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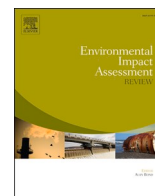
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Environmental impacts of supercritical fluids processes: A critical review of life cycle assessment studies

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ABSTRACT

The application of supercritical fluids (SCF) in industrial and research processes has gained attention in recent years for their unique properties and potential environmental benefits. Frequently described as “green solvents”, SCF can reduce or replace the use of conventional organic solvents. However, broader adoption requires a clear understanding of their full life cycle environmental impacts. Life cycle assessment (LCA) has been widely used to evaluate the environmental performance of SCF technologies.

This study critically reviews 70 LCA studies of SCF processes across various applications through the four phases of LCA: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation to identify methodological gaps and trends in energy use, solvent consumption, and environmental impacts. Despite variability in modelling approaches, process-level trends emerge: for gasification, global warming results range from -0.2 to $5 \text{ kg CO}_2\text{eq.kg}_{\text{input}}^{-1}$; for extraction from 0.2 to $153 \text{ kg CO}_2\text{eq.kg}_{\text{input}}^{-1}$ depending on feed and scale. Contribution analyses highlight that energy is the main hotspot, especially in supercritical water gasification and transesterification, even though yielding higher-quality output and lower solvent consumption. Benchmarking results are mixed: 27 studies reporting lower environmental impacts for SCF processes, while 18 studies report higher impacts, especially in extraction applications. Sensitivity analyses highlight the influence of electricity mix, feed concentration, and solvent recycling on LCA outcomes.

This review provides targeted recommendations to enhance consistency and accuracy in future LCA studies. By synthesizing current findings, it supports the development of more sustainable SCF technologies from early stage to support their broader adoption.

1. Introduction

Supercritical fluids (SCF) are described in a distinct domain, above its critical temperature (T_c) and pressure (p_c), where fluids exhibit intermediate physical and chemical properties between gas and liquid phases. These properties – such as density, viscosity and diffusivity - can be tuned by varying temperature and pressure, enabling SCFs to serve a variety of functions, including solvents, anti-solvents, or reagents (Li and Xu, 2019; Knez et al., 2014; Manjare and Dhingra, 2019). Their versatility makes SCFs highly promising for a wide range of applications, including synthesis, extraction, recycling, and waste treatment processes (Knez et al., 2019; Munshi and Bhaduri, 2009). In particular, the use of SCFs demonstrates a wide range of alternative processes that

totally or partially replace the use of organic solvents (Knez et al., 2014). One prominent example is the use of SCFs in extraction, such as in caffeine or oil removal, where SCFs act as effective nontoxic solvents. The critical parameters—temperature and pressure—needed to achieve this domain vary across fluids. For instance, water has a critical temperature of $374 \text{ }^\circ\text{C}$ and a critical pressure of 221 bar, while carbon dioxide (CO_2) reaches its critical point at $31 \text{ }^\circ\text{C}$ and 73.8 bar. Ethanol and methanol exhibit critical temperatures of $241 \text{ }^\circ\text{C}$ and $239 \text{ }^\circ\text{C}$, with corresponding critical pressures of 62.7 bar and 81 bar, respectively (Aymonier et al., 2018). These variations in critical conditions influence the physicochemical properties of supercritical fluids, thereby determining their suitability for diverse industrial applications, including extraction, reaction engineering, and material processing.

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The development of SCF technologies has been particularly active in recent decades, as researchers and industry aim to demonstrate their environmental and economic feasibility compared to conventional methods (Chemat and Vian, 2014; Preetam et al., 2023). SCFs have shown notable potential to reduce environmental impacts across various industrial processes, leading to their adoption in diverse applications such as green chemistry, pharmaceutical extraction and drug particle formulation (Chakravarty et al., 2019), food industry processes (e.g., decaffeination of coffee and tea) (Peker et al., 1992), and the synthesis of advanced materials (Aymonier et al., 2006).

As aforementioned, the environmental benefits of SCFs are associated with their ability to minimize the reliance on conventional organic solvents. By utilizing the adjustable chemical and physical properties of SCFs, the need for volatile organic compounds, such as hexane, typically employed in traditional extraction technologies, can be substantially reduced (Manjare and Dhingra, 2019). However, the extent of these environmental benefits is highly dependent on specific process parameters, including energy requirements, infrastructure demands, and the use of co-solvents, and therefore requires rigorous evaluation and validation.

Life Cycle Assessment (LCA) is an international standardized method for evaluating the environmental impacts of a product or process across its entire life cycle, from raw material extraction to disposal (International Organisation for Standardization, 2006a). LCA is an effective method to evaluate trade-offs and guide the design of

sustainable processes even from lab-scale (Thonemann and Schulte, 2019). In recent years, there has been a growing interest in assessing environmental impacts and optimizing SCF processes through eco-design strategies. While prior reviews, such as Kamjam et al., have recognized the need for LCA in evaluating SCF's environmental impacts (Kamjam et al., 2024), they have not conducted the kind of structured and in-depth analysis presented here. Similarly, works by Hessel et al. have focused more broadly on technical aspects of SCF technologies, without applying a systematic LCA framework to discuss gaps and trends (Hessel et al., 2022).

The analysis begins with a broad categorization of relevant LCA studies using a landscape grid to provide an overview of existing knowledge. This is followed by an in-depth analysis of 70 selected case studies focusing on the four phases of LCA standards (International Organisation for Standardization, 2006a) – goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation of results. Although all reviewed studies aim to provide quantitative insights to support the development of emerging SCF technologies, they vary significantly in scope and focus. By critically analysing these 70 studies, this review identifies methodological inconsistencies, highlights key environmental hotspots, and offers practical recommendations to improve future assessments. Through this structured approach, grounded in the four LCA phases, this review seeks to promote more robust and consistent LCA studies, ultimately supporting the development and broader adoption of SCF technologies.

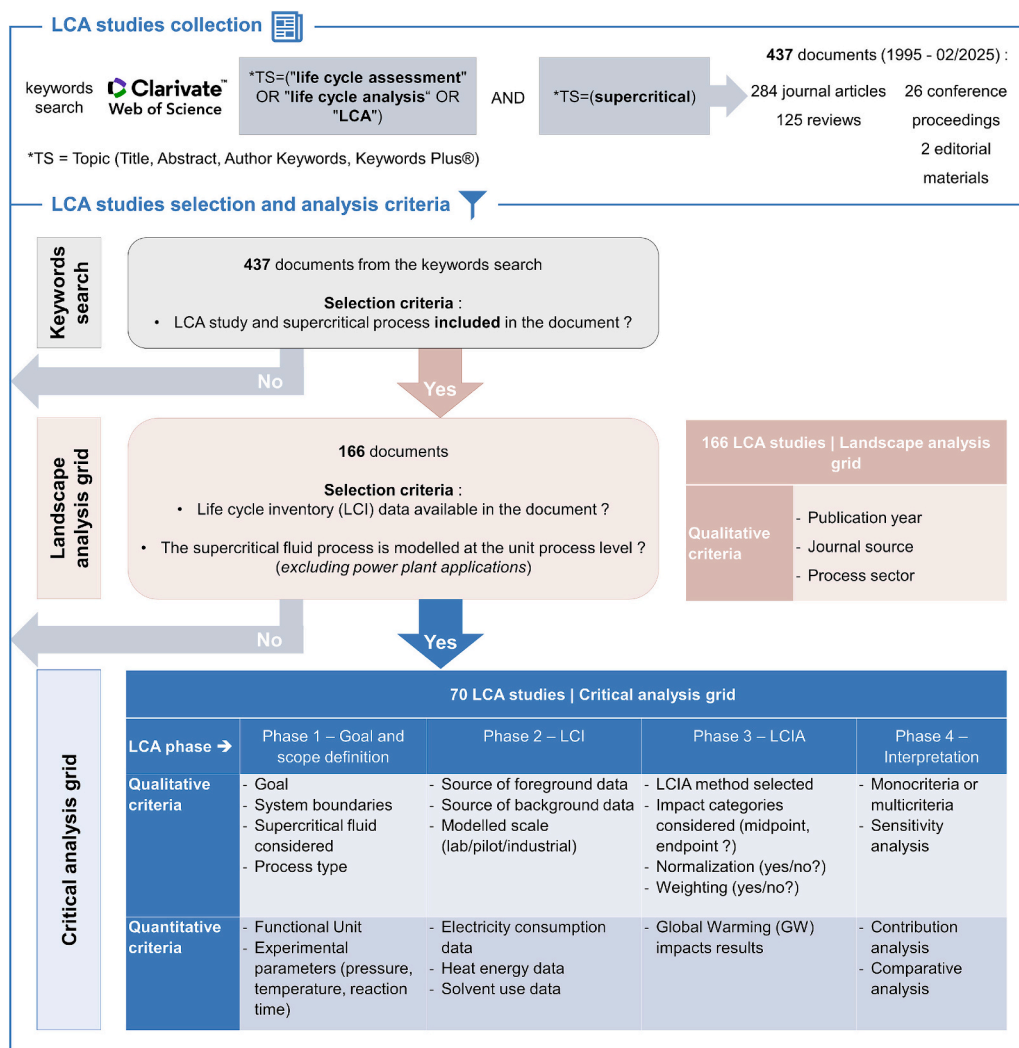


Fig. 1. Review method for articles collection, selection and analysis based on 2 grids: a landscape grid and a critical review grid based on the 4 phases of LCA.

2. Materials and methods

2.1. Selection of LCA papers dealing with supercritical fluid processes

As illustrated in Fig. 1, the initial document pool consisted of 437 papers identified through the following words search in Web of Science: (“life cycle assessment” OR “life cycle analysis” or “LCA”) AND “supercritical”. Each document was manually screened against two primary selection criteria:

- The paper must be an LCA study or contain a dedicated LCA section,
- The paper must discuss a supercritical fluid-based process within the LCA context.

After applying these criteria, 166 papers were selected for the landscape analysis. This subset provides insights into the increasing focus on assessing the environmental impacts of SCF processes. The analysis includes trends across different sectors, countries, and journals, illustrating the growing academic and industrial interest in SCF environmental assessments.

For the critical review, additional quantitative and qualitative information aligned with the four phases of LCA are required. This includes disclosing LCI data and modelling the supercritical fluid process at the unit process level—the smallest modelling entity in LCA—both serving as key selection criteria for the review grid. This approach ensures the collection of process-specific data for accurately assessing the technology’s environmental implications. Power plant applications were excluded from this analysis, as they are typically modelled at the plant level, making it impossible to isolate data specific to the supercritical fluid process. Supercritical fluids are commonly used in such applications due to their high thermal efficiency and enhanced heat transfer properties, which enable a more efficient energy conversion (Kamjam et al., 2024; Wang et al., 2025). As a result, 70 LCA papers were selected for the critical review.

2.2. Analysis criteria

2.2.1. Global analysis grid criteria (landscape)

The analysis criteria for this landscape review (166 papers) include journal sources, years of publication, and process sectors. Examining journal sources helps to identify the main publishers and research contributors in the field. Analysing publication years allows for tracking trends and developments over time. Finally, categorizing studies by process sectors provides insights into the industries where supercritical fluid processes are the most commonly applied.

2.2.2. Critical analysis grid criteria

The analysis criteria for the critical review (70 papers) follow the four established phases of LCA, as defined by ISO standards (International Organisation for Standardization, 2006a): phase 1 – definition of goal and scope, phase 2 – life cycle inventory, phase 3 – life cycle impact assessment, and, phase 4 – interpretation of the results. The set of criteria is detailed below and a summary is provided in Fig. 1.

2.2.2.1. Criteria for LCA phase 1 – goal and scope. The goals of the studies vary based on their intended applications and motivations. In this review, they are categorized according to goal archetypes commonly found of goals definitions found in the literature (Schrijvers et al., 2020). These goals fall into three categories: (i) ecodesign, where LCA is used to guide process development and establish strategies to reduce environmental impacts; (ii) benchmarking, which compares supercritical fluid processes with conventional alternatives to demonstrate their (potential) relevance; and (iii) quantification, which focuses on identifying environmental hotspots without necessarily proposing specific improvements. In analysing the scope definitions, we examined

several key elements, including: the choice of functional unit (FU), system boundaries—specifically, whether and how inputs are modelled within the studies, and the specific process components considered, such as energy, chemicals, infrastructure, and waste.

2.2.2.2. Criteria for LCA phase 2 – LCI. The LCI phase involves tracking all material and energy flows in and out of the modelled system, including those identified in the steps in the goal and scope phase—namely, energy, chemicals, infrastructure, and waste. These flows are categorized as either foreground or background data. The foreground system consists of processes directly controlled by the decision-maker involved in the study, while the background system encompasses processes that are part of the system but not directly managed, with data typically sourced from established LCA databases. Data sources for the foreground system vary, including literature reviews, manual calculations, primary experimental data, and process simulations, a tool to extract LCI data discussed in the review by Gutiérrez Ortiz et al. (Gutiérrez Ortiz and Kruse, 2020). Background data, on the other hand, often requires access to specific databases, which may be either subscription-based or freely available.

Another key criterion is the modelled scale—whether the data are drawn from lab-scale, pilot-scale, or industrial-scale processes. If scale-up adjustments were applied, these were carefully documented in the analysis. In terms of data type, we collected and reviewed values related to feedstock, raw material inputs and products outputs, nature and quantity of solvent, key parameters (temperature, pressure, and reaction time with the supercritical fluid), as well as any secondary solvents used, including their types and quantities. Finally, data on heating energy and electricity consumption was also collected, as these energy metrics are of particular interest to experts in the field.

2.2.2.3. Criteria for LCA phases 3 and 4 – LCIA and interpretation. The criteria used to analyse the LCIA phase of the case studies include the selected LCIA methodology, the range of impact and damage categories considered, and whether normalization and weighting—optional elements—were applied.

In Phase 4, interpretation criteria focus on whether studies conducted a mono- or multicriteria analysis, addressed contribution analysis, performed comparative analysis, examined sensitivity scenarios, discussed quantitative results, and outlined key conclusions regarding their processes. Specific LCIA results were collected and compared across studies that share relevant characteristics, such as the type of fluid, modelled scale, and process type. To ensure consistency, global warming (GW) impact results were harmonized based on input and output values among studies with similar parameters.

3. Results

3.1. Overview of the landscape analysis

The landscape analysis reveals that supercritical fluid technologies are primarily applied to four key sectors: energy (45 %), chemicals (26 %), recycling and waste treatment (21 %) and materials (8 %), as presented in Fig. 2 (pie chart). There is a notable growth in interest over time, particularly in the last decade, reflecting increasing attention to address sustainability and evaluating the environmental impacts of supercritical fluids processes in different sectors, especially energy and chemicals. A clear increase is observed from 2010 onward, with a peak in 2020–2024.

While many documents were excluded during the screening process, the share of publications meeting our review criteria has steadily grown since 2016. The steady growth of these publications meeting the landscape or critical review criteria from 2016 onward underscores a shift toward more structured, focused assessments of environmental impacts in these studies, especially following LCA framework. Moreover, SCFs

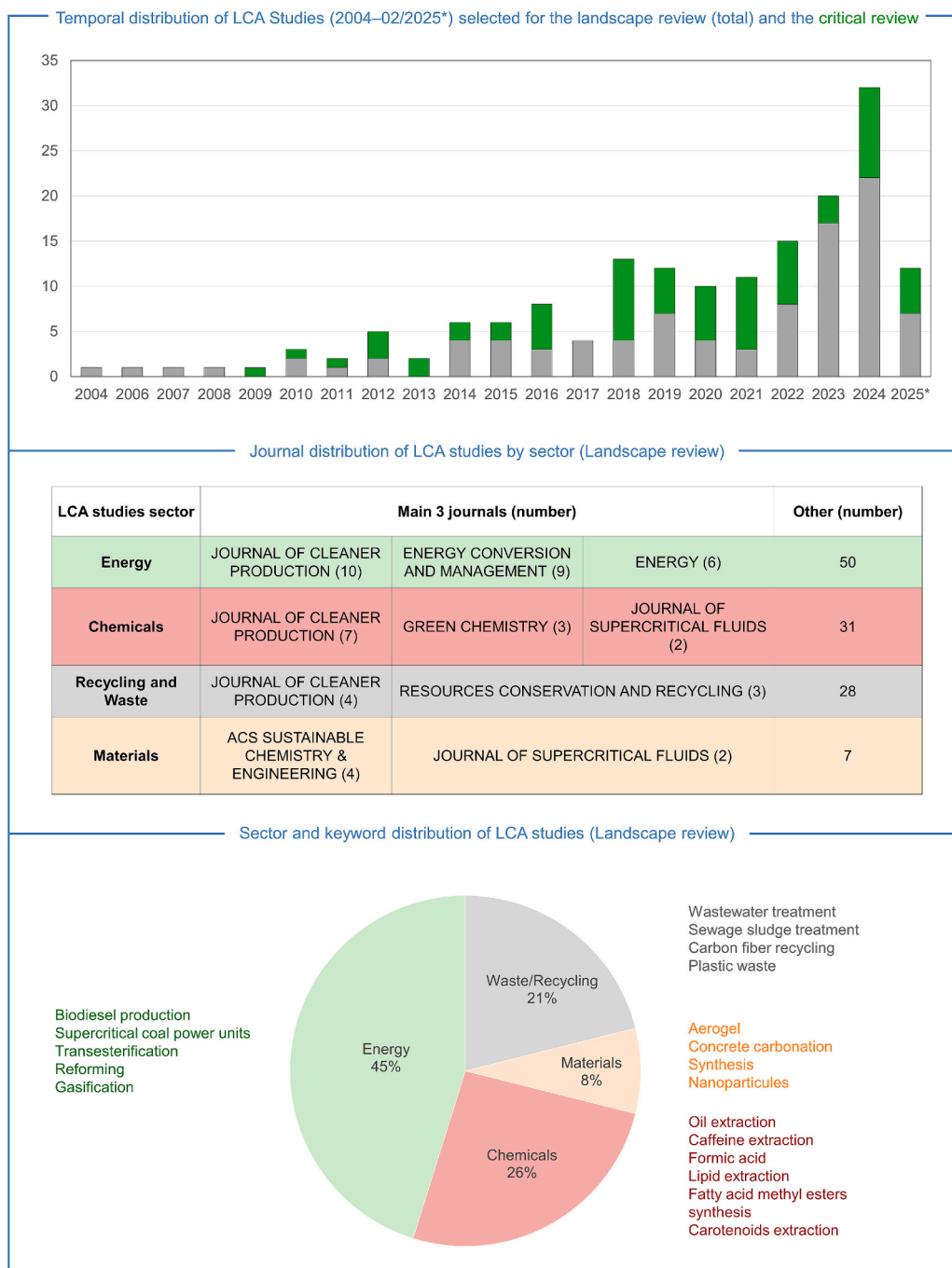


Fig. 2. Overview of LCA studies collected in the landscape review. The top graph shows the temporal distribution of publications (2004–2025), with selected critical review papers in green. The middle table presents the main journals by sector. The bottom pie chart illustrates the sectoral distribution and key research topics. *2025 papers only cover January and February 2025, date at the last keywords search. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are increasingly referenced in broader discussions on green technologies and cleaner production, underscoring their relevance in sustainability research (Hessel et al., 2022; Ramsey et al., 2009).

3.2. Types of processes for the critical review

After conducting the landscape analysis of 166 papers, we narrow our focus to 70 studies that met our selection criteria for the critical review. The selected studies span various supercritical fluid applications, which we categorize into seven process types: gasification/reforming, extraction, transesterification, recycling, waste treatment,

synthesis, and drying.

Among the reviewed studies, extraction processes were the most frequently analysed (37 %), followed by gasification and reforming (21 %). Energy-related studies primarily focus on supercritical water gasification, while chemical studies emphasize extraction and synthesis processes. As shown in Fig. 3, supercritical fluids are widely applied across various processes:

Gasification and reforming consist of using supercritical water (sc-H₂O) to decompose organic molecules in the absence of oxygen through hydrothermal reactions (Pinkard et al., 2019). Depending on the desired output, the process is classified as reforming, which aims to produce

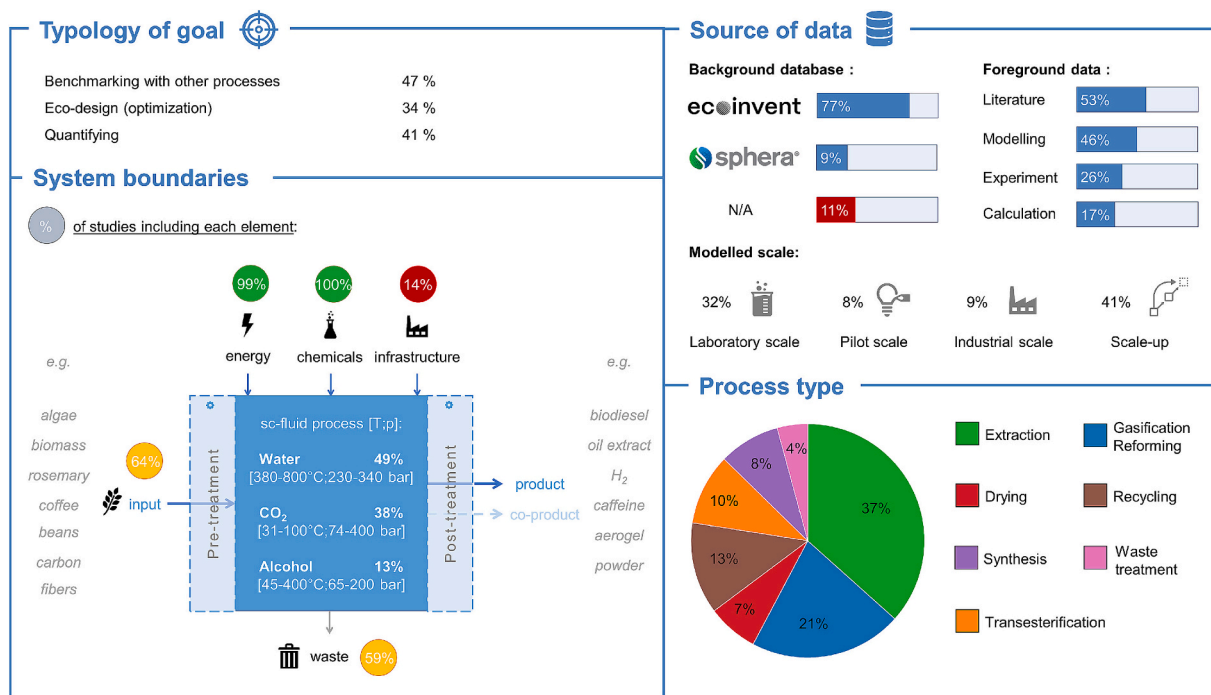


Fig. 3. Quantitative results of the reviewed paper after screening for the critical analysis.

hydrogen (H₂), or gasification, which involves three main reactions such as steam reforming converting biomass in sc-H₂O into a mixture of H₂ and CO, followed by the water-gas shift reaction where CO reacts with water to form CO₂ and H₂, and finally methanation, where CO reacts with H₂ to produce methane (CH₄) and water.

Transesterification processes involve an alcohol in supercritical conditions (e.g. methanol or ethanol) to produce biodiesel from triglycerides found in vegetable oils and animal fats by obtaining the corresponding ester without the need of a catalyst (Ngamprasertsith and Sawangkeaw, 2011).

Extraction processes employ supercritical CO₂ (sc-CO₂) or sc-H₂O to selectively recover valuable compounds such as lipids from plants or algae, particularly for biodiesel production (Cooney et al., 2009). Other common target extractions involve protein (McKuin et al., 2023; Syrpas et al., 2018), rosemary leaves oil (Rodríguez-Meizoso et al., 2012; Moura et al., 2022), beta-carotene (Ferreira et al., 2024; Espada et al., 2020), antioxidants (Arias et al., 2022), and phenolic compounds from spruce bark (Carlqvist et al., 2022) or asparagus (Santiago et al., 2021).

Waste treatment processes include supercritical water oxidation for wastewater treatment eliminating organic pollutants, in the presence of oxygen from sewage sludge (Loppinet-Serani et al., 2010) and printing ink wastewater (Yuan et al., 2025). Additionally, sc-CO₂ has been employed for surface cleaning, effectively removing paint, carbon deposits, grease, and rust from various materials (Peng et al., 2016).

In recycling applications, supercritical fluids, including sc-CO₂, sc-butanol and sc-H₂O, are used to remove pollutants from polymers, recycle carbon fibers from carbon fiber-reinforced polymers (CFRPs), recycle asphalt, and recover valuable metals from Li-ion batteries (Pillain et al., 2019; Khalil, 2018; Hermansson et al., 2022; Arena and Ardolino, 2022; Liu et al., 2021; Premathilake et al., 2024; Li et al., 2024). The choice of solvent depends on factors such as solubility, reaction requirements, and separation efficiency (Goto, 2009).

Synthesis processes cover chemicals and materials synthesis where sc-H₂O is commonly used for the synthesis of talc (Glogic et al., 2021), titanium dioxide (TiO₂) nanoparticles (Tsang et al., 2018), and barium strontium titanate Ba_{1-x}Sr_xTiO₃ (Tsang et al., 2016), while sc-CO₂ has been applied in the synthesis of formic acid (Thonemann and Schulte, 2019).

Finally, **drying** processes with sc-CO₂ enable the production of aerogels for diverse applications, including drug delivery (e.g., starch aerogels (De Marco et al., 2018a; De Marco et al., 2019; De Marco et al., 2016)), tissue engineering (e.g., PLA aerogels (Gay et al., 2018)), and insulation materials (e.g., silica aerogels) (Dowson et al., 2012).

The specificities of these processes, including their inputs, outputs, quantities, and environmental considerations, will be discussed in the following section.

3.3. Phase 1: goal and scope definition

3.3.1. Goal of the studies

The goals of the studies are categorized into three types according to literature (Schrijvers et al., 2020), with their respective percentages shown in Fig. 3, where studies can pursue multiple goals at once. Approximately one-third (41 %) aim to quantify the environmental impacts of their processes, focusing primarily on determining their environmental footprint. Among these, some also compare their results with existing literature or alternative scenarios, although such comparisons are not always explicitly stated as an initial goal. Notably, only five studies did not include any form of comparison while focusing on quantifying the environmental impacts.

Another third approximately of these studies (accounting for 34 % of the total) prioritized identifying and addressing hotspots in their processes to lower the environmental impacts of their scenarios, highlighting eco-design strategies as the main stated goal.

Finally, a significant proportion of LCA studies (47 %) explicitly stated their primary goal as performing a benchmark analysis. These studies aimed to compare their results and demonstrate the environmental advantages of their supercritical fluid processes, standing apart from studies that solely focused on assessment.

3.3.2. Scope, FU, system boundaries, life cycle steps

Table 1 summarizes key elements collected from the 70 papers under review, categorized by process type, functional unit (FU), elements considered, modelled scale, feed type, and nature of supercritical fluid (sc-fluid) used. For better readability, the data is also available in Supporting Information (SI). The choice of functional unit varies across

Table 1

Key elements from the critical review analysis of the 70 papers. Elements of the process are abbreviated: Input = In; Energy = En; Chemicals = Chem; Infrastructure = Infra; Waste = W.

Reference	Process type	Functional unit	Elements of the process considered	Modelled scale	Feed type (input)	Sc-fluid
Kiwjaroun et al., 2009	Transesterification	1 kg of biodiesel based on 100,000 tons of annual production capacity	En, Chem, W	scale-up	palm oil	Methanol
Morais et al., 2010	Transesterification	1000 kg of biodiesel	In, En, Chem, W	scale-up	waste vegetable oil	Methanol
Brentner et al., 2011	Extraction/ Transesterification	Production of 10 GJ Algal biodiesel	In, En, Chem, Infra, W	scale-up	algae	CO ₂ / methanol
Rodríguez-Meizoso et al., 2012	Extraction	10 g rosemary extract having an equivalent antioxidant activity	En, Chem, W	lab	Rosemary	CO ₂
Sawangkeaw et al., 2012	Transesterification	1 kg of biodiesel based on 100,000 tons of annual production capacity	En, Chem	scale-up	crude palm oil	Methanol/ Ethanol
Dowson et al., 2012	Drying	1 m ³ of aerogel	In, En, Chem	lab	aerogel	Methanol
Ferreira et al., 2013	Extraction	1 MJ of biodiesel	In, En, Chem	lab	microalga	CO ₂
Kralisch et al., 2013	Transesterification	1 kg of biodiesel	En, Chem, W	lab/scale-up	waste oil	Methanol
Pérez-López et al., 2014	Extraction	1 kg of valorized biomass	In, En, Chem, W	lab	macroalgal (<i>S. muticum</i>)	CO ₂
Kiss et al., 2014	Transesterification	1 kg of biodiesel produced	In, En, Chem	lab	rapeseed oil	Methanol/ Ethanol
Galera and Gutiérrez Ortiz, 2015	Reforming	1 kg of H ₂ produced	In, Chem, W	lab	glycerol	Water
Chan et al., 2015	Extraction	1 kg of bio-oil produced	En, Chem	scale-up	oil palm biomass	Water
Monari et al., 2016	Extraction	1 MJ of biodiesel	In, En, Chem	lab	algae (<i>Nannochloropsis</i>)	CO ₂
Shimako et al., 2016	Extraction	1 MJ of produced energy	In, En, Chem, Infra, W	scale-up	microalgae	CO ₂
De Marco et al., 2016	Drying	1 g of final aerogel	In, En, Chem	lab	aerogel	CO ₂
Tsang et al., 2016	Synthesis	1 kg of dry BST (Barium Strontium Titanate) nanoparticles	In, En, Chem, W	lab/scale-up	barium isopropoxide; titanium isopropoxide; strontium isopropoxide	Water
Peng et al., 2016	Waste treatment	Cleaning a square meter of paint and oil fouling on the workpieces' surface until reach certain cleanliness	En, Chem, Infra, W	scale-up	N/A	CO ₂
Lombardi et al., 2018	Transesterification	1 ton of used cooking oil	En, Chem	lab	used cooking oil (mixture of 99.8 % triolein and of 0.2 % oleic acid)	Methanol
Albarelli et al., 2018	Extraction	Extraction of lipids and proteins from wet microalgal biomass	In, En, Chem, W	lab	algae	CO ₂
Chan et al., 2018	Extraction	1 kg of bio-oil extract (containing improved phenol concentration of ~7–8 wt% as compared to ~5 wt% in raw bio-oil)	En, Chem	scale-up	milled palm kernel shell (PKS)	CO ₂
De Marco et al., 2018a	Drying	1 g of starch aerogel obtained on bench or pilot scale plant	In, En, Chem	lab/pilot/ industrial	alcogel from corn starch	CO ₂
Syrpas et al., 2018	Extraction	Production of 1 g of oil extract	En, Chem, W	lab	cyanobacterial biomass	CO ₂
De Marco et al., 2018b	Extraction	1 kg of decaf blend coffee beans (600 g of Arabica and 400 g of Robusta) corresponding to 11.4 g of dry caffeine recovered from the blend	In, En, Chem	industrial	coffee beans	CO ₂
Gay et al., 2018	Drying	50 units of PLA scaffolds of 1 mL each	In, En, Chem	scale-up	polymer solution	CO ₂
Tsang et al., 2018	Synthesis	1 kg of dry nano-TiO ₂ powder	In, En, Chem, W	scale-up	titanium isopropoxide	Water
Khalil, 2018	Recycling	1 kg of carbon fiber reinforced polymer	En, Chem, W	N/A	carbon fiber reinforced polymer (CFRP)	Water
De Marco et al., 2019	Drying	120 mg SA tablet containing the daily therapeutic dose of TOC (15 mg)	In, En, Chem	industrial	alcogel - from starch	CO ₂
Thonemann and Schulte, 2019	Synthesis	Production of 1 kg of FA in commercial purity grade (85.0 wt%)	In, En, Chem, Infra, W	lab/scale-up	aqueous solution	CO ₂
Chen et al., 2019	Gasification	1 kg H ₂	In, En, Chem, Infra, W	pilot	wood sawdust	Water
García-García and Rahimifard, 2019	Extraction	1.35 kg of pure wax obtained in one valorisation batch	In, En, Chem, W	industrial	barley straw	CO ₂
Pillain et al., 2019	Recycling	Managing the end of life of 1 kg of CFRP composed of 60 wt% carbon fibers and 40 wt % resin	En, Chem, W	scale-up	carbon fiber reinforced polymer (CFRP)	Water
Bora et al., 2020	Gasification	Management of 1000 kg of fresh or wet poultry litter with a 25 % w/w moisture content	En, Chem, Infra, W	N/A	poultry liter	Water
Pankratz et al., 2020	Gasification	Production of 1 MJ of energy from algae cultivation	In, En, Chem	industrial	algae	Water

(continued on next page)

Table 1 (continued)

Reference	Process type	Functional unit	Elements of the process considered	Modelled scale	Feed type (input)	Sc-fluid
Gutiérrez Ortiz et al., 2020	Reforming	1 MJ biofuel	In, En, Chem, W	scale-up	aqueous phase from bio-oil (pine wood chips)	Water
Fózer et al., 2020	Gasification	1 kWh retrieved electricity from storage	In, En, Chem	scale-up	microalgae (<i>Spirulina platensis</i>)	Water
Espada et al., 2020	Extraction	1 kg of β -carotene with a plant capacity of 8 tons year ⁻¹	In, En, Chem, W	industrial	dried biomass from microalgae (<i>Dunaliella salina</i>)	CO ₂
Gwee et al., 2020	Extraction	Extraction of 1 kg of crude volatile oil	In, En, Chem	scale-up	lignified biomass (<i>Aquilaria sinensis</i>)	CO ₂
Iannotta et al., 2020	Gasification	1 ton of treated waste: carbon black, heavy oil, and leachate	En, Chem	pilot	carbon black; heavy oil; leachate	Water
Khalil, 2021	Reforming	1 kg of produced H ₂	In, En, Chem	N/A	glycerol	Water
Bussa et al., 2021	Extraction	1 kg of algal biomass	In, En, Chem, Infra, W	scale-up	microalgae (<i>C. vulgaris</i>)	CO ₂
Yan et al., 2021	Extraction	1 kg of bio-oil output	En, Chem, W	lab	palm kernel shell (PKS)	Water
Santiago et al., 2021	Extraction	1 kg of rutin	En, Chem, W	lab	asparagus waste	CO ₂
Liu et al., 2021	Gasification	1 kg of ammonia	In, En, Chem, Infra	scale-up	algae	Water
Glogic et al., 2021	Synthesis	Gel containing 1 kg of synthetic talc	In, En, Chem, W	lab/scale-up	sodium metasilicate; magnesium acetate; acetic acid	Water
Liu et al., 2021	Recycling	Treatment of 1 kg CFRP waste	In, En, Chem, Infra, W	pilot	carbon fiber reinforced polymer (CFRP)	n-butanol
Chen et al., 2022	Gasification	1 ton of SSF (simultaneous saccharification and fermentation) residue	En, Chem	scale-up	corn stover residue (SSF)	Water
De Marco, 2022	Synthesis	180 mg tablet consisting of 150 mg of PVP and 30 mg of prednisolone	In, En, Chem	scale-up	PVP + PDS solution	CO ₂
Carlqvist et al., 2022	Extraction	Production of an extract with 1 kg phenolic compounds	In, En, Chem, W	scale-up	spruce bark (<i>Picea abies</i>)	CO ₂
Arias et al., 2022	Extraction	Production of 1 g of antioxidant extract, with a purity of 95 %	In, En, Chem, W	scale-up	beet leaves/beet stalk residues	CO ₂
Moura et al., 2022	Extraction	1 g of aromatic extract/1 g of alpha-pinene	En, Chem, W	lab	rosemary	CO ₂
Arena and Ardolino, 2022	Extraction	Management of 1 t of the selected polymers	En, Chem, W	N/A	plastic waste	CO ₂
Hermansson et al., 2022	Recycling	The service provided by one piece of fictitious product φ used for σ years	In, En, Chem	N/A	composite (70 % polyamide +30 % carbon fiber)	Water
McKuin et al., 2023	Extraction	1 kg crude protein	In, En, Chem, W	scale-up	microalgae (<i>Nannochloropsis</i> sp.)	CO ₂
Liang et al., 2023	Gasification	1 ton of printing paper	In, En, Chem	pilot	black liquor	Water
Krzyżaniak et al., 2023	Extraction	1 kg of packaged dry extract	In, En, Chem	industrial	poplar biomass	CO ₂
Ferreira et al., 2024	Extraction	obtaining 1 kg of carotenoids	In, En, Chem	lab	dry biomass	CO ₂
Qiu et al., 2024	Gasification	N/A	En, Chem	N/A	oily sludge sewage	Water
Li et al., 2024	Recycling	The production of 1 ton of alternative asphalt mixtures for road pavements located in China	In, En, Chem, W	scale-up	crumb rubber	CO ₂
Huang et al., 2024	Gasification	1 ton of crude steel produced	En, Chem	scale-up	black liquor	Water
Premathilake et al., 2024	Recycling	The treatment of 1 kg of NMC111 cathode active material	En, Chem, W	scale-up	NMC111 cathode active material	CO ₂
Arias et al., 2024	Extraction	1 batch process	In, En, Chem, W	lab	algae	CO ₂
Fonseca-Pérez et al., 2024	Extraction	1 kg of grape seed oil produced at the refinery	In, En, Chem, Infra, W	scale-up	grape pomace	CO ₂
Sadeghi Sheshdeh et al., 2024	Gasification	The management of 1000 kg bagasse/1 kWh net electricity	En, Chem, W	N/A	bagasse biomass	Water
Silva et al., 2024	Recycling	One aeronautic composite laminate	In, En, Chem, W	pilot	aeronautic carbon composite residues	Water
Yuan et al., 2025	Waste treatment	COD removal capacity of 268.8 kg	En, Chem	scale-up	printing ink wastewater (high COD wastewater)	Water
Deng et al., 2025	Gasification	1 kg of dry sewage sludge (DDS)	En, Chem, W	scale-up	sewage sludge	Water
Caudle et al., 2025	Recycling	Mass of recycled PP that has been extruded into pellets	In, En, Chem, W	lab	plastic waste (PP 24 %wt.)	propane
Peng et al., 2025	Synthesis	Preparing 1 kg of Cu	In, En, Chem	lab	biomass	Water
Yanhong et al., 2025	Waste treatment	1 kg of shrimp shell consumption	En, Chem, W	lab	shrimp shell	CO ₂
Vogiantzi and Tserpes, 2025	Recycling	1 kg of CFRP waste	In, En, Chem, W	lab	CFRP waste	Water

process types, reflecting their different objectives.

Gasification and reforming processes primarily use energy and mass-based FUs, such as 1 MJ of energy produced (Gutiérrez Ortiz et al., 2020; Pankratz et al., 2020) or 1 kg of hydrogen generated (Khalil, 2021; Chen et al., 2019; Galera and Gutiérrez Ortiz, 2015). Most gasification LCA studies model the input feedstock characteristics, due to its

influence on the process efficiency. However, two studies took different approaches – one attributed the environmental impact of the input to an upstream system by applying a cut-off method (Chen et al., 2022), while another assumed the feedstock to be identical across scenarios for benchmarking purposes (Bora et al., 2020).

Extraction studies often define FU in terms of mass-based outputs,

such as 1 kg of crude protein (McKuin et al., 2023), oil extract (Syrpas et al., 2018; Chan et al., 2018), or carotenoids (Ferreira et al., 2024; Espada et al., 2020), caffeine (De Marco et al., 2018b). Purity-based criteria can be used in the FU definition, such as 1 g of antioxidant extract with 95 % purity (Arias et al., 2022).

Transesterification processes for biodiesel production frequently express FU in terms of mass and energy content, such as 1 kg (Kralisch et al., 2013; Sawangkeaw et al., 2012; Kiwjaroun et al., 2009; Kiss et al., 2014) or 1 ton (Morais et al., 2010), or 10 GJ (Brentner et al., 2011) of biodiesel, allowing direct comparison with other energy sources.

Recycling and waste treatment studies define FU based on waste management goals, such as 1 kg of treated composite waste, that can be polymer waste (Arena and Ardolino, 2022; Caudle et al., 2025), carbon fiber waste (Pillain et al., 2019; Khalil, 2018; Liu et al., 2021), or spent Li-ion batteries (Premathilake et al., 2024), but also for example shrimp shell valorisation (Yanhong et al., 2025).

Synthesis processes focus on the output quantity such as 1 kg in the case of nanoparticles of titanium oxide (Tsang et al., 2018), or barium strontium titanate (Tsang et al., 2016), or still for synthetic talc (Glogic et al., 2021) but also for pharmaceuticals applications for example tablets with a quantity of therapeutic dose (De Marco et al., 2019).

Drying cover aerogel preparation, with FU expressed per unit of aerogel prepared (De Marco et al., 2018a).

Regarding modelled scale, process types exhibit distinct trends. Gasification studies are often modelled at pilot scale or with a scale-up projection, demonstrating efforts to transition from laboratory research to industrial application. Extraction studies, on the other hand, exist at lab scale but also at industrial scale, such as for the caffeine extraction.

As presented in Fig. 3 on the system boundaries data, the elements considered across studies reveal key priorities in process assessment. Energy and chemical usage are the most frequently analysed elements in the system boundaries, whereas infrastructure and waste management are often overlooked due to limited availability of primary data – only 14 % and 59 % of studies include these elements, respectively.

In terms of supercritical fluid usage, 49 % of case studies employ water, 38 % use CO₂, and 13 % alcohols. CO₂ is mainly used in extraction processes, while water is commonly applied in gasification and reforming. Methanol and ethanol are primarily involved in transesterification, serving as reactants in biodiesel production.

3.4. Phase 2: life cycle inventory

Source of data. Foreground LCI data originates from direct measurements (26 %), from industrial processes real data, laboratory experiments, or pilot-scale plants. Additionally, 46 % of foreground data is derived from process modelling using software like Aspen Plus, Aspen HYSYS, or SuperPro Designer. Literature sources also play a considerable role, either as the sole data source or in combination with experiments or modelling, contributing to 53 % of foreground data in the studies under review.

Background data is often drawn from LCA databases, with ecoinvent (versions 2.2 to 3.6) being the most cited due to its extensive coverage of international LCI (77 % of the papers under review). Other databases include Sphera (formerly GaBi) database, the European Life Cycle Database (ELCD), and Agri-footprint. However, eight studies do not specify the database used. A summary of the distribution of foreground and background data sources is presented in Fig. 3.

Modelled scale. The modelled scale is important in LCA, especially for emerging technologies like supercritical fluids. While some industrial applications exist (e.g., decaffeination), a significant portion of studies (32 %) focus on lab-scale processes. At this stage, LCA results are influenced by limited process optimization and incomplete data on infrastructure, waste generation, and energy efficiency.

Scaling up data from laboratory experiments to project outcomes at industrial scale is the most common approach in the reviewed studies,

representing 41 % of cases. This shift increasingly relies on process simulations for LCI data generation, especially to benchmark against conventional processes at the industrial scale, as lab-scale models often rely on approximations. A smaller share evaluates pilot (8 %) or industrial-scale (9 %) implementations.

Fig. 4 categorizes processes by solvent type (CO₂, water, alcohol) on the x-axis and displays key parameters extracted from the 70 LCA studies (e.g., solvent use, energy inputs, GW per kg input) on a log-scaled y-axis. Process types are color-coded. Data used are detailed in the Supporting Information (SI). Table 2 presents the ranges of solvent use, energy consumption, and global warming impacts, categorized by process type, solvent, and modelled scale.

Solvents. The consumption of solvents in supercritical fluids-based processes varies widely based on the process type, scale, and optimization level, as shown in Fig. 4 (third panel from the left). For sc-CO₂-based processes, extraction requires between 10 g and 4 kgCO₂.kg_{input}⁻¹ (i.e. quantity of solvent CO₂ per kg of input) which can rise up to 40 kg for more resource-intensive extractions, in the case of algae extraction (Syrpas et al., 2018; Pérez-López et al., 2014). Aerogel drying generally uses 35–78 kgCO₂.kg_{input}⁻¹ (De Marco et al., 2018a; De Marco et al., 2019; Gay et al., 2018), while synthesis and precipitation processes consume around 20 kgCO₂.kg_{input}⁻¹ (De Marco, 2022). However, extreme inefficiencies are observed at the lab scale, where aerogel drying can require as much as 1000 kgCO₂.kg_{input}⁻¹ (De Marco et al., 2018a). Despite this variability, a median value for CO₂ solvent consumption across applications is 0.9 kgCO₂.kg_{input}⁻¹.

In sc-H₂O processes, consumption tends to follow a more compact trend: 0.2–19 kg_{water}.kg_{input}⁻¹ (avg. 7 kg), but can spike in unoptimized lab-scale cases (e.g., 120 kg_{water}.kg_{input}⁻¹ for talc synthesis (Glogic et al., 2021) and 47 kg_{water}.kg_{input}⁻¹ for nanoparticles (Tsang et al., 2016)).

Supercritical alcohols, such as methanol and ethanol, are primarily used in transesterification reactions, with a mean value around 0.2 kg.kg_{input}⁻¹. Outliers like a 42:1 methanol-to-input molar ratio have been reported in lab-scale waste oil conversion (Kralisch et al., 2013).

Secondary solvents (e.g., ethanol, acetone, toluene) vary from 10 g to 48 kg.kg_{input}⁻¹, with the high end observed in lab-scale barium strontium titanate synthesis (Tsang et al., 2016).

Energy. Energy consumption is a key consideration in nearly all LCA studies, as the high temperature and pressures require considerable inputs of heating energy and electricity for pumps and cooling, respectively (Chen et al., 2019). Electricity and heating energy values per kg of input are presented in Fig. 4.

Electricity consumption in sc-H₂O processes, especially in gasification is generally low, as these systems require less energy for pumps and cooling compared to CO₂-based systems. Reported values range from 0.3 Wh to 2 kWh.kg_{input}⁻¹, with an average of 0.4 kWh.kg_{input}⁻¹. However, the heating demand is significantly higher due to the higher critical temperature of water, ranging from 4 to 80 MJ.kg_{input}⁻¹, with an average of 40 MJ.

Supercritical CO₂ extraction processes require more electricity, with reported values between 10 Wh and 8 kWh.kg_{input}⁻¹, averaging 1.5 kWh.kg_{input}⁻¹, usually linked with energy for CO₂ cooling. Some extreme values (e.g., 500 kWh.kg_{input}⁻¹) appear in non-optimized lab-scale studies. Heating energy demand ranges from 0.3 to 20 MJ.kg_{input}⁻¹, averaging at 6 MJ, which is lower than that of sc-H₂O processes due to lower temperature requirements.

Energy consumption in supercritical transesterification, which involves supercritical alcohols falls between that of water and CO₂ processes. The average electricity requirement is 0.02 kWh.kg_{input}⁻¹, while heating energy needs average 4 MJ.kg_{input}⁻¹. This lower energy demand is due to alcohols typically being injected as a liquid, requiring less energy for pumping than CO₂, which needs to be cooled before compression.

When primary energy data for industrial-scale processes are available, they are obtained from studies on aerogel production (De Marco et al., 2019), pharmaceutical manufacturing (De Marco, 2022) and caffeine extraction (De Marco et al., 2018b). However, when primary

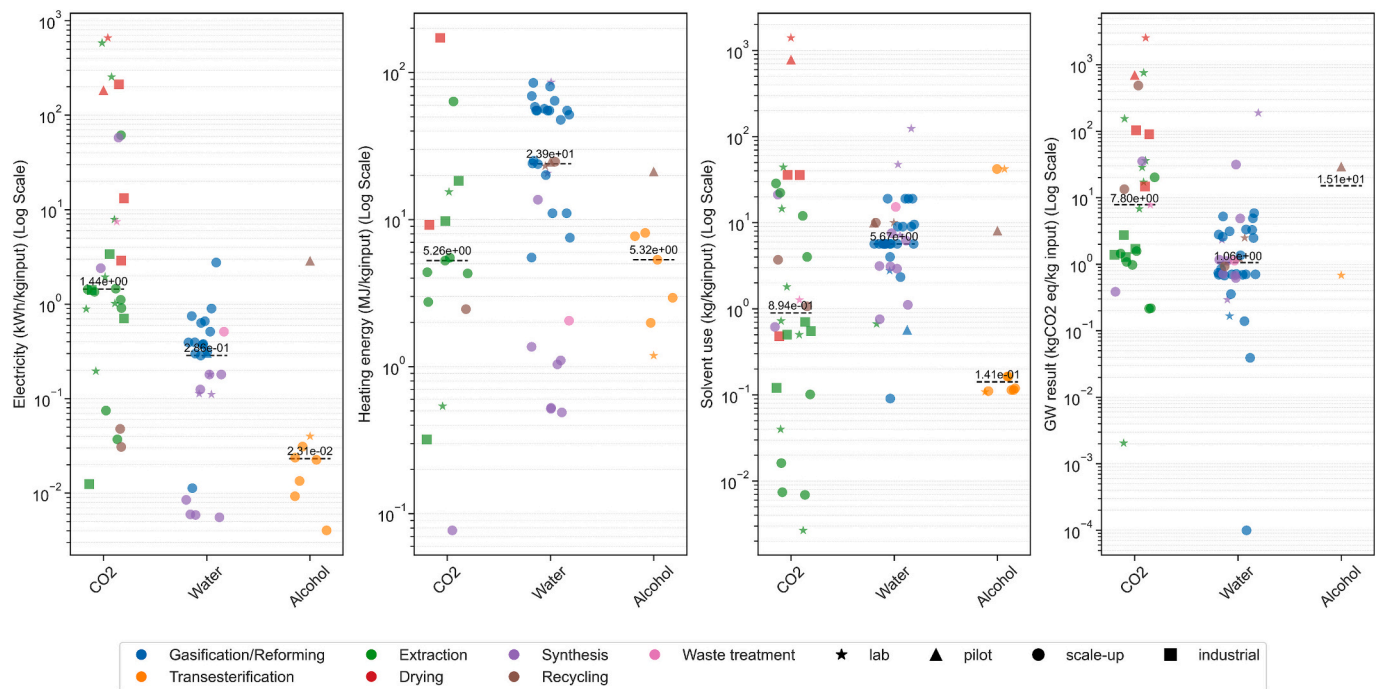


Fig. 4. Overview of the trends on solvent use (CO₂, water, alcohol), heating energy, electricity and GW result associated from different processes, organized by solvent. Colours represent the type of processes. The mean value is just indicative for each solvent.

Table 2

Ranges of data reported in the reviewed LCA studies, categorized by process type, solvent, and modelled scale. N indicates the number of studies used to calculate each range. Extreme values are not displayed. An asterisk (*) denotes cases where only a single value was available.

	N	Electricity range (kWh.kg _{input} ⁻¹)	Heating energy range (MJ.kg _{input} ⁻¹)	Solvent consumption range (kg.kg _{input} ⁻¹)	GW results range (kgCO ₂ eq.kg _{input} ⁻¹)
Process					
Gasification and reforming	12	0.01–2.7	4.6–84	0.01–19	–0.2–5.8
Transesterification	7	0.004–0.03	1.2–8.1	0.1–42	0.68*
Extraction	18	0.01–8	0.3–18	0.01–4	0.2–30
Waste treatment	2	0.5–7	2*	1.2–15	1–7.8
Recycling	8	0.03–3	0.6–66	1–10	0.2–30
Synthesis	6	0.01–57	0.1–20	0.6–20	0.3–35
Drying	3	2.9–200	9–171	0.5–35	15–100
Solvent					
CO ₂	27	0.01–200	0.3–171	0.01–35	0.2–100
Water	22	0.01–2.7	0.5–84	0.1–19	–0.2–30
Alcohol	5	0.004–3	1.2–21	0.1–42	0.68–30
Modelled scale					
Lab	15	0.1–580	0.5–85	0.1–123	0.2–187
Pilot	3	0.3–3	21–25	0.5–10	1–30
Scale-up	21	0.01–57	0.1–80	0.1–42	–0.2–35
Industrial	5	0.01–13	0.3–171	0.1–35	1–100

data are unavailable, energy use is estimated through:

- Process simulations (e.g. Aspen HYSYS, SuperPro Designer) to model energy requirements, differentiate between heating and electricity needs, and assess system performance (Thonemann and Schulte, 2019; Espada et al., 2020; Khalil, 2021),
- Experimental and theoretical approaches using equipment specs (equipment power ratings, operational times, and component capacities) (Peng et al., 2016; Peng et al., 2025) or thermodynamic properties (Tsang et al., 2018),
- Secondary data from related LCA literature (e.g., using caffeine extraction data for oil extraction (Chan et al., 2018)).

Energy consumption trends across studies vary widely, but most indicate that supercritical fluid processes tend to require more energy than conventional alternatives (Ferreira et al., 2024; Kiwjaroun et al., 2009; Pérez-López et al., 2014). However, one study notes that despite the high energy intensity of supercritical methanol processing, the simplified downstream operations (e.g., easier methanol recovery and product purification) result in lower overall energy consumption compared to alternative processes (Morais et al., 2010).

Infrastructure. Fewer than 15 % of studies explicitly model infrastructure. Approaches range from simplified reactor modelling, such as considering only steel by using the dataset from ecoinvent “steel, low-alloyed” with 10⁻⁴ kg of steel per kg of input biomass for extraction and transesterification (Shimako et al., 2016), to more detailed designs

accounting for material strength, thickness, and high-temperature materials like stainless steel with chromium and nickel. In Liu et al. study, a stainless steel reactor was modelled with $6.89 \cdot 10^{-3}$ kg of stainless steel and $3.6 \cdot 10^{-3}$ kg of aluminum silicate wool – used as an insulating layer – per kg of carbon fiber input (Liu et al., 2021).

Others expand the scope to include entire chemical plants, using datasets from ecoinvent such as “chemical factory, organics”, with values ranging from $6.74 \cdot 10^{-11}$ and $6.10 \cdot 10^{-10}$ items.kg_{input}⁻¹ (Bussa et al., 2021). Similarly, sector-specific datasets can be employed, as seen in a study on oil extraction that used the “vegetable oil refinery” dataset from ecoinvent, assigning $1.18 \cdot 10^{-10}$ items per kg of extracted grape seed oil (Fonseca-Pérez et al., 2024).

Thonemann and Schulte took a different approach by adapting generic dataset from ecoinvent and incorporating additional infrastructure elements, such as Nafion membranes and copper electrodes. In their lab-scale model, $2.4 \cdot 10^{-9}$ items of chemical factory and $5.5 \cdot 10^{-3}$ kg of copper electrode are assigned per kg of formic acid produced. After scaling up, these values were significantly reduced to $5 \cdot 10^{-10}$ items of chemical factory, 10^{-11} kg of copper electrode and 10^{-7} kg of Nafion membrane per kg of formic acid (Thonemann and Schulte, 2019).

Waste. Some studies assert that supercritical processes result in outputs with little to no waste requiring treatment. These studies often model their processes assuming “waste-free” operation (Kiwjaroun et al., 2009) or report reduced waste generation (Morais et al., 2010). For example, it has been noted that the absence of catalysts in the supercritical methanol process simplifies biodiesel purification steps, thereby reducing waste production. In terms of downstream emissions, liquid residuals—such as wastewater rich in nitrogen and organics pollutants are a notable by-product and are typically treated using conventional wastewater treatment methods (Yan et al., 2021).

Post-extraction residues are often valorised to produce energy in the form of heat or electricity. For instance, residual biomass from algae extraction can be anaerobically digested at 38 °C to generate biogas and recover nutrients (Espada et al., 2020; Brentner et al., 2011). Similarly, solid waste from asparagus extraction, such as residues containing rutin, can be digested and integrated in the model as foreground data for energy recovery (Santiago et al., 2021).

In some cases, wastewater is assumed to be sent to conventional water treatment facilities (Santiago et al., 2021). Other studies model the management of solid waste, wastewater, and solvent mixtures using datasets from ecoinvent (Syrpas et al., 2018; Rodríguez-Meizoso et al., 2012; Pillain et al., 2019). However, not all studies clearly specify how waste management is incorporated into their models. Approximately 60 % of studies explicitly model waste within their analyses, while the remaining studies omit these considerations.

3.5. Phase 3: life cycle impact assessment

A variety of LCIA methods were applied in the reviewed studies, including IMPACT 2002+, ReCiPe, CML-IA, TRACI, Eco-indicator 99, IPCC, ILCD and BEES. ReCiPe was the most frequently applied method (40 % of the studies), likely due to its broad impact coverage and multicriteria analysis. It was followed by CML (29 %) and IMPACT 2002+ (11 %). Endpoint-based assessments were conducted in 24 % of the studies. Other methods, including IPCC GWP, TRACI, EI99, ILCD, and BEES, were employed less frequently.

Notably, 23 % of the reviewed studies applied a monocriteria analysis, exclusively evaluating global warming (GW) impacts. In addition, 15 studies incorporated Cumulative Energy Demand (CED) as an energy-centric impact category, quantifying the primary energy consumed throughout the process (Frischknecht et al., 2015). Other commonly reported midpoint categories included acidification, eutrophication, and toxicity, reflecting broader environmental concerns beyond GW impacts.

Among the 59 studies that explicitly reported GW impacts, results varied widely depending on the process type, system boundaries, and

included inventory elements (e.g., energy use, chemical inputs, infrastructure, waste). The reported GW impacts ranged from -0.2 kgCO₂eq.kg_{input}⁻¹ observed in a gasification process incorporating carbon capture and storage (CCS) (Chen et al., 2022), or applying heat and electricity substitution avoided burdens in another gasification case study (Sadeghi Sheshdeh et al., 2024), to 2500 kgCO₂eq.kg_{input}⁻¹ in a lab-scale starch aerogel drying process (De Marco et al., 2018a).

Despite the variability in system modelling approaches, certain processes trends emerge when analysing larger sample groups. For gasification processes, reported GW values range between -0.2 and 5 kgCO₂eq.kg_{input}⁻¹ with an average of 1.6 kgCO₂eq.kg_{input}⁻¹. In extraction processes, GW impacts span from 0.2 to 153 kgCO₂eq.kg_{input}⁻¹, corresponding to a scale-up scenario for spruce bark extraction (Carlqvist et al., 2022) and a lab-scale rosemary oil extraction (Rodríguez-Meizoso et al., 2012), respectively, with an average of 15 kgCO₂eq.kg_{input}⁻¹. For other process groups, mean values are more challenging to interpret due to limited data availability. A more detailed visualization of these trends is provided in Fig. 4.

3.6. Phase 4: interpretation

In Phase 4 (interpretation), the reviewed studies investigate three main aspects: identification of environmental hotspots (notably energy and solvent use), assessment of mitigation strategies through sensitivity analyses, and comparison of supercritical processes with conventional alternatives to evaluate benefits and trade-offs.

3.6.1. Contribution analysis

In this study, seven examples were selected to illustrate contribution analyses, covering applications in gasification/reforming (Gutiérrez Ortiz et al., 2020), extraction (Carlqvist et al., 2022), transesterification (Lombardi et al., 2018), recycling (Premathilake et al., 2024), synthesis (Thonemann and Schulte, 2019), drying (Gay et al., 2018), and waste treatment (Yanhong et al., 2025), as presented in Fig. 5.

The results highlight that energy consumption is a predominant contributor in most cases, particularly in gasification and transesterification, due to the higher temperature requirements of supercritical water and alcohol-based processes. For example, Brentner et al. highlighted the high energy burden of supercritical methanol transesterification due to reaction temperatures (~250 °C) and methanol recovery requirements. However, this process eliminates the need for biomass drying and integrates lipid extraction with conversion, offering advantages over sc-CO₂ extraction (Brentner et al., 2011). Across studies, electricity and heat usage consistently emerge as major GW contributors, with extraction processes being particularly affected by electricity demand for CO₂ cooling and pumping (Ferreira et al., 2024; Arias et al., 2022; Pérez-López et al., 2014; Lombardi et al., 2018).

Solvent use is another environmental hotspot, particularly in extraction, synthesis, and recycling applications. In the extraction of spruce bark (in the example in Fig. 5), ethanol use accounts for 74 % of the total impact, mainly due to solvent losses in residual bark, with only 82 % recoverable and reusable (Carlqvist et al., 2022). The use of sc-CO₂ as a solvent also appears as a major hotspot in recycling and drying applications. In the Li-ion battery recycling example (Fig. 5), solvent use and waste generation are key contributors, with sodium hydroxide consumption playing a major role in cleaning vented CO₂ emissions (Premathilake et al., 2024).

Feedstock composition also influences environmental performance, particularly in gasification and recycling. In the gasification example, pine wood bio-oil aqueous phase (35 % wt.) was used as feedstock. While the process is highly energy-intensive, heat recovery mitigates its impact by 12 %. In the synthesis of formic acid, a batch reactor scale-up has been considered, where the carbon savings from CO₂ solvent supply (captured from emitting plants) can reduce the overall global warming impact by up to 25 %. However, energy remains the dominant hotspot. Infrastructure is included in the modelling but contributes only 4 % to

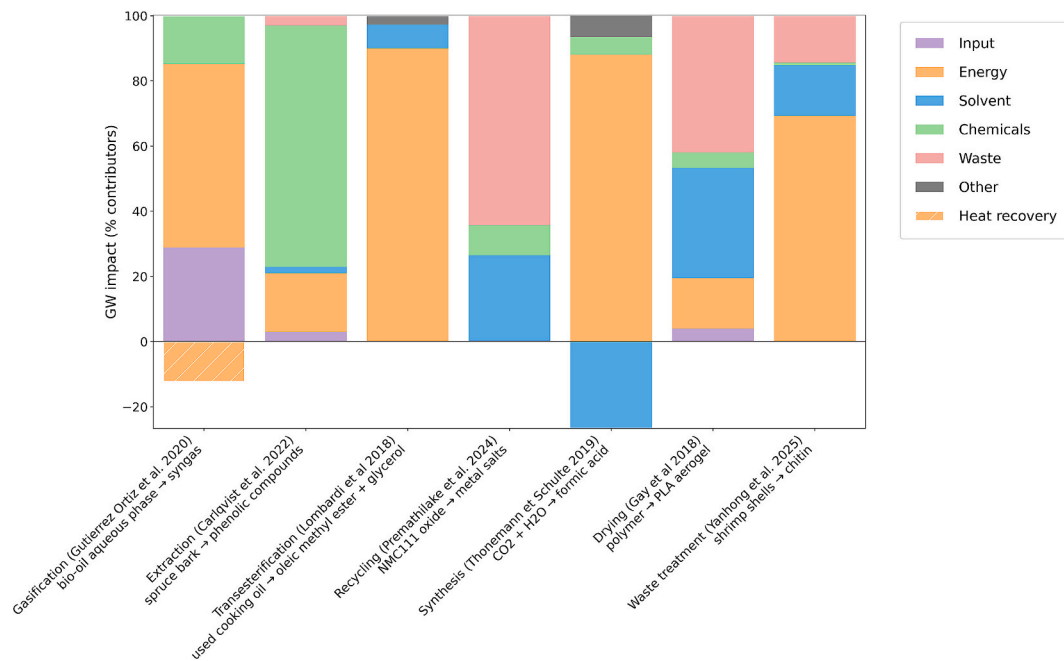


Fig. 5. Contribution analysis of GW impact across seven selected examples of supercritical fluid-based processes.

the GW impact, categorized under “Other” (Thonemann and Schulte, 2019). In some cases, chemical precursors are the dominant contributors, such as in TiO₂ and talc synthesis (Glogic et al., 2021; Tsang et al., 2018).

Drying processes require an important amount of CO₂ to dry PLA aerogels. The process also generates a substantial amount of waste, mainly vented gases released into the atmosphere. The authors suggest that future work should consider recycling gaseous and liquid solvents, though a lack of data on retreatment scenarios currently limits this (Gay et al., 2018). Lastly, for the waste treatment process of shrimp cell valorisation, energy consumption is the primary contributor to the impact, but its energy requirement is still lower than that of the conventional process (Yanhong et al., 2025).

Overall, a contribution analysis is included in 64 % of the studies under review, assessing either the contribution of the supercritical process within a system or the breakdown of hotspots within the supercritical process itself, as presented above. However, only 28 case studies (40 %) specifically examine contributions within the supercritical processes, allowing for a more detailed identification of environmental hotspots.

3.6.2. Comparative analysis

Among the 70 reviewed LCA studies, 55 (79 %) conducted comparative analyses, often benchmarking SCF processes against conventional methods. This means that 15 studies did not compare SCF processes to non-supercritical alternatives. Among these 55 comparative studies, conclusions varied:

- 27 studies found SCF processes to have lower environmental impacts. Six credited this to carbon capture (CC) scenarios, while one attributed improved outcome to methane co-production using an avoided burden approach have reported that the supercritical process under study had lower environmental impacts, compared to conventional methods (Iannotta et al., 2020).
- 10 studies reported conditional advantages based on several factors:
 - The relative environmental performance of SCF processes often depends on which processes they are compared to, which represent 6 case studies. For instance, sc-H₂O gasification outperformed landfilling poultry litter but was less favourable than conventional

gasification due to electricity and heat recovery (Bora et al., 2020). Similarly, sc-H₂O glycerol reforming had lower global warming, ecotoxicity, and acidification impacts than autothermal reforming, but was surpassed by aqueous-phase reforming (Khalil, 2021).

- Allocation methods also influenced outcomes. In carbon fiber recycling, applying an avoided burden approach favoured solvolysis due to higher material quality (Pillain et al., 2019).
- One study found SCF extraction advantageous for aromatic compounds but less for alpha-pinene due to selectivity issues (Moura et al., 2022).
- Two studies highlighted trade-offs between impact categories: a lower carbon footprint but a higher toxicity (Espada et al., 2020), and a lower carbon footprint but a higher human health impact (Tsang et al., 2018), emphasizing the necessity of multicriteria analysis.
- Finally, 18 LCA studies reported that the supercritical process under study had higher environmental impacts than conventional alternatives, mainly on extraction processes, due to higher energy requirement (Glogic et al., 2021; Garcia-Garcia and Rahimifard, 2019) or solvent use, particularly when derived from fossil sources (Kiwjaroun et al., 2009).

However, several of these studies highlighted specific trade-offs in SCF applications, where higher environmental impacts were counterbalanced by process advantages:

- SCF extraction yielded higher-quality pigments and extracts despite higher environmental impacts (Ferreira et al., 2013),
- Integrating anaerobic digestion for residual biomass reduced net energy use, improving environmental outcomes (Santiago et al., 2021; Krzyżaniak et al., 2023),
- Supercritical water processing of wet biomass cut drying energy, though excess water sometimes increased material inputs and CO₂ emissions (McKuin et al., 2023; Pankratz et al., 2020; Fózér et al., 2020).

Studies assessing the environmental impact of supercritical methanol transesterification have reached conflicting conclusion:

- Kiwjaroun et al. (Kiwjaroun et al., 2009) questioned its environmental viability due to high energy demand and important fossil fuel consumption,
- Morais et al. (Morais et al., 2010) reported lower impacts compared to conventional alkali-catalysed methods, citing reduced waste and more efficient conditions (lower temperatures, methanol-to-oil ratios, and an alternative distillation process).
- Kiss et al. (Kiss et al., 2014) explored the use of bioethanol instead of petroleum-based methanol to lower environmental impacts by leveraging more renewable sources.

Overall, SCF processes present advantages including reduced solvent toxicity, shorter extraction time and higher product quality. However, their environmental performance is nuanced and context-dependent. Some disadvantages include high energy demands for pressurization and heating, as well as the need for auxiliary solvents, even in small amounts which can offset some of their benefits.

3.6.3. Sensitivity analysis

Sensitivity analysis was conducted in 63 % of the reviewed LCA studies to assess the effects of varying key parameters, including electricity mix, feed concentration, and solvent recycling loops, as detailed below.

Given that supercritical processes require considerable energy input, the choice of the **electricity mix** is a critical factor influencing the environmental footprint. Studies have demonstrated that modifying the energy mix can lead to variations in LCA results. For example, replacing Poland's coal-heavy energy mix with the European average in a poplar biomass SCF extraction notably reduced impacts (Krzyżaniak et al., 2023), due to the latter's higher share of low-carbon sources. Similarly, analyses using European, Swedish, and Nordic energy mixes for spruce bark extraction helped identify optimal locations for implementation (Carlqvist et al., 2022). Substituting fossil energy with renewables like photovoltaics (De Marco et al., 2018b; De Marco, 2022), or hydroelectricity (Arias et al., 2022) was also explored to lower impacts. Another study compared in situ electricity generation to U.S. grid electricity for powering pumps and compressors in sc-H₂O reforming, reducing emissions 0.4 kgCO₂eq per kg of H₂ produced (Khalil, 2021).

Beyond the energy mix, sensitivity analysis has been employed to assess the effects of modifying **key process parameters** such as biomass concentration before and after harvesting, solvent ratio, lipid and protein content in the case of a microalgae biorefinery. A global sensitivity analysis with 4000 input sets aimed to identify optimal configurations for minimizing energy use and environmental impacts (Bussa et al., 2021).

Sensitivity analysis also plays a crucial role in evaluating **ecodesign actions**. One prominent approach involves solvent recycling, particularly ethanol, which has been identified as a major contributor to emissions during algogel formation. Scenario analysis has shown that recycling ethanol can substantially reduce emissions, and modifications in carbon dioxide condensation conditions within supercritical processes can further decrease environmental impact. A study proposed an improved solution, achieving a 30 % reduction in global impact compared to the base case (De Marco et al., 2019). Lowering temperatures in sc-CO₂-assisted hydrothermal liquefaction from 390 to 300 °C reduces thermal energy consumption by 23 % (Chan et al., 2018).

Finally, sensitivity analysis has been used to test the effects of **system boundaries** choices. For starch aerogels, including or excluding the agricultural phase significantly altered impact assessments: agriculture (corn cultivation and starch production) dominated ecosystem impacts, while industrial processing contributed more to human health, global warming, and resource depletion (De Marco et al., 2018a).

4. Discussions and perspectives

4.1. Key findings and implications

The reviewed LCA studies on SCF processes reveal a complex sustainability profile, with both promising advantages and notable challenges. SCF technologies have demonstrated potential environmental benefits, particularly in reducing chemical consumption, improving process efficiency and using less toxic solvent thus reducing waste generation. However, despite these advantages, the environmental benefits of SCF processes are not uniform across applications. One of the most critical findings is the high energy demand associated with achieving and maintaining supercritical conditions. Many studies highlight that the energy required for heating and pressurization often outweighs the reductions in solvent use, particularly in processes such as transesterification and aerogel drying. This trade-off is particularly evident in lab-scale studies, where the process efficiency is often not optimized for industrial application.

Another key insight is the strong dependency of SCF processes on the energy mix. Several studies show that integrating renewable energy sources, such as hydro or solar, significantly reduces their carbon footprint, underscoring the need for low-carbon energy infrastructure.

Fig. 4 illustrates the high variability in environmental impacts across SCF processes, even for similar applications—largely due to inconsistent system boundaries, functional units, and process parameters. These findings highlight that SCF processes should not be broadly labelled as “green” technologies without a comprehensive environmental evaluation. To maximize their potential environmental benefits, future research and industrial applications must prioritize process optimization, solvent recovery, energy efficiency, and apply scale-up frameworks when technologies are still at the lab scale. Nonetheless, these conclusions must be interpreted with caution given several limitations in the reviewed studies—limitations that are discussed along with recommendations in the following section.

4.2. Limitations and recommendations

This review highlights limitations in applying LCA to supercritical fluid technologies. Addressing these gaps is essential to improve the robustness, comparability, and relevance of future studies. Key aspects requiring improvement are detailed below, and summarized in Table 3.

4.2.1. Goal and scope

A first challenge in LCA studies on SCF processes lies in the definition of the functional unit, which is often unclear or incomplete. This issue is particularly critical when SCF processes are compared with conventional technologies, as differences in product quality, yield, or performance may not be properly captured. To improve comparability, FU definitions should explicitly reflect these parameters and be aligned with the study objectives.

Another common limitation is incomplete system boundaries, where key aspects such as inputs, infrastructure, and waste generation are omitted—reported in only 64 %, 14 %, and 59 % of reviewed studies, respectively. All relevant elements should be included or explicitly excluded with justification. Infrastructure is especially overlooked despite SCF systems' need for corrosion-resistant materials and specific design. Waste generation, whether reduced or shifted, also requires thorough modelling, using literature-based data when necessary (Doka, 2023).

Allocation choices, particularly when co-products are involved, are often unclear or absent. Studies should explicitly state whether co-products are generated and justify the selected allocation method (Schrijvers et al., 2020), to improve transparency and comparability.

These limitations often reflect a lack of consistency in how LCA is applied across studies. Some research presents well-structured assessments with clear methodological choices, while others adopt LCA more

Table 3
Limitations of existing studies and recommendations and perspectives regarding Life Cycle Assessment of supercritical fluid technologies.

Limitations	Recommendations	Literature for further discussion
Goal and scope		
Functional unit lacking precision	Define FU clearly, including product quality if relevant.	ILCD Handbook (European Commission et al., 2010)
System boundaries are unclear, especially regarding feedstock	Clearly define boundaries, model feedstock explicitly especially when feedstock characteristics differ from conventional processes.	ISO 14040, ILCD Handbook (International Organisation for Standardization, 2006a; European Commission et al., 2010) Liu et al. (2021); Sarrade et al. (2017)
Infrastructure considerations are overlooked	Incorporate infrastructure considerations with specific material requirements, due to high pressure and corrosive media.	Doka (2023)
Waste generation is partially omitted	Incorporate waste generation, even if reduced, to ensure a comprehensive assessment. Use literature-based modelling approaches (e.g., Doka, 2023) for specific waste streams.	Schrijvers et al. (2020)
Allocation issues	State the co-products if applicable and apply the selected allocation procedure with clarity.	
Life cycle inventory		
LCI data are unavailable	Ensure data is reported for benchmarking and reproducibility.	Hauschild and Rosenbaum (2018)
LCI lacks transparency in data sources and assumptions	Clearly document foreground and background data sources. Validate mass and energy balances.	ISO 14044, ILCD Handbook (International Organisation for Standardization, 2006b; European Commission et al., 2010)
Generic proxy for foreground data	Prioritize process-specific foreground data collection through experimental measurements, process simulations, and structured scale-up frameworks.	ILCD Handbook (European Commission et al., 2010)
Data approximation at lab scale	Apply scale-up methods early with sensitivity checks.	Tsoy et al. (2020); Piccinno et al. (2016)
Emerging technology future scenarios	Prospective LCA on foreground and background data, if possible.	Arvidsson et al. (2018)
Life cycle impact assessment		
Monocriteria analysis – only assessing carbon footprint	Conduct multicriteria analysis to assess trade-offs (e.g., energy vs. toxicity related impacts) including both midpoint (e.g., global warming, toxicity) and endpoint indicators (ecosystem quality, human health, resource use).	Hauschild and Rosenbaum, 2018
Inclusion of carbon capture scenario	Integrate CCS/CCU scenarios accurately and improve carbon accounting, following LCA guidelines for carbon capture modelling.	Müller et al. (2020)
Coverage of toxicity related impacts	Include potential indirect toxicity impacts of SCFs (high pressure and temperature, leaks, aerosol). Follow SSbD principles to accurately assess the	JRC report on SSbD (European Commission and Joint Research Centre, 2024); Clavier and Perrut (1996); Burgess et al. (2011)

Table 3 (continued)

Limitations	Recommendations	Literature for further discussion
	toxicity trade-offs or benefits of SCFs in process development stage.	
Interpretation		
Reporting LCIA results	Provide absolute and relative values to help build comparison.	Hauschild and Rosenbaum, 2018
Contribution analysis	Conduct detailed contribution analyses to identify environmental hotspots; Efforts in eco-design development on the most contributing processes, especially for emerging technologies.	Hauschild and Rosenbaum, 2018
Sensitivity analysis	Test influence of key variables (e.g., recovery, yield, energy source).	Hauschild and Rosenbaum, 2018
Comparison analysis	Benchmark SCF processes against conventional alternatives under consistent system boundaries and FU.	International Organisation for Standardization, 2006b
Non-LCA comments		
Sustainable relevance of the SCF process	Include TEA and LCSA to capture economic and social trade-offs.	Valdivia et al. (2021), Thomassen et al. (2019), Padilla-Rivera et al. (2023)

as a supporting tool for experimental work (Syrpas et al., 2018; Caudle et al., 2025; Fózer et al., 2020; Chan et al., 2015). Ensuring methodological rigor and transparency, by systematically following ISO 14040-44 standards is essential for conducting robust and reliable LCA.

4.2.2. Life cycle inventory

A first limitation in LCI step on the reviewed studies on supercritical fluid processes is their reliance on prior research data, such as caffeine extraction (Chan et al., 2018), highlighting the pressing need for validated, high-quality reference datasets to ensure robust environmental impact. In fact, limited LCI data availability, only in 52 % of the studies in the landscape analysis, significantly reduced our number of LCA studies for the critical review, reducing overall the reproducibility and benchmarking efforts. This is particularly critical as many analyses remain done at laboratory-scale, introducing major uncertainties when extrapolating results to industrial scales. To address this, future studies should integrate structured scale-up frameworks early in process development, combining experimental measurements, process simulations, and sensitivity analyses on key parameters like solvent ratios and energy consumption (Carlqvist et al., 2022). Pilot-scale experimental validation should also be considered a critical step to help build industrial-scale projections.

Moreover, transparency and quality of LCI remain areas for improvement. Many studies do not clearly document data modelling choices, particularly in differentiating between foreground and background data, which undermines the interpretability and comparability of results as highlighted by Chan et al. (Chan et al., 2015). Ensuring transparent reporting of all input/outputs data sources, modelling assumptions, and mass and energy balances is essential. Foreground data quality remains a particular weakness, with studies often relying on generic proxies instead of process-specific data. This calls for a shift toward collecting experimental or simulation-based data wherever possible, supported by structured scale-up and validation frameworks. Since several supercritical fluid applications—such as sc-CO₂ decaffeination of coffee, oil extraction, cleaning of cork closures for wine bottles,

and bioactive compound extraction from biomass—are already operated at industrial scale, future efforts should prioritize collaborations between researchers and the companies identified in the literature (Kamjam et al., 2024) to access high-quality, process-specific data essential for robust modelling in LCA studies of SCF processes.

Ex-ante LCA of emerging technologies often face methodological challenges due to fundamental data gaps, as illustrated by a study on *Aquilaria sinensis* plant oil extraction using sc-CO₂, which recognized the absence of commercial-scale data as a critical limitation (Gwee et al., 2020). In this context, applying prospective LCA—where both foreground and background systems are adjusted to reflect future conditions—should become standard practice to better inform long-term environmental impact (Arvidsson et al., 2018) and toward achieving carbon neutrality goals (Fang et al., 2025) for future emerging technologies.

Finally, clear process descriptions and detailed infrastructure modelling are essential. Studies should include flow diagrams mapping all inputs, outputs, and transformations, alongside explicit reporting of materials, energy use, and key process parameters (e.g., temperature, pressure, solvent ratios). If based on laboratory-scale data, studies must include preliminary industrial-scale projections supported by process simulation tools that provide thermodynamic insights, ensuring a more realistic representation of scaling effects.

4.2.3. Life cycle impact assessment

LCIA step in reviewed studies are often limited by narrow impact scope. Notably, 18 % of studies apply monocriteria assessments focused solely on carbon footprint, neglecting potential environmental trade-offs. Multicriteria analysis is essential to capture a comprehensive range of impacts and analyse trade-offs—including global warming, toxicity, resource depletion—using both midpoint and endpoint indicators.

Additionally, although SCF such as CO₂ and water are often promoted as safer alternatives to conventional solvents, LCA studies frequently neglect toxicity-related impacts—especially those arising indirectly from high-pressure, high-temperature operating conditions, potential leaks, aerosol formation, or co-solvent use (Clavier and Perrut, 1996; Burgess et al., 2011). To align with the Safe and Sustainable by Design (SSbD) framework, it is essential to strengthen both LCI and LCIA data regarding solvent emissions, occupational exposure, and potential local environmental effects. This will support a more accurate evaluation of SCF toxicity trade-offs or benefits and guide the development of low-toxicity, sustainable technologies from the early design stages.

Accurate accounting of CO₂ flows is crucial during both the inventory and impact assessment phases. This becomes particularly important in SCF processes that incorporate Carbon Capture and Storage (CCS) or Carbon Capture and Utilization (CCU) strategies. In such contexts, CO₂ serves dual roles—as a feedstock and as an emission—necessitating precise differentiation between positive emissions (CO₂ released into the atmosphere) and negative emissions (CO₂ captured or sequestered). The guidelines developed by Zimmermann et al. provide comprehensive methodologies for conducting LCAs on CCU technologies, emphasizing the importance of consistent accounting practices to accurately assess environmental impact (Müller et al., 2020; Zimmermann et al., 2018).

4.2.4. Interpretation

Robust interpretation of LCIA results is vital for meaningful conclusions in SCF-related LCA studies. It is recommended to report both absolute and relative impact values to facilitate clear comparisons across processes, scenarios, and studies. Detailed contribution analysis should also be performed to identify environmental hotspots—such as energy consumption, solvent use and feedstock—and guide ecodesign efforts toward the most impactful processes, particularly in emerging technologies.

To enhance the robustness of findings, sensitivity and uncertainty

analyses can be conducted, especially when relying on lab-scale data. These analyses help refine conclusions by testing the influence of key parameters and assumptions. It is also recommended to include projected data estimations at industrial scale. Discussions on material quality considerations are necessary to ensure fair comparisons across different studies (Pillain et al., 2019; Glogic et al., 2021). Early-stage scale-up projections are particularly useful in bridging the gap between laboratory research and industrial feasibility (Carlqvist et al., 2022; Chan et al., 2018). Benchmarking SCF processes against conventional alternatives under consistent system boundaries and functional units is also strongly recommended.

4.2.5. Broader sustainability aspects

Finally, future studies should expand beyond environmental impacts by integrating techno-economic analysis (TEA) and life cycle sustainability assessment (LCSA). This comprehensive approach will support early-stage SCF ecodesign by assessing environmental, economic, and social trade-offs for both emerging and established SCF technologies. As highlighted in a recent review on the industrial versatility of SCF processes, future research is expected to increasingly combine TEA and LCA to evaluate profitability alongside environmental performance when considering industrial applications (Kamjam et al., 2024). Existing frameworks in the literature aim to bridge environmental, economic, and social dimensions (Hoogmartens et al., 2014).

From an economic perspective, significant progress has already been made, with nearly 20 % of the reviewed LCA studies including cost analyses. Supercritical fluid technologies are often perceived as expensive due to high capital investment requirements compared to conventional low-pressure equipment, although they generally offer lower operating costs. However, economic feasibility remains process-specific and requires systematic evaluation (Clavier and Perrut, 2025). Among the various methodologies, life cycle costing is the most commonly applied approach for evaluating the economic dimension within LCSA for emerging technologies (Padilla-Rivera et al., 2023).

In contrast, social aspects are absent from current assessments and are rarely considered even as a future research direction. Yet, social life cycle assessment (s-LCA) provides a framework to address important topics relevant to SCF implementation, particularly regarding worker health and safety. This includes evaluating chemical and mechanical hazards, safety measures, use of protective equipment, and injury rates associated with operating high-pressure (Traverso et al., 2021). Given the inherent risks of handling pressurized equipment, incorporating social indicators will be crucial for a comprehensive sustainability assessment of SCF technologies (Clavier and Perrut, 1996).

4.3. Authors' perspective on SCF: Limits and opportunities

Based on this critical review, we consider SCF technologies to be promising, but not yet optimized from an environmental point of view. From a technical point of view, SCF offer valuable properties such as tuneable density and solubility, improved mass transfer, and the possibility to combine extraction and reaction steps. These features can reduce or eliminate the use of conventional solvents, avoid energy-intensive purification steps, and allow for more compact processes. However, our review also highlights several key limitations:

- High energy demand: SCF processes often require significant amounts of energy to reach and maintain supercritical conditions. This also raises safety concerns, such as risks of leaks.
- Dependence on the electricity mix: Because of their energy intensity, the environmental impacts of SCF processes are highly dependent on the carbon intensity of the electricity used. Their deployment should be prioritized in regions with low-carbon electricity mix.
- Infrastructure impacts often overlooked: Most studies we reviewed do not account for the environmental impact of specific SCF

equipment, especially at lab scale. This should be addressed transparently in future LCA to better assess real impacts.

In our view, the environmental future of SCF depends on how well they are integrated into sustainable systems, rather than their performance as a standalone process. Unlocking their full potential will require:

- Integration with low-carbon energy sources (e.g., solar heat, waste heat recovery, hydroelectricity...),
- Closed-loop solvent systems to minimize losses, especially for volatile compounds like CO₂,
- Eco-design approaches that combine environmental analysis and process design from early development stages,
- And transparent and standardized LCA practices, especially for system boundaries, allocation rules, and scale-up assumptions.

In conclusion, SCFs are not a sustainability solution by default. But with the right design choices and system-level integration, they can contribute meaningfully to less impactful processes. We see them as enabling technologies with real potential, if developed with clear environmental thinking from the start in a life cycle perspective.

5. Conclusion

This review provides a comprehensive analysis of 70 LCA studies on supercritical fluid processes, highlighting both their environmental potential and key challenges. SCF technologies are often promoted for their reduced solvent use and ability to deliver high-quality outputs. However, their environmental performance strongly depends on energy consumption, solvent recycling strategies, and modelled scale. Contribution analyses consistently identify energy use—particularly in gasification, transesterification, and extraction processes—as the primary environmental hotspot. Benchmarking results remain mixed, with nearly half of the reviewed studies reporting environmental benefits of SCF processes compared to conventional alternatives, while others highlight higher impacts, especially for extraction applications.

To improve the robustness of future assessments, this review recommends improving system boundary transparency, systematically including infrastructure and waste management, enhancing toxicity impact evaluations, and applying sensitivity analyses to key process parameters. Integrating LCA with techno-economic analysis (TEA) and social life cycle assessment (s-LCA) will also be essential to fully capture sustainability trade-offs, particularly for processes at early development stages.

The future development and industrial deployment of SCF technologies will depend on their capacity to achieve environmental and economic competitiveness compared to conventional processes. In this context, LCA will serve as a critical tool to quantify environmental impacts, identify optimization opportunities, inform ecodesign strategies, and provide benchmarking data to support decision-making. By addressing current limitations and broadening the sustainability scope, future studies can better support the responsible deployment of SCF technologies, ensuring that safety, environmental, and economic criteria are considered from the design stage.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

References

- Albarelli, J.Q., Santos, D.T., Ensinas, A.V., Maréchal, F., Cocero, M.J., Meireles, M.A.A., 2018. Comparison of extraction techniques for product diversification in a supercritical water gasification-based sugarcane-wet microalgae biorefinery: Thermo-economic and environmental analysis. *J. Clean. Prod.* 201, 697–705. <https://doi.org/10.1016/j.jclepro.2018.08.137>.
- Arena, U., Ardolino, F., 2022. 54. Technical and environmental performances of alternative treatments for challenging plastics waste. *Resour. Conserv. Recycl.* 183, 106379. <https://doi.org/10.1016/j.resconrec.2022.106379>.
- Arias, A., Feijoo, G., Moreira, M.T., 2022. 26. Assessing of the most appropriate biotechnological strategy on the recovery of antioxidants from beet wastes by applying the life cycle assessment (LCA) methodology. *Food Bioprod. Process.* 135, 178–189. <https://doi.org/10.1016/j.fbp.2022.08.003>.
- Arias, A., Feijoo, G., Moreira, M.T., 2024. Macroalgae as a sustainable biostimulant for crop production according to techno-economic and environmental criteria. *Sustain Prod Consum* 48, 169–180. <https://doi.org/10.1016/j.spc.2024.05.019>.
- Arvidsson, R., Tillman, A., Sandén, B.A., Janssen, M., Nordlöf, A., Kushnir, D., Molander, S., 2018. Environmental assessment of emerging technologies: recommendations for prospective LCA. *J. Ind. Ecol.* 22, 1286–1294. <https://doi.org/10.1111/jiec.12690>.
- Aymonier, C., Loppinet-Serani, A., Reverón, H., Garrabos, Y., Cansell, F., 2006. Review of supercritical fluids in inorganic materials science. *J. Supercrit. Fluids* 38, 242–251. <https://doi.org/10.1016/j.supflu.2006.03.019>.
- Aymonier, C., Philippot, G., Erriguible, A., Marre, S., 2018. Playing with chemistry in supercritical solvents and the associated technologies for advanced materials by design. *J. Supercrit. Fluids* 134, 184–196. <https://doi.org/10.1016/j.supflu.2017.12.021>.
- Bora, R.R., Lei, M., Tester, J.W., Lehmann, J., You, F., 2020. 1. Life cycle assessment and Technoeconomic analysis of thermochemical conversion technologies applied to poultry litter with energy and nutrient recovery. *ACS Sustain. Chem. Eng.* 8, 8436–8447. <https://doi.org/10.1021/acssuschemeng.0c02860>.
- Brentner, L.B., Eckelman, M.J., Zimmerman, J.B., 2011. 3. Combinatorial life cycle assessment to inform process design of industrial production of algal biodiesel. *Environ. Sci. Technol.* 45, 7060–7067. <https://doi.org/10.1021/es2006995>.
- Burgess, R.M., Hawthorne, S.B., Perron, M.M., Cantwell, M.G., Grabanski, C.B., Miller, D. J., Ho, K.T., Pelletier, M.A., 2011. Assessment of supercritical fluid extraction use in whole sediment toxicity identification evaluations. *Environ. Toxicol. Chem.* 30, 819–827. <https://doi.org/10.1002/etc.457>.
- Bussa, M., Zollfrank, C., Röder, H., 2021. 10. Life cycle assessment with parameterised inventory to derive target values for process parameters of microalgae biorefineries. *Algal Res.* 57, 102352. <https://doi.org/10.1016/j.algal.2021.102352>.
- Carlqvist, K., Wallberg, O., Lidén, G., Börjesson, P., 2022. 23. Life cycle assessment for identification of critical aspects in emerging technologies for the extraction of phenolic compounds from spruce bark. *J. Clean. Prod.* 333, 130093. <https://doi.org/10.1016/j.jclepro.2021.130093>.
- Caudle, B., Nguyen, T.T.H., Kataoka, S., 2025. 61. Evaluation of three solvent-based recycling pathways for circular polypropylene. *Green Chem.* 27, 1667–1678. <https://doi.org/10.1039/D4GC02646B>.
- Chakravarty, P., Familii, A., Nagapudi, K., Al-Sayah, M.A., 2019. Using supercritical fluid technology as a green alternative during the preparation of drug delivery systems. *Pharmaceutics* 11, 629. <https://doi.org/10.3390/pharmaceutics11120629>.
- Chan, Y.H., Yusup, S., Quitain, A.T., Tan, R.R., Sasaki, M., Lam, H.L., Uemura, Y., 2015. 39. Effect of process parameters on hydrothermal liquefaction of oil palm biomass for bio-oil production and its life cycle assessment. *Energ. Convers. Manage.* 104, 180–188. <https://doi.org/10.1016/j.enconman.2015.03.075>.
- Chan, Y.H., Tan, R.R., Yusup, S., Quitain, A.T., Loh, S.K., Uemura, Y., 2018. 18. Life cycle assessment (LCA) of production and fractionation of bio-oil derived from palm kernel shell: a gate-to-gate case study. *Proc. Integr. Optim. Sustain.* 2, 343–351. <https://doi.org/10.1007/s41660-018-0052-3>.
- Chemat, F., Vian, M.A., 2014. *Alternative Solvents for Natural Products Extraction*. Springer Berlin Heidelberg, Berlin, Heidelberg. <https://doi.org/10.1007/978-3-662-43628-8>.
- Chen, J., Xu, W., Zuo, H., Wu, X., Wang, J.E.T., Zhang, F., Lu, N., 2019. 33. System development and environmental performance analysis of a solar-driven supercritical water gasification pilot plant for hydrogen production using life cycle assessment

- approach. *Energ. Convers. Manage.* 184, 60–73. <https://doi.org/10.1016/j.enconman.2019.01.041>.
- Chen, J., Liu, Y., Wu, X., Leng, J.E.E., Zhang, F., Liao, G., 2022. 5. Thermodynamic, environmental analysis and comprehensive evaluation of supercritical water gasification of biomass fermentation residue. *J. Clean. Prod.* 361, 132126. <https://doi.org/10.1016/j.jclepro.2022.132126>.
- Clavier, J.Y., Perrut, M., 1996. Safety in supercritical operations. In: *Process Technology Proceedings*. Elsevier, pp. 627–631. [https://doi.org/10.1016/S0921-8610\(96\)80107-5](https://doi.org/10.1016/S0921-8610(96)80107-5).
- Clavier, J.Y., Perrut, M., 2025. *Supercritical Fluid Applications: Industrial Development And Economic Issues* (n.d.).
- Cooney, M., Young, G., Nagle, N., 2009. Extraction of bio-oils from microalgae. *Separat. Purif. Rev.* 38, 291–325. <https://doi.org/10.1080/15422110903327919>.
- De Marco, I., 2022. 17. The supercritical antisolvent precipitation from a sustainable perspective: a life cycle assessment. *J. CO₂ Util* 55, 101808. <https://doi.org/10.1016/j.jccou.2021.101808>.
- De Marco, I., Iolanda, Miranda, Salvatore, Riemma, Stefano, 2016. Raffaele Iannone, 46. Lca of starch aerogels for biomedical applications. *Chem. Eng. Trans.* 49, 319–324. <https://doi.org/10.3303/CET1649054>.
- De Marco, I., Iannone, R., Miranda, S., Riemma, S., 2018a. 24. An environmental study on starch aerogel for drug delivery applications: effect of plant scale-up. *Int. J. Life Cycle Assess* 23, 1228–1239. <https://doi.org/10.1007/s11367-017-1351-6>.
- De Marco, I., Riemma, S., Iannone, R., 2018b. 41. Life cycle assessment of supercritical CO₂ extraction of caffeine from coffee beans. *J. Supercrit. Fluids* 133, 393–400. <https://doi.org/10.1016/j.supflu.2017.11.005>.
- De Marco, I., Riemma, S., Iannone, R., 2019. 16. Life cycle assessment of supercritical impregnation: starch aerogel + α -tocopherol tablets. *J. Supercrit. Fluids* 143, 305–312. <https://doi.org/10.1016/j.supflu.2018.09.003>.
- Deng, J., Tang, Y., Tang, J., Liu, H., Chen, W., Sun, Z., Peng, S., Ma, X., 2025. From sewage sludge to Hydrogen: Life cycle Techno-Environment-Economic assessment of combined system with supercritical water Gasification, organic Rankine cycle and carbon capture and storage. *Energy Convers. Manag.* 323 (119221), 119221. <https://doi.org/10.1016/j.enconman.2024.119221>.
- Doka, G., 2023. Guidance on how to Consider Waste Disposal in Inventories of Waste-Producing Activities. *Doka Life Cycle Assessments*, Zurich, Switzerland. <https://www.doka.ch/publications.htm>.
- Dowson, M., Grogan, M., Birks, T., Harrison, D., Craig, S., 2012. 45. Streamlined life cycle assessment of transparent silica aerogel made by supercritical drying. *Appl. Energy* 97, 396–404. <https://doi.org/10.1016/j.apenergy.2011.11.047>.
- Espada, J.J., Pérez-Antolín, D., Vicente, G., Bautista, L.F., Morales, V., Rodríguez, R., 2020. 19. Environmental and techno-economic evaluation of β -carotene production from *Dunaliella salina*. A biorefinery approach. *Biofuels Bioprod. Biorefin.* 14, 43–54. <https://doi.org/10.1002/bbb.2012>.
- European Commission, Joint Research Centre, 2024. Safe and Sustainable by Design Chemicals and Materials: Methodological Guidance. Publications Office, LU. <https://data.europa.eu/doi/10.2760/28450> (accessed March 21, 2025).
- European Commission, Joint Research Centre, Institute for Environment and Sustainability, 2010. International Reference Life Cycle Data System (ILCD) Handbook :General Guide for Life Cycle Assessment : Detailed Guidance. Publications Office, LU. <https://data.europa.eu/doi/10.2788/38479> (accessed March 1, 2023).
- Fang, Y.-X., Wu, P.-Z., Chen, S., Li, Y., Cui, S.-F., Zhu, J.-X., Cao, H.-Z., Jiang, K.-J., Zhong, L., 2025. Prospective LCA towards achieving carbon neutrality goals: framework application and challenges. *Environ. Impact Assess. Rev.* 111, 107733. <https://doi.org/10.1016/j.eiar.2024.107733>.
- Ferreira, A.F., Ribeiro, L.A., Batista, A.P., Marques, P.A.S.S., Nobre, B.P., Palava, A.M.F., da Silva, P.P., Gouveia, L., Silva, C., 2013. 13. A biorefinery from *Nannochloropsis* sp. microalga – energy and CO₂ emission and economic analyses. *Bioresour. Technol.* 138, 235–244. <https://doi.org/10.1016/j.biortech.2013.03.168>.
- Ferreira, J., Braga, M.Q., da Gama, R.C.N., Magalhães, I.B., Marangon, B.B., de Castro, J. S., Lorentz, J.F., Henriques, B.S., de Pereira, A.S.A., Assemany, P.P., Calijuri, M.L., 2024. 56. Carotenoids from wastewater-grown microalgae biomass: life cycle assessment and techno-economic analysis. *J. Clean. Prod.* 434, 140526. <https://doi.org/10.1016/j.jclepro.2023.140526>.
- Fonseca-Pérez, R.M., Almena, A., Ramírez-Márquez, C., Bonilla-Petriciolet, A., Martín, M., 2024. 67. Techno-economic and environmental comparison of processes for the production of grape oil. *J. Clean. Prod.* 441, 141041. <https://doi.org/10.1016/j.jclepro.2024.141041>.
- Fózer, D., Volanti, M., Passarini, F., Varbanov, P.S., Klemeš, J.J., Mizsey, P., 2020. 9. Bioenergy with carbon emissions capture and utilisation towards GHG neutrality: power-to-gas storage via hydrothermal gasification. *Appl. Energy* 280, 115923. <https://doi.org/10.1016/j.apenergy.2020.115923>.
- Frischknecht, R., Wyss, F., Büsser Knöpfel, S., Lützkendorf, T., Balouktsi, M., 2015. Cumulative energy demand in LCA: the energy harvested approach. *Int. J. Life Cycle Assess.* 20, 957–969. <https://doi.org/10.1007/s11367-015-0897-4>.
- Galera, S., Gutiérrez Ortiz, F.J., 2015. 36. Life cycle assessment of hydrogen and power production by supercritical water reforming of glycerol. *Energ. Convers. Manage.* 96, 637–645. <https://doi.org/10.1016/j.enconman.2015.03.031>.
- García-García, G., Rahimifard, S., 2019. 42. Life-cycle environmental impacts of barley straw valorisation. *Resour. Conserv. Recycl.* 149, 1–11. <https://doi.org/10.1016/j.resconrec.2019.05.026>.
- Gay, S., Lefebvre, G., Bonnin, M., Nottelet, B., Boury, F., Gibaud, A., Calvignac, B., 2018. 43. PLA scaffolds production from thermally induced phase separation: effect of process parameters and development of an environmentally improved route assisted by supercritical carbon dioxide. *J. Supercrit. Fluids* 136, 123–135. <https://doi.org/10.1016/j.supflu.2018.02.015>.
- Glogic, E., Claverie, M., Jubayed, M., Musumeci, V., Carème, C., Martin, F., Sonnemann, G., Aymonier, C., 2021. 44. Greening pathways for synthetic talc production based on the supercritical hydrothermal flow process. *ACS Sustain. Chem. Eng.* 9, 16597–16605. <https://doi.org/10.1021/acscuschemeng.1c05120>.
- Goto, M., 2009. Chemical recycling of plastics using sub- and supercritical fluids. *J. Supercrit. Fluids* 47, 500–507. <https://doi.org/10.1016/j.supflu.2008.10.011>.
- Gutiérrez Ortiz, F.J., Kruse, A., 2020. The use of process simulation in supercritical fluids applications. *React. Chem. Eng.* 5, 424–451. <https://doi.org/10.1039/C9RE000465C>.
- Gutiérrez Ortiz, F.J., Alonso-Fariñas, B., Campanario, F.J., Kruse, A., 2020. 7. Life cycle assessment of the Fischer-Tropsch biofuels production by supercritical water reforming of the bio-oil aqueous phase. *Energy* 210, 118648. <https://doi.org/10.1016/j.energy.2020.118648>.
- Gwee, Y.L., Yusup, S., Tan, R.R., Yiin, C.L., 2020. 25. Techno-economic and life-cycle assessment of volatile oil extracted from *Aquilaria sinensis* using supercritical carbon dioxide. *J. CO₂ Util* 38, 158–167. <https://doi.org/10.1016/j.jccou.2020.01.002>.
- Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. *Life Cycle Assessment: Theory and Practice*. Springer International Publishing, Cham. <https://doi.org/10.1007/978-3-319-56475-3>.
- Hermansson, F., Ekvall, T., Janssen, M., Svanström, M., 2022. 55. Allocation in recycling of composites - the case of life cycle assessment of products from carbon fiber composites. *Int. J. Life Cycle Assess.* 27, 419–432. <https://doi.org/10.1007/s11367-022-02039-8>.
- Hessel, V., Tran, N.N., Asrami, M.R., Tran, Q.D., Van Duc Long, N., Escribà-Gelonch, M., Tejada, J.O., Linke, S., Sundmacher, K., 2022. Sustainability of green solvents – review and perspective. *Green Chem.* 24, 410–437. <https://doi.org/10.1039/D1GC03662A>.
- Hoogmartens, R., Van Passel, S., Van Acker, K., Dubois, M., 2014. Bridging the gap between LCA, VCC and CBA as sustainability assessment tools. *Environ. Impact Assess. Rev.* 48, 27–33. <https://doi.org/10.1016/j.eiar.2014.05.001>.
- Huang, Y., Chen, J., Liu, Y., Jiaqiang, E., 2024. Life cycle assessment of a process integrating supercritical water gasification with direct reduced iron production. *J. Clean. Prod.* 483 (144250), 144250. <https://doi.org/10.1016/j.jclepro.2024.144250>.
- Iannotta, P., Caputo, G., Scargiali, F., Longo, S., Cellura, M., Brucato, A., 2020. 52. Combined gasification-oxidation system for waste treatment with supercritical water: LCA and performance analysis. *Sustainability* 13, 82. <https://doi.org/10.3390/su13010082>.
- International Organisation for Standardization, 2006a. *ISO 14040 — Environmental Management — Life Cycle Assessment — Principles and Framework*. Geneva.
- International Organisation for Standardization, 2006b. *ISO 14044 - Environmental Management - Life Cycle Assessment - Requirements and Guidelines, the International Organization for Standardization (ISO)*. Switzerland, Geneva.
- Kamjam, M., Ngamprasertsith, S., Sawangkeaw, R., Charoenchaitrakool, M., Privat, R., Jaubert, J.-N., Molière, M., 2024. The great versatility of supercritical fluids in industrial processes: a focus on chemical. *Agri-Food Energy Appl. Process.* 12, 2402. <https://doi.org/10.3390/pr12112402>.
- Khalil, Y.F., 2018. 51. Comparative environmental and human health evaluations of thermolysis and solvolysis recycling technologies of carbon fiber reinforced polymer waste. *Waste Manag.* 76, 767–778. <https://doi.org/10.1016/j.wasman.2018.03.026>.
- Khalil, Y.F., 2021. 2. Simulation-based environmental-impact assessment of glycerol-to-hydrogen conversion technologies. *Clean Energy* 5, 387–402. <https://doi.org/10.1093/ce/zkab018>.
- Kiss, F.E., Micic, R.D., Tomić, M.D., Nikolić-Djorić, E.B., Simikić, M.D., 2014. 35. Supercritical transesterification: impact of different types of alcohol on biodiesel yield and LCA results. *J. Supercrit. Fluids* 86, 23–32. <https://doi.org/10.1016/j.supflu.2013.11.015>.
- Kiwjarun, C., Tubtimdee, C., Piumsomboon, P., 2009. 34. LCA studies comparing biodiesel synthesized by conventional and supercritical methanol methods. *J. Clean. Prod.* 17, 143–153. <https://doi.org/10.1016/j.jclepro.2008.03.011>.
- Knez, Z., Markocić, E., Leitgeb, M., Primozic, M., Hrnčić, M., Skerget, 2014. Industrial applications of supercritical fluids : a review. *Energy* 77, 235–243. <https://doi.org/10.1016/j.energy.2014.07.044>.
- Knez, Ž., Pantić, M., Čor, D., Novak, Z., Knez Hrnčić, M., 2019. Are supercritical fluids solvents for the future? *Chem. Eng. Process.* 141, 107532. <https://doi.org/10.1016/j.cep.2019.107532>.
- Kralisch, D., Staffel, C., Ott, D., Bensaïd, S., Saracco, G., Bellantoni, P., Loeb, P., 2013. 15. Process design accompanying life cycle management and risk analysis as a decision support tool for sustainable biodiesel production. *Green Chem.* 15, 463–477. <https://doi.org/10.1039/C2GC36410G>.
- Krzyżaniak, M., Stolarski, M.J., Warmański, K., Rój, E., Tyśkiewicz, K., Olba-Zięty, E., 2023. 40. Life cycle assessment of poplar biomass for high value products and energy. *Energies* 16, 7287. <https://doi.org/10.3390/en16217287>.
- Li, K., Xu, Z., 2019. A review of current progress of supercritical fluid technologies for e-waste treatment. *J. Clean. Prod.* 227, 794–809. <https://doi.org/10.1016/j.jclepro.2019.04.104>.
- Li, J., Santos, J., Vargas-Farias, A., Castro-Fresno, D., Xiao, F., 2024. 60. Prospective LCA of valorizing end-of-life tires in asphalt mixtures with emerging pretreatment technologies of crumb rubber. *Resour. Conserv. Recycl.* 210, 107828. <https://doi.org/10.1016/j.resconrec.2024.107828>.
- Liang, J., Liu, Y., Chen, J., Jiaqiang, E., Leng, E., Zhang, F., Liao, G., 2023. Performance comparison of black liquor gasification and oxidation in supercritical water from thermodynamic, environmental, and techno-economic perspectives. *Fuel (Lond)* 334 (126787), 126787. <https://doi.org/10.1016/j.fuel.2022.126787>.
- Liu, W., Huang, H., Liu, Y., Li, L., Cheng, H., Liu, Z., 2021. 49. Life cycle assessment and energy intensity of CFRP recycling using supercritical N-butanol. *J. Mater. Cycles Waste Manag.* 23, 1303–1319. <https://doi.org/10.1007/s10163-021-01206-7>.

- Lombardi, L., Mendecka, B., Carnevale, E., 2018. 4. Comparative life cycle assessment of alternative strategies for energy recovery from used cooking oil. *J. Environ. Manage.* 216, 235–245. <https://doi.org/10.1016/j.jenvman.2017.05.016>.
- Loppinet-Serani, A., Aymonier, C., Cansell, F., 2010. Supercritical water for environmental technologies. *J. Chem. Tech. Biotech.* 85, 583–589. <https://doi.org/10.1002/jctb.2323>.
- Manjare, S.D., Dhingra, K., 2019. Supercritical fluids in separation and purification: a review. *Mater. Sci. Energy Technol.* 2, 463–484. <https://doi.org/10.1016/j.mset.2019.04.005>.
- McKuin, B., Kapuscinski, A.R., Sarker, P.K., Cheek, N., Lim, J., Sabarsky, M., 2023. 12. Comparative life cycle assessment of marine microalgae, *Nannochloropsis* sp. and fishmeal for sustainable protein ingredients in aquaculture feeds. *Elem. Sci. Anth.* 11, 00083. <https://doi.org/10.1525/elementa.2022.00083>.
- Monari, C., Righi, S., Olsen, S.I., 2016. Greenhouse gas emissions and energy balance of biodiesel production from microalgae cultivated in photobioreactors in Denmark: a life-cycle modeling. *J. Clean. Prod.* 112, 4084–4092. <https://doi.org/10.1016/j.jclepro.2015.08.112>.
- Morais, S., Mata, T.M., Martins, A.A., Pinto, G.A., Costa, C.A.V., 2010. 31. Simulation and life cycle assessment of process design alternatives for biodiesel production from waste vegetable oils. *J. Clean. Prod.* 18, 1251–1259. <https://doi.org/10.1016/j.jclepro.2010.04.014>.
- Moura, B., Monteiro, H., Mata, T.M., Martins, A.A., 2022. 30. Life cycle energy and carbon emissions of essential oil extraction from rosemary. *Energy Rep.* 8, 291–297. <https://doi.org/10.1016/j.egy.2022.01.063>.
- Müller, L.J., Kätelhön, A., Bachmann, M., Zimmermann, A., Sternberg, A., Bardow, A., 2020. A guideline for life cycle assessment of carbon capture and utilization. *Front. Energy Res.* 8, 15. <https://doi.org/10.3389/fenrg.2020.00015>.
- Munshi, P., Bhaduri, S., 2009. Supercritical CO₂: a twenty-first century solvent for the chemical industry. *Curr. Sci.* 97.
- Ngamprasertsith, S., Sawangkeaw, R., 2011. Transesterification in supercritical conditions. In: Stoytcheva, M. (Ed.), *Biodiesel - Feedstocks and Processing Technologies*. InTech. <https://doi.org/10.5772/26239>.
- Padilla-Rivera, A., Hannouf, M., Assefa, G., Gates, I., 2023. A systematic literature review on current application of life cycle sustainability assessment: a focus on economic dimension and emerging technologies. *Environ. Impact Assess. Rev.* 103, 107268. <https://doi.org/10.1016/j.eiar.2023.107268>.
- Pankratz, S., Kumar, M., Oyedun, A.O., Gemechu, E., Kumar, A., 2020. 6. Environmental performances of diluents and hydrogen production pathways from microalgae in cold climates: open raceway ponds and photobioreactors coupled with thermochemical conversion. *Algal Res.* 47, 101815. <https://doi.org/10.1016/j.algal.2020.101815>.
- Peker, H., Srinivasan, M.P., Smith, J.M., McCoy, B.J., 1992. Caffeine extraction rates from coffee beans with supercritical carbon dioxide. *AIChE J.* 38, 761–770. <https://doi.org/10.1002/aic.690380513>.
- Peng, S., Li, T., Tang, Z., Shi, J., Zhang, H., 2016. 53. Comparative life cycle assessment of remanufacturing cleaning technologies. *J. Clean. Prod.* 137, 475–489. <https://doi.org/10.1016/j.jclepro.2016.07.120>.
- Peng, Z., Tian, J., Dong, R., Jia, H., Wu, L., Liu, Z., Xu, J., Jin, H., Chen, B., Guo, L., 2025. 63. Thermodynamic analysis and life cycle assessment of a new method for the preparation of ultrafine copper powders by supercritical hydrothermal synthesis integrating biomass supercritical water gasification. *Energy* 315, 134396. <https://doi.org/10.1016/j.energy.2025.134396>.
- Pérez-López, P., Balboa, E.M., González-García, S., Domínguez, H., Feijoo, G., Moreira, M.T., 2014. 28. Comparative environmental assessment of valorization strategies of the invasive macroalgae *Sargassum muticum*. *Bioresour. Technol.* 161, 137–148. <https://doi.org/10.1016/j.biortech.2014.03.013>.
- Piccinno, F., Hirschler, R., Seeger, S., Som, C., 2016. From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies. *J. Clean. Prod.* 135, 1085–1097. <https://doi.org/10.1016/j.jclepro.2016.06.164>.
- Pillain, B., Loubet, P., Pestalozzi, F., Woidasky, J., Erriguible, A., Aymonier, C., Sonnemann, G., 2019. 50. Positioning supercritical solvolysis among innovative recycling and current waste management scenarios for carbon fiber reinforced plastics thanks to comparative life cycle assessment. *J. Supercrit. Fluids* 154, 104607. <https://doi.org/10.1016/j.supflu.2019.104607>.
- Pinkard, B.R., Gorman, D.J., Tiwari, K., Rasmussen, E.G., Kramlich, J.C., Reinhall, P.G., Novoselov, I.V., 2019. Supercritical water gasification: practical design strategies and operational challenges for lab-scale, continuous flow reactors. *Heliyon* 5, e01269. <https://doi.org/10.1016/j.heliyon.2019.e01269>.
- Preetam, A., Jadhao, P.R., Naik, S.N., Pant, K.K., Kumar, V., 2023. Supercritical fluid technology - an eco-friendly approach for resource recovery from e-waste and plastic waste: a review. *Sep. Purif. Technol.* 304, 122314. <https://doi.org/10.1016/j.seppur.2022.122314>.
- Premathilake, D.S., Ambaye, T.G., Botelho Junior, A.B., Lima, A.T.M., Espinosa, D.C.R., Vaccari, M., 2024. 64. Comparative environmental and economic assessment of emerging hydrometallurgical recycling technologies for Li-ion battery cathodes. *Sustain. Prod. Consump.* 51, 327–344. <https://doi.org/10.1016/j.spc.2024.09.015>.
- Qiu, Y., Liu, Y., Fang, C., Ju, M., Xia, R., Wang, Y., 2024. Supercritical water gasification of oily sludge and its life cycle assessment. *Bioresour. Technol.* 342, 128277. <https://doi.org/10.1016/j.biortech.2024.128277>.
- Ramsey, E., Sun, Q., Zhang, Z., Zhang, C., Gou, W., 2009. Mini-review: green sustainable processes using supercritical fluid carbon dioxide. *J. Environ. Sci.* 21, 720–726. [https://doi.org/10.1016/S1001-0742\(08\)62330-X](https://doi.org/10.1016/S1001-0742(08)62330-X).
- Rodríguez-Meizoso, I., Castro-Puyana, M., Börjesson, P., Mendiola, J.A., Turner, C., Ibáñez, E., 2012. 22. Life cycle assessment of green pilot-scale extraction processes to obtain potent antioxidants from rosemary leaves. *J. Supercrit. Fluids* 72, 205–212. <https://doi.org/10.1016/j.supflu.2012.09.005>.
- Sadeghi Sheshdeh, A., Sabour, M.R., Mohammadi, F., Hui, J., Birkved, M., Khoshnevisan, B., 2024. 68. Early environmental sustainability guidance on supercritical water gasification technologies for sugarcane bagasse management. *Sustain. Prod. Consump.* 44, 312–329. <https://doi.org/10.1016/j.spc.2023.12.014>.
- Santiago, B., Feijoo, G., Moreira, M.T., González-García, S., 2021. 21. Identifying the sustainability route of asparagus co-product extraction: from waste to bioactive compounds. *Food Bioprod. Process.* 129, 176–189. <https://doi.org/10.1016/j.fbp.2021.08.005>.
- Sarrade, S., Féron, D., Rouillard, F., Perrin, S., Robin, R., Ruiz, J.-C., Turc, H.-A., 2017. Overview on corrosion in supercritical fluids. *J. Supercrit. Fluids* 120, 335–344. <https://doi.org/10.1016/j.supflu.2016.07.022>.
- Sawangkeaw, R., Teeravitut, S., Piumsomboon, P., Ngamprasertsith, S., 2012. 32. Biofuel production from crude palm oil with supercritical alcohols: comparative LCA studies. *Bioresour. Technol.* 120, 6–12. <https://doi.org/10.1016/j.biortech.2012.06.014>.
- Schrijvers, D., Loubet, P., Sonnemann, G., 2020. Archetypes of goal and scope definitions for consistent allocation in LCA. *Sustainability* 12, 5587. <https://doi.org/10.3390/su12145587>.
- Shimako, A.H., Tiruta-Barna, L., Pigné, Y., Benetto, E., Navarrete Gutiérrez, T., Guiraud, P., Ahmadi, A., 2016. 37. Environmental assessment of bioenergy production from microalgae based systems. *J. Clean. Prod.* 139, 51–60. <https://doi.org/10.1016/j.jclepro.2016.08.003>.
- Silva, D., Rocha, R., Ribeiro, F., Monteiro, H., 2024. Environmental impact of an innovative aeronautic carbon composite manufactured via heated Vacuum-Assisted Resin Transfer Molding. *Sustainability* 16 (8), 3253. <https://doi.org/10.3390/su16083253>.
- Syrpas, M., Bukauskaitė, J., Paškauskas, R., Bašinskienė, L., Venskutonis, P.R., 2018. 27. Recovery of lipophilic products from wild cyanobacteria (*Aphanizomenon flos-aquae*) isolated from the Curonian lagoon by means of supercritical carbon dioxide extraction. *Algal Res.* 35, 10–21. <https://doi.org/10.1016/j.algal.2018.08.006>.
- Thomassen, G., Van Dael, M., Van Passel, S., You, F., 2019. How to assess the potential of emerging green technologies? Towards a prospective environmental and techno-economic assessment framework. *Green Chem.* 21, 4868–4886. <https://doi.org/10.1039/C9GC02223F>.
- Thonemann, N., Schulte, A., 2019. 20. From laboratory to industrial scale: a prospective LCA for electrochemical reduction of CO₂ to formic acid. *Environ. Sci. Technol.* 53, 12320–12329. <https://doi.org/10.1021/acs.est.9b02944>.
- Traverso, M., Valdivia, S., Luthin, A., Roche, L., Arcese, G., Neugebauer, S., Petti, L., D'Eusanio, M., Tragnone, B.M., Mankaa, R., Hanafi, J., Benoit Norris, C., Zamagni, A., 2021. Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021, p. 150.
- Tsang, M., Philippot, G., Aymonier, C., Sonnemann, G., 2016. 48. Anticipatory life-cycle assessment of supercritical fluid synthesis of barium strontium titanate nanoparticles. *Green Chem.* 18, 4924–4933. <https://doi.org/10.1039/C6GC00646A>.
- Tsang, M.P., Philippot, G., Aymonier, C., Sonnemann, G., 2018. 47. Supercritical fluid flow synthesis to support sustainable production of engineered nanomaterials: case study of titanium dioxide, ACS sustainable. *Chem. Eng.* 6, 5142–5151. <https://doi.org/10.1021/acssuschemeng.7b04800>.
- Tsoy, N., Steubing, B., van der Giesen, C., Guinée, J., 2020. Upscaling methods used in ex ante life cycle assessment of emerging technologies: a review. *Int. J. Life Cycle Assess.* 25, 1680–1692. <https://doi.org/10.1007/s11367-020-01796-8>.
- Valdivia, S., Backes, J.G., Traverso, M., Sonnemann, G., Cucurachi, S., Guinée, J.B., Schaubroeck, T., Finkbeiner, M., Leroy-Parmentier, N., Ugaya, C., Peña, C., Zamagni, A., Inaba, A., Amaral, M., Berger, M., Dvarioniene, J., Vakhitova, T., Benoit-Norris, C., Prox, M., Foolmaun, R., Goedkoop, M., 2021. Principles for the application of life cycle sustainability assessment. *Int. J. Life Cycle Assess.* 26, 1900–1905. <https://doi.org/10.1007/s11367-021-01958-2>.
- Vogiatzi, C., Tserpes, K., 2025. A comparative environmental and economic analysis of carbon fiber-reinforced polymer recycling processes using Life Cycle Assessment and life cycle costing. *J. Compos. Sci.* 9 (1), 39. <https://doi.org/10.3390/jcs9010039>.
- Wang, Y., Shao, S., Gao, Q., Zhang, Y., Wang, X., Gao, X., 2025. Life cycle environmental impact and economic analysis of post-combustion carbon capture technologies in supercritical coal-fired power plants. *Environ. Impact Assess. Rev.* 114, 107933. <https://doi.org/10.1016/j.eiar.2025.107933>.
- Yan, S., Xia, D., Mao, R., Liu, X., 2021. 11. A conceptual biomass liquefaction system with supercritical water for bio-oil, power and heating trigeneration: thermodynamic and environmental analysis. *Eng. Conver. Manage.* 244, 114474. <https://doi.org/10.1016/j.enconman.2021.114474>.
- Yanhong, F., Hongwei, L., Xiaochun, Y., Bo, L., 2025. 65. An environmentally effective separation strategy of chitin from shrimp shells based on steam explosion and supercritical carbon dioxide. *Ind. Crop. Prod.* 224, 120369. <https://doi.org/10.1016/j.indcrop.2024.120369>.
- Yuan, Y., Zhang, F., Qiu, Y., Zhao, Y., Rong, W., 2025. 58. Comparative life cycle assessment of traditional and emerging methods for high concentration organic wastewater treatment. *Sci. Total Environ.* 958, 177986. <https://doi.org/10.1016/j.scitotenv.2024.177986>.
- Zimmerman, A., Wunderlich, J., Technische Universität Berlin, G. Buchner, Technische Universität Berlin, L. Müller, RWTH Aachen University, K. Armstrong, The University of Sheffield, S. Michailos, The University of Sheffield, A. Marxen, Institute for Advanced Sustainability Studies e.V. Potsdam, H. Naims, Institute for Advanced Sustainability Studies e.V. Potsdam, F. Mason, CO₂ Sciences, G. Stokes, CO₂ Sciences, E. Williams, 2018. CO₂ Sciences, Techno-Economic Assessment & Life-Cycle Assessment Guidelines for CO₂ Utilization, Global CO₂ Initiative. University of Michigan. <https://doi.org/10.3998/2027.42/145436>.