. Müller. 2008. "From a Literature Review to a Conceptual Framework for Sustainable Supply Chain Management." *Journal of Cleaner Production* 16, no. 15: 1699–1710. https://doi.org/10.1016/j.jclepro.2008.04.020.

Sharno, M. A., and M. Hiloidhari. 2024. "Social Sustainability of Biojet Fuel for Net Zero Aviation." *Energy for Sustainable Development* 79: 101419. https://doi.org/10.1016/j.esd.2024.101419.

Sikdar, S. K. 2003. "Sustainable Development and Sustainability Metrics." *AICHE Journal* 49, no. 8: 1928–1932. https://doi.org/10.1002/aic.690490802.

Silva, M. E., M. M. C. Fritz, and W. H. El-Garaihy. 2022. "Practice Theories and Supply Chain Sustainability: A Systematic Literature Review and a Research Agenda." *Modern Supply Chain Research and Applications* 4, no. 1: 19–38. https://doi.org/10.1108/mscra-01-2021-0001.

Stadler, N. 2020. *Sustainability Assessments of Research Projects: Exploring the Case of Sustainability Readiness Level (SRL)*. Lund University.

Stahl, B. C., K. Chatfield, C. Ten Holter, and A. Brem. 2019. "Ethics in Corporate Research and Development: Can Responsible Research and Innovation Approaches Aid Sustainability?" *Journal of Cleaner Production* 239: 118044. https://doi.org/10.1016/j.jclepro.2019.118044.

Stankiewicz, A. I., and J. A. Moulijn. 2000. "Process Intensification: Transforming Chemical Engineering." *Chemical Engineering Progress* 96, no. 1: 22–34.

Stilgoe, J., R. Owen, and P. Macnaghten. 2013. "Developing a Framework for Responsible Innovation." *Research Policy* 42, no. 9: 1568–1580. https://doi.org/10.1016/j.respol.2013.05.008.

Tcharkhtchi, A., H. R. Vanaei, A. Lucas, and S. Farzaneh. 2024. *Hydrogen Production, Storage, and Utilization*. CRC Press. https://doi.org/10.1201/9781032718453.

Thakuri, P. K., L. Alkki, and L. Aarikka-Stenroos. 2025. "Digital Technologies Enabling Component Reuse in Circular Value Chains: Using Digital Twin, Internet of Things and Robots in Construction and Manufacturing Sectors." *R&D Management* 55: 1161–1216. https://doi.org/10.1111/radm.12744.

Thorley, J., J. A. Garza-Reyes, and A. Anosike. 2019. "The Circular Economy Impact on Small to Medium Enterprises." *WIT Transactions on Ecology and the Environment* 231: 257–267. https://doi.org/10.2495/WM180241.

Tian, X., and F. You. 2024. "Broaden Sustainable Design and Optimization of Decarbonized Campus Energy Systems With Scope 3 Emissions Accounting and Social Ramification Analysis." *Applied Energy* 373, no. October 2023: 123963. https://doi.org/10.1016/j.apenergy.2024.123963.

Tokede, O., and M. Traverso. 2020. "Implementing the Guidelines for Social Life Cycle Assessment: Past, Present, and Future." *International Journal of Life Cycle Assessment* 25, no. 10: 1910–1929. https://doi.org/10.1007/s11367-020-01814-9.

Tranfield, D., D. Denyer, and P. Smart. 2003. "Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review." *British Journal of Management* 14, no. 3: 207–222. https://doi.org/10.1111/1467-8551.00375.

UNEP/SETAC. 2009. *UNEP-SETAC: Guidelines for SCLA of Product*. United Nations Environment Programme. https://wedocs.unep.org/bitstream/handle/20.500.11822/7912/-GuidelinesforSocialLifeCycleAssessmentofProducts-20094102.pdf?sequence=3&amp%3BisAllowed=.

United Nations. 1948. *Universal Declaration of Human Rights*. United Nations.

Valizadeh, N., H. Azimi-Nejadian, and H. Azadi. 2024. "Conservation Agriculture Measures as a Strategy to Create Sustainable Social and Psychological Changes in Agricultural Communities." *Environmental and Sustainability Indicators* 24: 100522. https://doi.org/10.1016/j.indic.2024.100522.

Vallance, S., H. C. Perkins, and J. E. Dixon. 2011. "What Is Social Sustainability? A Clarification of Concepts." *Geoforum* 42, no. 3: 342–348. https://doi.org/10.1016/j.geoforum.2011.01.002.

Valsaraj, K. T. 2013. "Environmental Sustainability and the Chemical Engineering Profession." *Journal of Chemical and Process Engineering* 1: 1. https://doi.org/10.17303/jce.2014.e101.

Van Hattum-Janssen, N., M. D. S. Fernández, S. Caires, and S. Kahn. 2012. "Social Responsibility in Engineering Curricula." Proceedings of the 40th SEFI Annual Conference 2012—Engineering Education 2020: Meet the Future, December 2016 https://doi.org/10.19091/reced.v1i28.253.

Van Schoubroeck, S., M. Van Dael, S. Van Passel, and R. Malina. 2018. "A Review of Sustainability Indicators for Biobased Chemicals." *Renewable and Sustainable Energy Reviews* 94, no. June: 115–126. https://doi.org/10.1016/j.rser.2018.06.007.

Van Steen, J. 2012. "Modes of Public Funding of Research and Development: Towards Internationally Comparable Indicators." In

OECD Science, Technology and Industry Working Papers, No. 2012/04. OECD Publishing. https://doi.org/10.1787/5k98ssns1gzs-en.

Vanclay, F. 2002. "Conceptualising Social Impacts." *Environmental Impact Assessment Review* 22, no. 3: 183–211. https://doi.org/10.1016/S0195-9255(01)00105-6.

Vanclay, F., A. M. Esteves, I. Aucamp, and D. M. Franks. 2015. *Social Impact Assessment: Guidance for Assessing and Managing the Social Impacts of Projects*. Vol. 1, 98. International Association for Impact Assessment.

Vordoagu, J. J., and C. A. Adams. 2024. "Improvement in Compaction Characteristics of Lateritic Gravel Soils Stabilized With Locust Bean Pod Extract." *African Journal of Applied Research* 10, no. 2: 537–568. https://doi.org/10.26437/ajar.v10i2.843.

Waddock, S. 2008. "The Development of Corporate Responsibility/Corporate Citizenship." *Organization Management Journal* 5, no. 1: 29–39. https://doi.org/10.1057/omj.2008.5.

Walker, H. L., and E. C. Clausen. 2024. "Development of an Introduction to Sustainable Engineering Course as a Chemical Engineering Elective Paper Presented at 2024 ASEE Annual Conference & Exposition." https://doi.org/10.18260/1-2--47181.

Wang, W., A. AL-Huqail, E. Ali, M. Abbas, and H. Assilzadeh. 2024. "Analysis of the Sustainability Index for Ecologically Low-Input Integrated Farming: A Comprehensive Assessment of Environmental, Economic, and Social Impact." *Ecological Modelling* 493, no. September 2023: 110701. https://doi.org/10.1016/j.ecolmodel.2024.110701.

WCED. 1987. *Our Common Future*. Oxford University Press.

West, J. J., A. Cohen, F. Dentener, et al. 2016. "What we Breathe Impacts Our Health: Improving Understanding of the Link Between Air Pollution and Health." *Environmental Science & Technology* 50, no. 10: 4895–4904. https://doi.org/10.1021/acs.est.5b03827.

Yang, Y., L. Li, J. Qu, et al. 2024. "Using an Optimal Digital Twin to Integrate Geoengineering Solutions and ML-Assisted Diagnostics in an Underground Gas Storage System." In *Paper Presented at the Mediterranean Offshore Conference*. https://doi.org/10.2118/223284-MS.

Zimmerman, J. B., P. T. Anastas, H. C. Erythropel, and W. Leitner. 2020. "Designing for a Green Chemistry Future." *Science* 367, no. 6476: 397–400. https://doi.org/10.1126/science.aay3060.