A Suggested Methodological Framework to Enhance Comparability and Reliability for Life Cycle Assessment of CO_2 Adsorption in Energy-Intensive Industries

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Abstract

Among the various CO_2 capture technologies, adsorption capture appears to be an emerging and promising technology characterised by operational flexibility, low pollutant emissions, and low energy consumption. It is expected to be crucial in carbon capture and storage systems. Whilst Life Cycle Assessment (LCA) has emerged as the consensus methodology for evaluating the environmental impacts of this technology, methodological heterogeneity in LCA applications has limited the comparability and credibility of research findings. This study systematically reviews 31 LCA studies published between 2006 and 2025, examining methodological commonalities and differences across four aspects: goal and scope definition, inventory analysis, impact assessment and interpretation. Current LCA methodological standards and guidelines were used as benchmarks to analyse the challenges and opportunities in CO_2 adsorption LCA methodology and to propose a methodological framework. The findings reveal that commonalities (e.g., functional unit) and differences (e.g., system boundary, life cycle stages and process stage alignments) exist among LCA methodologies. Moreover, compared to existing standards and guidelines, current methodological applications demonstrate notable gaps (e.g., the lack of data quality evaluation and the classification of significance levels). Consequently, we propose a hierarchical improvement framework comprising three levels based on required additional effort levels— minor, moderate, and major efforts. This framework aims to systematically enhance the comparability and reliability of LCA studies. This work contributes to establishing common LCA application protocols and provides methodological guidance for future environmental assessments of CO_2 adsorption technologies.

Keywords: Life cycle assessment; Methodology; Carbon dioxide; Adsorption.

Abbreviation

Abbreviation	Full name
AC	Activated Carbon
CC	Climate Change
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation, and Storage
DAC	Direct Air Capture
DQR	Data Quality Rating
DQRs	Data Quality Requirements
ELCD	European Life Cycle Database
EF	Environmental Footprint
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MDEA	Methyl diethanolamine
MEA	Monoethanolamine
MOFs	Metal-Organic Frameworks
NDC	Nationally Determined Contributions
OAT	One-at-a-time
OEF	Organisational Environmental Footprint
PEF	Product Environmental Footprint
VSA	Vacuum Swing Adsorption
PSA	Pressure Swing Adsorption
VPSA	Vacuum Pressure Swing Adsorption
TSA	Temperature Swing Adsorption

1. Introduction

In the global context of climate change mitigation, limiting warming to 1.5°C (as adopted in the Paris Agreement) or even 2°C requires immediate and drastic reductions in Greenhouse Gas (GHG) emissions across all sectors [1]. Alongside the shift from fossil fuels to renewable energy, enhancing energy efficiency, and reducing consumption, Carbon Capture and Storage (CCS) is recognised as an essential solution—especially in hard-to-abate sectors such as cement, lime, steel production, and petroleum refining, where process-related emissions are important [2]. In this framework, CO_2 adsorption technology has emerged as a promising alternative to amines absorption/regeneration technologies due to its high selectivity, relatively low energy demand, and reliable performance over a broad range of temperatures and pressures, making it especially suitable for deployment in energy-intensive industries such as thermal power generation, cement manufacturing, and steel mills [3-8].

Evaluating the environmental performance of CO_2 adsorption technologies through Life Cycle Assessment (LCA) is essential to ensure their sustainable and large-scale application [9, 10]. LCA offers a comprehensive tool to: (1) Quantify GHG Reduction – Precisely determine the net CO_2 (equivalent) mitigation attributable to adsorption processes, which is central to their environmental benefit. (2) Identify Environmental Burdens – Detect potential shifting of impacts, such as increased resource use or secondary pollutant emissions, thereby preventing unintended burden transfers. (3) Highlight Life-Cycle Hotspots – Analyse each stage of the technology's life cycle to reveal process inefficiencies and guide improvements in both process flow and adsorbent performance. (4) Facilitate Technology Comparison and Decision-Making – Generate comparable environmental impact data across different adsorbents and process configurations to support informed decisions.

Despite the guidance provided by ISO 14040 and ISO 14044 for LCA [11, 12], these macro-level standards do not fully address the variability inherent in specific applications, leaving room for methodological interpretation. In the realm of CO_2 adsorption, variations in system boundary definitions, functional unit selections, and impact category considerations have led to inconsistencies among studies. Such discrepancies complicate direct comparisons—whether a study isolates the adsorption process or extends to cover adsorbent production and disposal, or whether different functional units (e.g., in power industries, CO_2 captured per tonne versus net electricity generated) are used—thereby potentially skewing policy decisions and resource allocation. Against this backdrop, establishing a consensus-based LCA framework tailored to CO_2 adsorption is crucial to ensure comparability and enhance decision reliability.

Several related review articles have emerged in recent years on the LCA of CO_2 adsorption [13-19], offering valuable insights into this developing field. Table 1 summarises the significant information of these studies. These reviews show several notable properties: (1) In terms of coverage, most works devote only one chapter to LCA, often as a subsection within broader discussions, suggesting that LCA remains a relatively underexplored dimension; (2) Regarding the scale of the reviewed object, these reviews span from adsorbent materials to full CCS systems, yet comprehensive attention to the intermediate scale of "CO_2 adsorption technology"—as a process situated between material and system—remains limited; (3) As for content focus, a substantial number of reviews prioritise LCA results—particularly impact assessment—while discussions on the LCA methodological practices are relatively scarce; (4) In terms of methodological coverage, only a few studies have attempted to systematically address all four classical LCA phases (goal and scope definition, inventory analysis, impact assessment, and interpretation), with most limiting their scope to selected components. (5) Regarding the solutions for the identified LCA methodological gaps, only one study has addressed this field but without any examples. All in all, these existing works have laid a valuable foundation for our work, indicating the potential contribution of a more holistic, methodology-oriented review focused on CO_2 adsorption technologies at the medium scale and further proposing the potential solutions with examples for the LCA methodological gaps.

Table 1. Summary of related review literature on LCA of CO_2 adsorption

Ref.	Year	Author	Length	Review Object	The scale of Review Object	Content and Proportion	Coverage of LCA Methodology	Solution for the LCA methodological gaps?	Example
[13]	2022	Wang et al.	One chapter	CO_2 capture	Large	LCA methodology	All four phases	No	No
[14]	2022	Yuan et al.	One chapter	Solid waste-derived porous carbons	Small	Half of the LCA results, half of the LCA methodology	Functional unit, system boundary, impact categories, database, software	No	No
[17]	2023	Karimi et al.	One chapter	CO_2 adsorption	Medium	LCA case studies	No	No	No
[16]	2023	Jiang et al.	Half chapter	Adsorption-based DAC	Medium	Focus on LCIA results	No	No	No
[15]	2023	Duval-Dachary et al.	Full text	Bioenergy with CCS	Large	Focused on inventory methodology	Inventory phase	Yes	No
[18]	2024	Jia et al.	One chapter	Engineered biochar-based CO_2 adsorbent	Small	Mostly LCIA results, less on methodology	Functional unit, system boundary, inventory data, impact categories, impact assessment	No	No
[19]	2025	Umar et al.	One chapter	Biomass-derived carbon adsorbents	Small	LCIA results only	No	No	No
This	2025	Yao et al.	Full text	CO_2	Medium	LCA	All four phases	Yes	Yes

work				adsorption		methodology			

Given the promising prospects of CO_2 adsorption in energy-intensive industries and the ambiguities in its LCA methodologies, this study seeks to address these gaps by proposing a comparable and reliable LCA framework explicitly tailored for CO_2 adsorption technologies. As depicted in Figure 1, the study focuses on three key aspects: (1) Systematically identifying commonalities and differences in LCA applications across published studies by examining the four phases—goal and scope definition, inventory analysis, impact assessment and interpretation—to distil typical paradigms and key differences; (2) Highlighting the gaps and opportunities between current practices and an ideal state, using the latest international standards (ISO 14040 [12] and its 2020 amendment [20]), European standards (ILCD handbook series [21-24]) and authoritative books (e.g., Environmental Life Cycle Assessment [25]) as references, while also identifying effective methods not explicitly covered by these requirements; (3) Developing a consensus-driven LCA methodological framework that enhances both comparability and reliability. This framework is intended to contribute to standardising LCA practices for CO_2 adsorption technologies, thereby providing researchers with a suggested evaluation basis and offering more robust scientific evidence for decision-makers to select optimal technological solutions and formulate effective environmental policies.

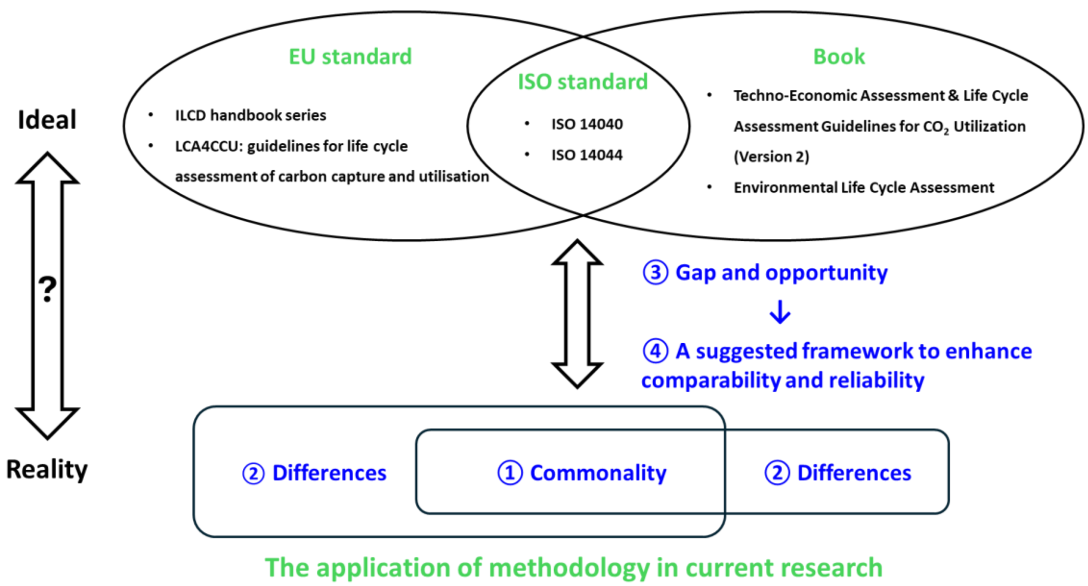

Figure 1. Research contents in this work

2. Method

The full process of this literature review and framework development is illustrated in Figure 2, which follows the principles and structure of the PRISMA guidelines [26, 27], with customised modifications to suit the specific objectives of this work. The process follows a top-to-bottom sequence along the left side of the flowchart, encompassing the following steps: Research questions, Search strategy, Identification, Screening, Included, Metadata analysis, Refinement, Alignment, and Framework roll-out. This approach ensures a systematic definition of research questions, a rigorous design of search strategies, transparent and efficient literature screening, and scientifically robust metadata analysis and synthesis, thereby providing a solid theoretical basis for LCA studies in the context of CO_2 adsorption.

During the literature retrieval phase, keywords such as "CO_2 adsorption" and "LCA" were used to search two academic scientific and technical databases—Scopus and Web of Science™—on 10 April 2025, yielding 287 records from Scopus and 452 records from Web of Science™, for a total of 739 records. In the subsequent screening phase, studies were excluded based on criteria including duplicate, language, article type, and relevance to the scope. This rigorous filtering process resulted in 28 eligible studies; additionally, 28-based citation tracking contributed 3 further relevant records, leading to a final total of 31 studies for subsequent metadata analysis.

Based on the included studies, a comprehensive metadata analysis and methodological refinement were performed, focusing on the four key phases of the LCA methodology (goal and scope definition, inventory analysis, impact assessment, and interpretation). Alignment with the last today's international standards and guidelines facilitated the identification of common gaps and potential opportunities in the current research landscape, ultimately culminating in developing a tailored LCA methodological framework to enhance compatibility and reliability for the CO_2 adsorption domain, with representative case examples illustrating its practical applicability.

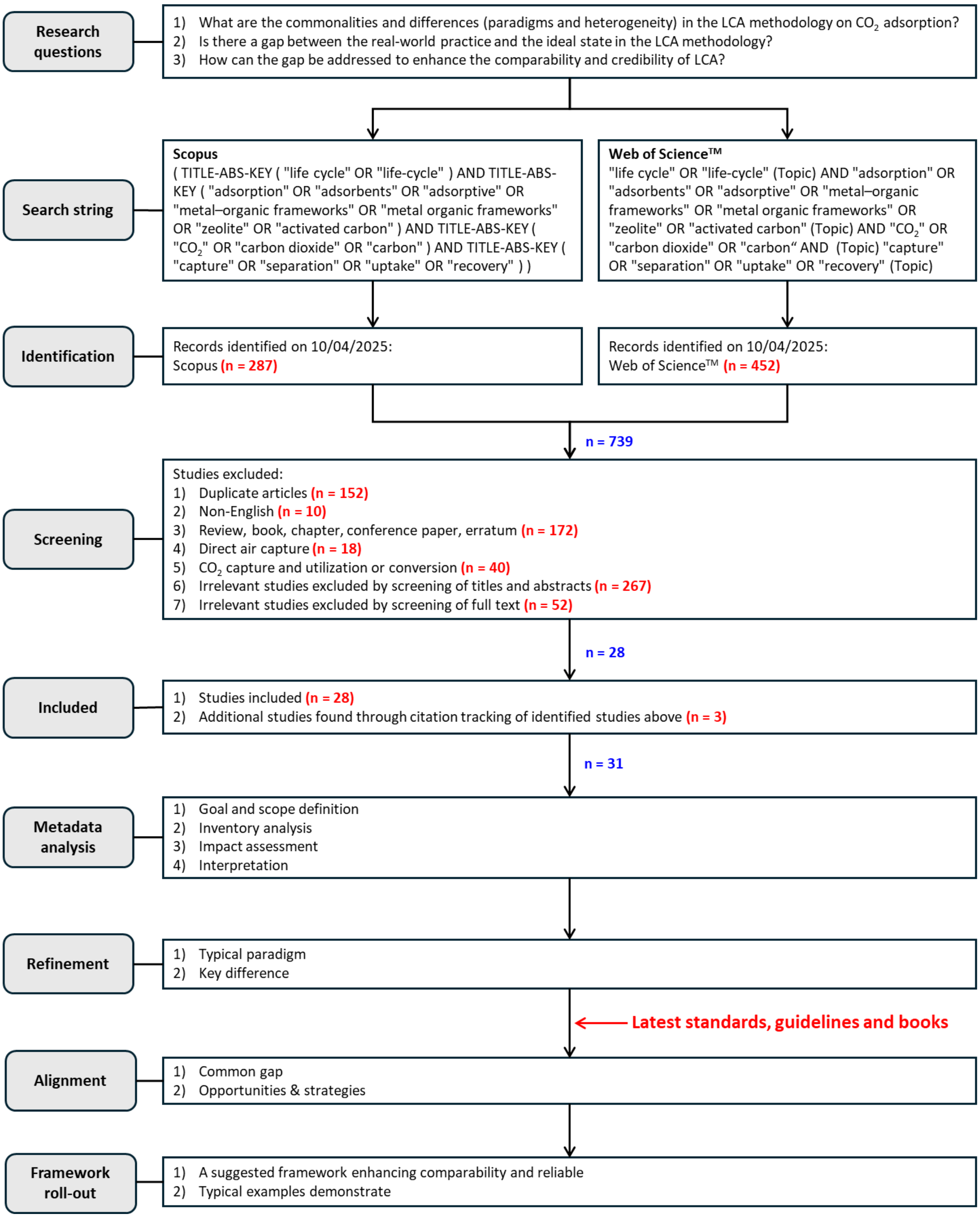

Figure 2. The integrated process of conducting a literature review and developing a suggested LCA methodological framework

3. Results

According to ISO 14040, LCA is divided into four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation [12]. This section is structured based on these four phases, with each subsection elaborating on the commonalities and differences in the methodological applications observed in existing studies. Subsequently, the gaps between the actual and ideal states are analysed, and potential opportunities for improvement are discussed. The fifth subsection builds upon the preceding four to propose a suggested methodological framework.

A total of 31 eligible publications were analysed in this study. Detailed information about these publications, including their identification numbers, titles, authors, and publication years, can be found in the "Supplementary Document 1_Metadata of Methodology". The numbering system follows a chronological order from the earliest to the most recent publications. Additionally, the Supplementary Document 1_Metadata of Methodology also contains detailed information on the specific methodological elements extracted from the four phases of the eligible publications. It includes the following phases: (I). Goal and scope definition (goal, type of comparison, type of LCA, system boundary, process or stage breakdown, functional unit, software or tool); (II). Inventory analysis (foreground data, background data, allocation criteria, inventory visibility); (III). Impact assessment (method, type/number of impact categories, final score); (IV). Interpretation (significance analysis type, uncertainty analysis object, uncertainty analysis type, uncertainty analysis method, sensitivity analysis object, sensitivity analysis type, sensitivity analysis method).

3.1. Goal and Scope Definition

In the goal and scope definition phase, the core elements that should be addressed include the goal, type of LCA, system boundary, life cycle stage and process breakdown, functional unit, cut-off rules, Data Quality Requirements (DQRs), and the software or tool used.

3.1.1. Goal definition and its type

The original description of the goal varies significantly due to differences in research subjects and the authors' writing styles, making it difficult to directly summarise a unified definition paradigm. However, as LCA is typically comparative and is conducted to analyse the environmental impact differences between various options [21], this study extracts and clusters the research objectives of existing publications based on the objects compared in comparative LCA. The complete results are presented in the "goal" column of the supplementary document 1. Furthermore, the objects of comparison are hierarchically arranged from broadest to narrowest, as shown in Figure 3.

Figure 3 illustrates that the comparative LCA of CO_2 adsorption can be categorised into five levels, corresponding to eight types. Specifically:

- ✧ Level 1 compares two options: with and without CCS systems, i.e., the differences before and after installing a CCS system.
- ✧ Level 2 focuses on the differences between various capture routes under the condition of a CCS system, including four typical options: pre-combustion, oxyfuel combustion, post-combustion, and chemical looping.

Level 3.1 and Level 3.2 are two parallel sub-levels:

- ✧ Level 3.1 compares different carbon capture technologies under the same capture route. For instance, carbon capture technologies in post-combustion capture include adsorption, absorption, membrane separation, and CaO looping.
- ✧ Level 3.2 compares different storage technologies under the same capture route. For example, storage technologies include geological storage, ocean storage, and others.

Level 4.1 and Level 4.2 are two parallel sub-levels:

- ✧ Level 4.1 examines the differences between various adsorbent materials used in CO_2 separation via adsorption technology. Examples include activated carbon (AC), zeolites, and metal-organic frameworks (MOFs).
- ✧ Level 4.2 compares different regeneration modes under CO_2 absorption. For instance, pressure swing adsorption (PSA), temperature swing adsorption (TSA), and hybrid mode.

Level 5.1 and level 5.2 are two parallel sub-levels:

- ✧ Level 5.1 compares different synthesis (manufacturing) methods for the same CO_2 adsorbent. For instance, MOFs can be synthesised via mechanochemical, solvothermal, and other methods.
- ✧ Level 5.2 compares different disposal methods for the same CO_2 adsorbent. For example, disposal methods for activated carbon include landfill, reactivation, and others.

In summary, from Level 1 to Level 5, the scope of the objects being compared becomes progressively narrower, and the scale of investigation becomes increasingly detailed, transitioning from a macro to a micro perspective. Additionally, Level 4 and Level 5 represent internal comparisons of CO_2 adsorbents, with the research focus entirely within the scope of adsorption technology. In contrast, Level 1 to Level 3 represents external comparisons of CO_2 adsorption. While CO_2 adsorption may be a significant subject in comparative LCA, other options (e.g., without CCS, capture routes, and capture technologies) are also critical objects of investigation. Therefore, in the hierarchical structure of comparative LCA, Level 4 and Level 5 treat CO_2 adsorption as the primary research subject, whereas in Level 1 to Level 3, CO_2 adsorption is more of an important branch within the broader CO_2 capture and storage chain.

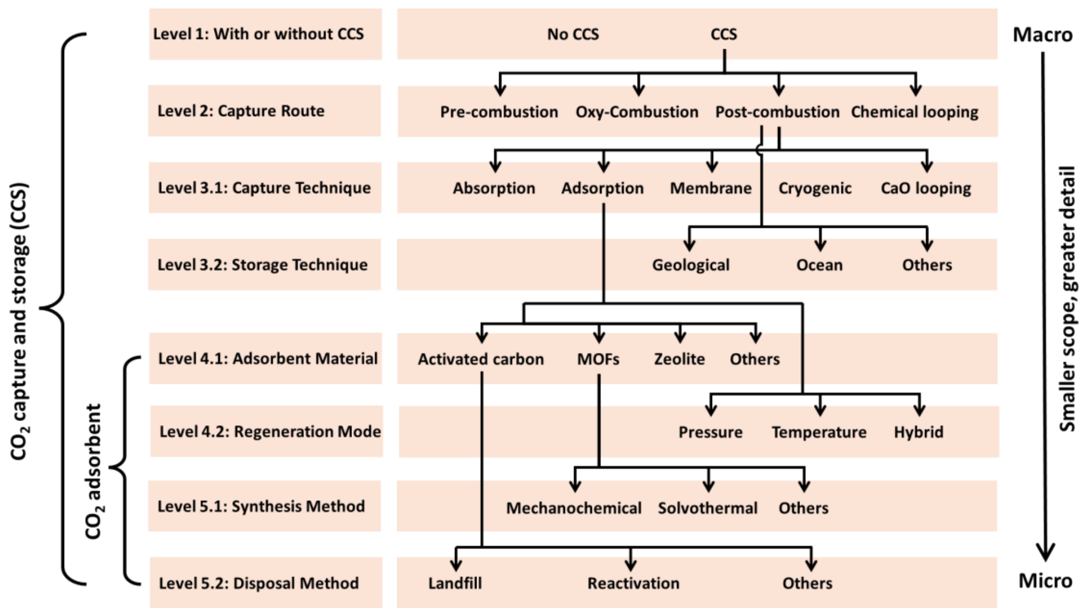

Figure 3. A hierarchical framework of comparative LCA for CO_2 adsorption

Figure 4 further illustrates the frequency of investigation for different types of comparative LCA. Overall, four types of comparisons are frequently conducted, including Level 1: With or without CCS (6 times), Level 3.1: Capture Technique (13 times), Level 4.1: Adsorption Material (8 times), and Level 5.1: Synthesis Method (9 times). In contrast, four comparisons are rarely conducted, including Level 2: Capture Route, Level 3.2: Storage Technique, Level 4.2 Regeneration mode, and Level 5.2: Disposal Method, each of which has only been investigated once. Additionally, two of the 31 LCA studies on CO_2 adsorption are non-comparative. These studies evaluate the environmental impacts of synthesising activated carbon from waste polyethene terephthalate plastics [28] and food waste [29] for application in CO_2 adsorption without comparing them to other alternatives.

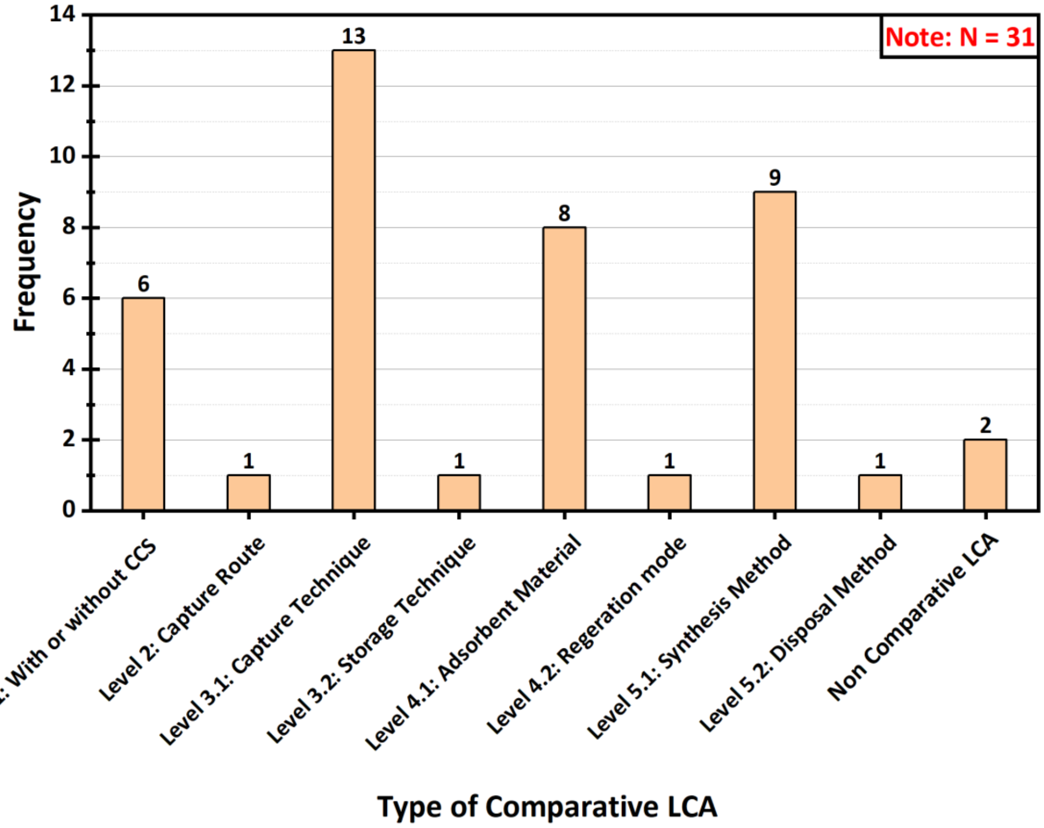

Figure 4. Statistics on types of comparative LCA focused on CO_2 adsorption

3.1.2. Type of LCA

LCA can be categorised into two types based on the temporal nature of its investigation: Retrospective and Prospective [30]. The term retrospective LCA is defined as: "LCA that models the product system at a recent or distant past point in time relative to the time at which the study is conducted" [31]. In contrast, prospective LCA is defined as: "LCA that models the product system at a future point in time relative to the time at which the study is conducted" [31, 32].

Figure 5 illustrates the frequency and proportion of the two types of LCA investigated in CO_2 adsorption. Among the 31 studies, 27 employed retrospective LCA, while only 4 adopted prospective LCA, accounting for 87% and 13%, respectively. Results suggest that researchers focus more on conducting LCA investigations of CO_2 adsorption technologies relevant to the present or the recent past, probably due to data availability.

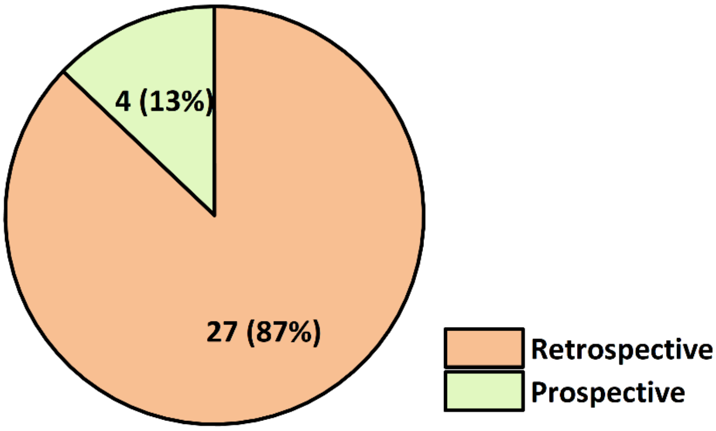

Figure 5. Types, frequency and percentage of temporal LCA in CO_2 adsorption studies

3.1.3. System boundary and life cycle stage breakdown

Typically, based on the scope of LCA stages covered, studies can be categorised into two typical types: cradle-to-gate and cradle-to-grave [12]. Among the 31 studies analysed, as shown in Figure 6, 21 (68%) clearly defined their system boundaries, while 10 (32%) did not specify their boundaries.

For those with clearly defined system boundaries, 10 studies (32%) adopted a cradle-to-gate approach [33-40]; 8 studies (26%) followed a cradle-to-grave approach [28, 41-45]; 1 study (3%) employed a cradle-to-use approach [46]; 2 study (6%) used a gate-to-gate approach [39]. Additionally, one study conducted both cradle-to-gate and cradle-to-grave analyses [29].

In summary, most studies have reported system boundaries, with cradle-to-gate and cradle-to-grave approaches being equally prevalent. Other types of system boundaries are relatively less common. However, a significant proportion of studies failed to explicitly clarify their system boundaries, which may impact the comparability and reliability of their findings.

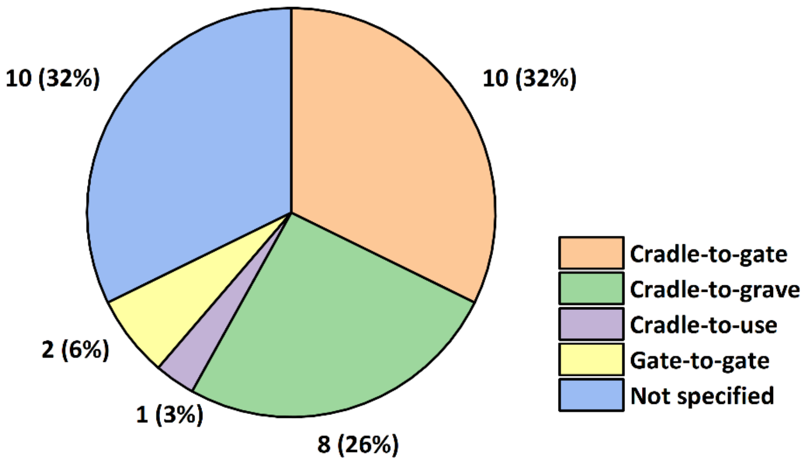

Figure 6. Types, frequency and percentage of system boundaries in LCA studies of CO_2 adsorption

However, potential inconsistencies and conflicts become apparent upon further examination of the 21 studies with clearly defined system boundaries, particularly through a comparative analysis of system boundaries and technical process stages. Specifically, even when studies claim to adopt the same system boundary, the associated scope of technical processes often differs. Two typical cases are outlined below, accompanied by illustrative examples:

Case (i): For cradle-to-gate studies on CO_2 adsorption, the scope of technical processes varies significantly. In the study by Grande et al., the process chain includes Mixing, Synthesis, Cleaning, and Drying [35]. In the study by Zakuciová et al., the process chain covers Turbomachinery, Combustion, Flue Gas Treatment, CO_2 Capture, and Water Consumption [36]. In the study by Luo et al., the process chain encompasses a Pulverized Coal Boiler, Steam Turbine, CO_2 Capture, and CO_2 Compression [34]. It is evident that Grande et al. focused on the synthesis of adsorbents, Zakuciová et al. considered the CO_2 capture process, while Luo et al. extended their scope to include both CO_2 capture and compression. Thus, although all three studies are categorised as "cradle-to-gate", the coverage of technical processes differs significantly.

Case (ii): For cradle-to-grave studies on CO_2 adsorption, the technical process scope also varies: Sathre and Masanet's study includes Coal Mining and Transport, Plant Infrastructure, Capture Media Production, Plant Stack Emissions, and CO_2 Transport and Storage [43]. Wang et al.'s study covers Polyethylene Terephthalate Bottle Production and Collection, activated carbon (AC) Production, CO_2 Capture, and AC Disposal [47]. Tao and Brander's study involves Raw Materials Extraction and manufacturing, Power Plants and use, Transportation, Recycling and disposal, with some scenarios considering, e.g., a 13% recycling rate for MOFs. For instance, Sathre and Masanet included CO_2 transport and storage, Wang et al. incorporated AC disposal, and Tao and Brander considered MOF recycling in specific scenarios. Therefore, even though all three studies aim to achieve CO_2 adsorption under a cradle-to-grave framework, the corresponding technical processes mapped by each study are not entirely consistent.

3.1.4. Functional unit

An essential step in defining the goal and scope of an LCA study is identifying the functional unit, which quantifies the function of a product or service to enable comparisons across different systems or similar studies [11, 12]. However, in practical contexts, the functional unit may refer to the product's function and the product itself [48]. For functional units related to CO_2 adsorption, among the 31 published studies reviewed, one study did not specify any functional unit [42], and another employed two functional units [47]. The remaining 31 functional units can be categorised into three types, as illustrated in Figure 7:

(i) Function-based CO_2 adsorption: CO_2 adsorption is the core function; thus, the specified amount of CO_2 adsorbed is often set as the functional unit. For example, 1 kg of CO_2 [39, 45], 1 tonne of CO_2 [33, 49], and 40 mg of CO_2 [50].

(ii) Function-based factory product: Since CO_2 adsorption and storage are often employed as decarbonisation technologies for energy-intensive factories, some studies use the factory's product as the functional unit. For instance, 1 kWh of net power for power plants [51, 52], 1 kWh of electricity [53], and 1 kg of clinker for cement plants [40].

(iii) Product-based CO_2 adsorbent: While function-oriented functional units are the first choice, in cases where the system boundary is cradle-to-gate and does not account for the product's use or subsequent stages—thus not fully realise the product's intended function—it may be more appropriate to set the functional unit based on the production of an equivalent amount of the product. Examples include 1 kg of ZIF-8 [38], 1 kg of AC [28], 1 kg of MIL-53(Al) [54], 1 kg of porous carbon [55], and 1 kg of UiO-66-NH_2 [34].

As shown in Figure 7, the occurrence and the frequency of the three categories—(i) Function-based CO_2 adsorption, (ii) Function-based factory product, and (iii) Product-based CO_2 adsorbent—are 12 (38%), 10 (31%), and 9 (28%), respectively. Results indicate that the occurrence and the frequency of function-oriented and product-oriented functional units are 22 (69%) and 9 (28%), respectively. Therefore, functional units based on service functions remain the dominant choice, while a smaller proportion are product-based, typically associated with cradle-to-gate analyses from the perspective of CO_2 adsorbents.

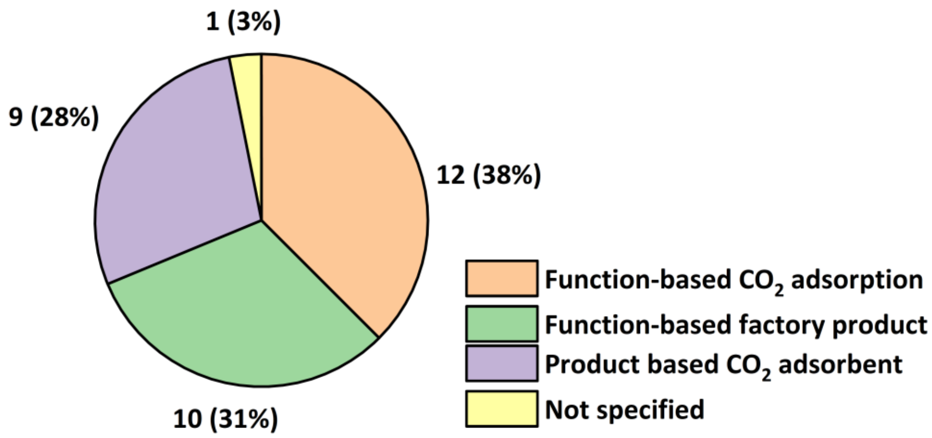

Figure 7. Types, frequency and percentage of function units in LCA studies of CO_2 adsorption

3.1.5. Software

The software or tools utilised in the 31 studies are summarised in Figure 8. The most widely used software is SimaPro, appearing in 16 instances (52%), significantly exceeding the combined usage of other software or tools (GaBi, eFootprint, Excel, NTNU-owned MATLAB-based routine, OpenLCA, and Umberto), which collectively account for ten instances (31%). Additionally, five studies (16%) did not disclose the software they employed.

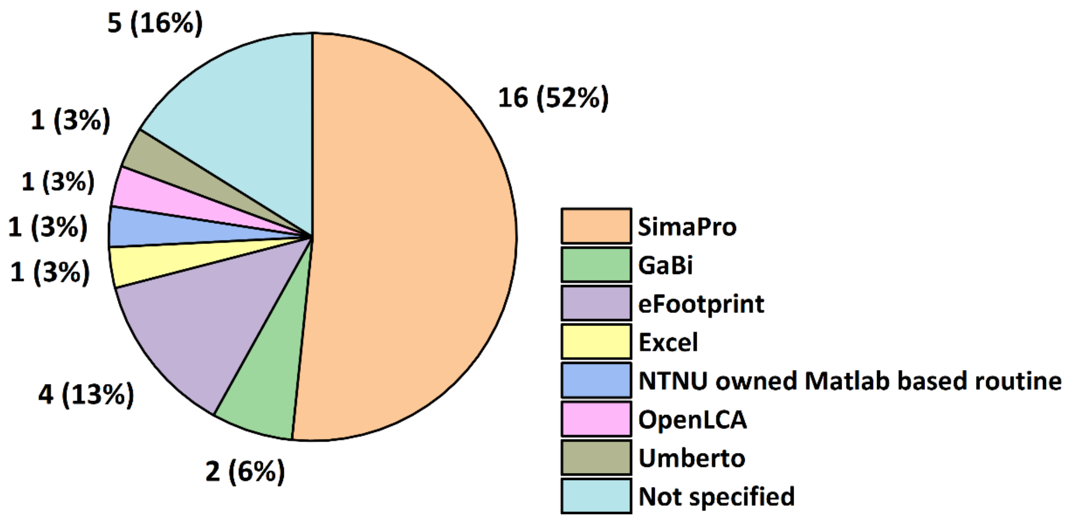

Figure 8. Types, frequency and percentage of software in LCA studies of CO_2 adsorption

3.1.6. Gaps and opportunities

3.1.6.1. Goal definition and common comparative reference

As mentioned in Section 3.1.1: Goal Definition and Its Type, although most LCA studies are inherently comparative—aiming to distinguish the environmental advantages and disadvantages of different options—the definition of the goal often varies significantly depending on the research context and the researchers' expression style. This variability makes it challenging to assess the comparability of different studies, potentially leading to a loss of comparability. Furthermore, it somewhat weakens the transferability and mutual validation of research findings. The excessive heterogeneity in goal definitions also obscures the positioning of the studied subjects within the overall CO_2 adsorption system, posing a challenge to the research's readability and comprehensibility.

Based on the above analysis, this study proposes the following recommendations:

(i) Clarify the positioning of the subjects in comparative LCA studies: While considering the contextual differences of the studied subjects, it is advisable to integrate the hierarchical framework presented in Figure 3 to refine the research objectives further and clearly articulate the positioning of the compared subjects within the system. For instance, does the comparison between capture technologies, adsorbents, or a hybrid comparison involve multiple approaches?

(ii) Establish a common benchmark for comparable LCA studies: Systematic and high-confidence LCA results are among the key pursuits of consensus-driven research. Achieving this requires collaborative efforts to build robust and systematic results across multiple studies. A critical prerequisite for this is establishing a set of consensus-based comparative benchmarks. Such benchmarks would leverage the collective strengths of group research findings, thereby advancing the development of a more robust system. The proposed benchmarks should centre around CO_2 adsorption and adopt the most generalised options as the standard. For example:

- ✧ Level 1: Factories without CCS equipment,

- Level 2: Post-combustion carbon capture routes,
- Level 3.1: MEA-based CO_2 scrubbing technology,
- Level 3.2: Geological storage,
- Level 4.1: Activated carbon or zeolite,
- Level 4.2: PSA or TSA,
- Level 5.1: Physical activation of activated carbon,
- Level 5.2: Landfilling of activated carbon.

These interconnected yet stratified benchmarks serve as the "trunk," other options can be referenced as "branches" extending from the trunk. Together, they form an interconnected and multidimensional "network" of comparability.

3.1.6.2. Type of LCA

Statistical analysis in Section 3.1.2 indicates that most current LCA studies on CO_2 adsorption technologies adopt a retrospective type, while prospective LCAs remain comparatively scarce. As a result, the outcomes tend to be static and may lack sufficient responsiveness to technological dynamics. Given the rapid pace of development in CO_2 adsorption — particularly under the urgent demand for climate change mitigation — static assessments are increasingly inadequate in capturing the environmental relevance of emerging technologies. Therefore, enhancing the use of prospective LCA is of notable value. For instance, patent-based prospective analysis can offer unique advantages in supplementing life cycle inventory data, modelling future scenarios, and improving the predictive capacity of LCA results [56, 57].

3.1.6.3. System boundary, life cycle stage breakdown and cut-off rules

Based on the analysis in Section 3.1.3 regarding system boundary and life cycle stage breakdown, certain variability exists in the correspondence between system boundary types and the coverage of actual technical processes and unit processes across different studies. To mitigate the implicit inconsistency in the correspondence amongst system boundaries, life cycle stages, and technical process stages, this study builds upon existing research practices and integrates the theoretical frameworks of ISO 14040 and the European Union guidelines. We propose a schematic diagram, as shown in Figure 9, which illustrates the system boundary, default LCA stages, detailed technical process chain for CO_2 adsorption, and their corresponding relationships. This diagram aims to enhance consistency and comparability in future research.

According to ISO 14040, the life cycle stages are categorised as: (1) Raw material acquisition, (2) Production, (3) Transport, (4) Use, Recycling/Reuse, and (5) Waste treatment [12]. ISO 14020 defines the life cycle stages as: (1) Raw material acquisition, (2) Production, (3) Distribution, (4) Use, and (5) End-of-life [58]. Meanwhile, the Product Environmental Footprint (PEF) framework specifies the default life cycle stages as: (1) Raw material acquisition and pre-processing, (2) Manufacturing, (3) Distribution, (4) Use, and (5) End-of-life [59]. Although the terminologies used in these two international standards and the latest methodological framework proposed by the European Commission are not entirely identical, their underlying meanings are (almost) consistent. Since PEF is the most recently published framework, this study adopts its terminology to guide the precise classification and alignment of system boundaries and technical processes in CO_2 adsorption.

The three subtypes of system boundaries mentioned earlier are (i) Cradle-to-gate, (ii) Cradle-to-use, and (iii) Cradle-to-grave, as shown in Figure 6. Additionally, a unique subtype, (iv) Cradle-to-cradle, needs to be included in the diagram. This subtype involves recovery or recycling during the "E. End-of-Life" stage, where waste is processed for reuse. For instance, the reactivation of activated carbon, as discussed in Figure 3, allows the reactivated carbon to enter a new life cycle.

For the complete technical process chain serving CO_2 adsorption, there are two subtypes with slight differences, corresponding to the CO_2 adsorption perspective, and CO_2 adsorption and storage perspective, ③ and ④, respectively, in Figure 9. The core distinction between the two lies in their scope: Studies focusing on the LCA of CO_2 adsorbents centre on the entire process related to the adsorbent itself, excluding B2. CCS system construction, the subsequent handling of the adsorbed CO_2 (D2. CO_2 process, D3. CO_2 transportation, and D4. CO_2 storage), and E2. Construction dismantling waste disposal. In contrast, studies on the LCA of CCS based on CO_2 adsorption encompass the entire CCS value chain, which is broader in scope than the adsorbent-focused studies. These typically include B2. CCS system construction, the subsequent handling of the adsorbed CO_2 (D2. CO_2 process, D3. CO_2 transportation, and D4. CO_2 storage), as well as E2. Construction dismantling waste disposal.

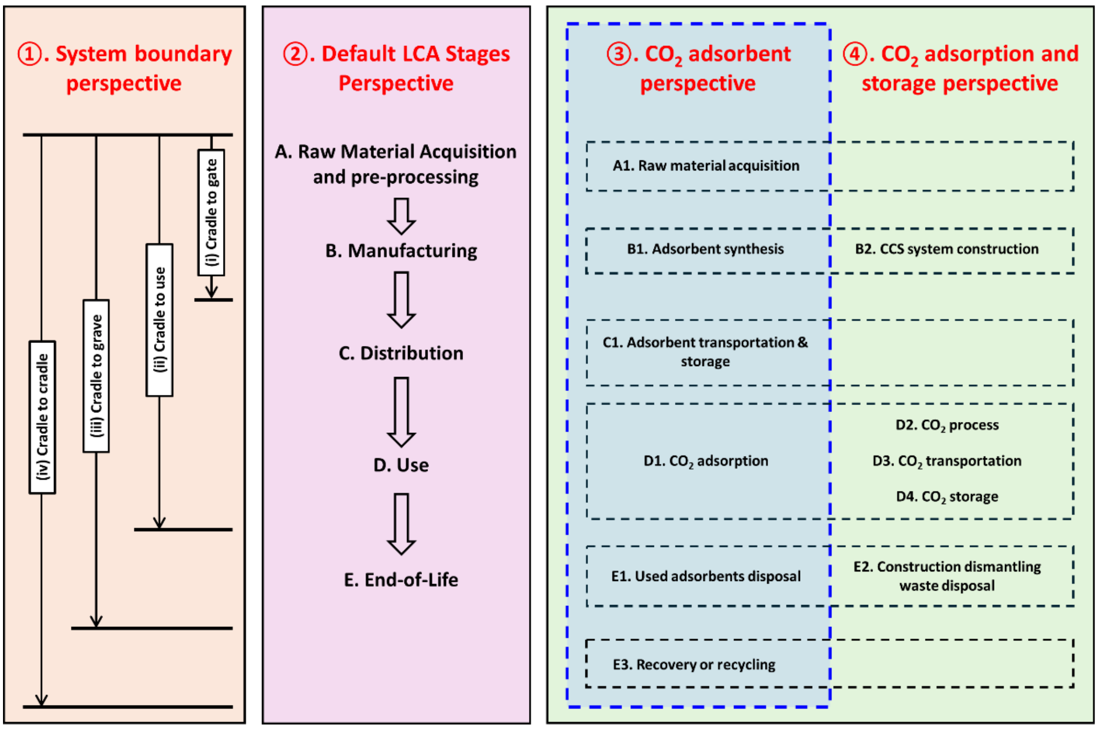

Figure 9. A schematic diagram showing the system boundary, default LCA stage and technological process chain (two sub-types: CO_2 adsorbent and CO_2 adsorption and storage) for CO_2 adsorption, as well as the matching relationships among these three elements

When defining system boundaries, an essential aspect that must not be overlooked is the explicit description of the criteria for including or excluding initial inputs and outputs. Unfortunately, only one study by Wang et.al [49] of the 31 studies reviewed clearly explained this point. The cause may be related to the widespread use of a default cut-off value of 1%. According to the European Union's PEF guidelines, "Processes and elementary flows may be excluded up to 3.0% (cumulatively) based on material and energy flows and the level of environmental significance (single overall score)" [59]. Therefore, this paper recommends that future studies briefly report the cut-off values applied to improve the transparency and comparability of research.

3.1.6.4. Data quality requirements (DQRs)

According to investigations, published studies typically disclose their data sources (In section 3.2.1) but rarely explain the requirements for data quality. Following ISO 14040 and ISO 14044 standards, specifications for data quality should include temporal coverage, geographical scope, technological representativeness, accuracy, completeness, representativeness, consistency, reproducibility, data sources, and uncertainty of the information [11, 12]. In addition, the Product Environmental Footprint (PEF) and the Organisational Environmental Footprint (OEF) also specified the Data Quality Requirements (DQRs) as follows:

- ✧ There are two minimum requirements: completeness, methodological appropriateness, and consistency.
- ✧ Four quality criteria: technical, geographical, temporal representativeness, and precision.
- ✧ Three quality aspects: documentation, nomenclature, and review [59].

Although different organisations may have slightly different DQRs, spelling out as clearly as possible the rules governing the DQRs to which the study adheres, facilitates subsequent Data Quality Assessment (DQA) and the implementation of uncertainty analyses.

3.1.6.5. Software

Research has shown that different software tools can yield varying LCA results [60-63], making software comparison both an intriguing and contentious topic [64-66]. In the context of CO_2 adsorption, the current dominance of SimaPro in LCA studies highlights its importance but may also constrain the diversity of methodological development. Although the software is merely a tool for conducting LCA and seems to have no strong correlation with the development of LCA methodologies, its implementation relies on these software platforms. Different software, each with varying degrees of maturity, offers differing functionalities—one of which aims to effectively realise LCA methodologies. For instance, the support for uncertainty analysis varies among software: For characterising LCI data uncertainty, SimaPro (v.8.4) supports four types of probability distributions, GaBi (v.8.5) supports two types, Umberto LCA+ supports none, while Brightway2 supports eleven types [67]. Therefore, depending too heavily on a single software package may lead to methodological homogenisation and possibly limit the practice and advancement of diverse methodologies due to the market dominance of one software. Thus, adopting a variety of software could foster innovation and diversify the implementation of methodologies to some extent.

3.2. Inventory Analysis

3.2.1. Data source

Figure 10 illustrates the types, frequencies, and proportions of foreground and background data sources in the inventory of CO_2 adsorption.

For foreground data, the sources can be roughly categorised as field, laboratory, simulation, theoretical calculation, literature, estimation, and assumption data. Typically, the inventory data in an LCA study is a mixture of these sources. Across 31 studies, the frequencies of these sources are as follows: 6, 18, 4, 1, 22, 2, and 7, respectively. Results indicate that laboratory data (e.g., [10, 47]) and literature data (e.g., [45, 51]) are frequently used, while field data (e.g., [29, 68]) and simulation data (e.g., [33, 39]) are also important sources. For the small proportion of missing real-world data, estimation (e.g., [43]) and assumptions (e.g., [44]) can serve as compensatory approaches.

For background data, Ecoinvent is the most widely used database, with a frequency (and proportion) as high as 22 times (85%). Due to the regional characteristics of background data, other regional databases are also adopted based on the location of the investigated object or as substitutes when the local data is unavailable. For instance, the Chinese Life Cycle Database (CLCD) [28, 29, 51], the European Life Cycle Database (ELCD) [28], and the US Life Cycle Inventory Database (USLCI) [47]. Additionally, three studies did not specify their background databases [10, 36, 69].

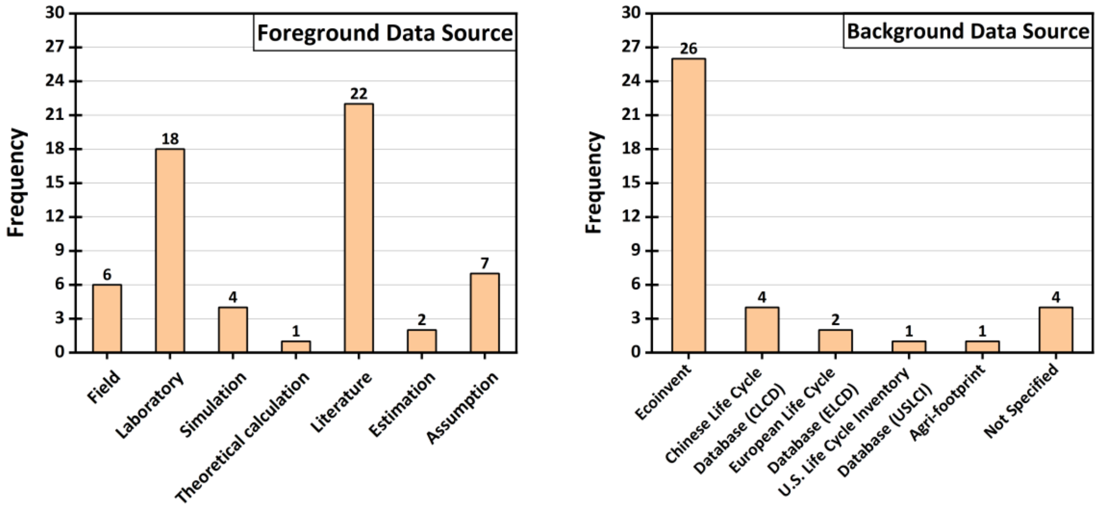

Figure 10. **Types, Frequency and Percentage of Foreground Data Sources and Background Data Sources in LCA Studies of CO_2 Adsorption**

3.2.2. Allocation

In the inventory analysis of the 31 studies, the majority (27 studies) did not involve the issue of functional allocation. However, four studies addressed multifunctional allocation; three studies adopted economic value as the allocation criterion [28, 29, 39], and only one set the mass as the allocation criterion [54].

3.2.3. Inventory visibility

Inventory visibility refers to whether the detailed data from the inventory analysis is published alongside the main text (including supporting documents) for reviewers and readers to access. According to statistics, the majority (25 studies) of the 31 studies provided the (at least in part) inventory analysis data, while a minority (6 studies) did not visualise their inventory results. Detailed inventory analysis can serve as a valuable reference for future research and enhance the transparency of the study, such as the work from Oreggioni et al. [53].

3.2.4. Gaps and opportunities

3.2.4.1. Data source, characteristics and iterative nature

LCA requires extensive data support to be successfully conducted. Section 3.2.1, "Data Source," provides a general overview of the data resources used in the studies and their frequency of use. However, there remains a certain degree of ambiguity regarding the type and quality of data employed at different life cycle stages. This ambiguity largely depends on the visibility of the inventory, the extent to which authors describe their data resources and sense of responsibility.

In 2022, the European Commission published the LCA4CCU: Guidelines for Life Cycle Assessment of Carbon Capture and Utilisation, which specifies the types and characteristics of data required for different life cycle stages [70]. A summary is as follows:

(i) For the most critical stages, core data is required. This refers to data describing the primary activities under consideration, typically derived from the surveyed entities' internal data. Such data is measured, calculated, and/or sourced from company reports. This type of data is also referred to as foreground data, primary data, activity data, or production data.

(ii) For upstream stages, supplier- and resource-oriented data are needed. Those data are either measured or calculated and may originate from company systems. They may also include secondary data reflecting specific circumstances or data sourced from literature and databases. Supplier- and resource-oriented data are often referred to as raw material data, supplier data, or upstream data.

(iii) For downstream stages, customer-, user-, and end-of-life-oriented data are required. Those data are typically derived from statistical sources, most commonly secondary data reflecting average conditions, and are sourced from literature or databases. Customer-, user-, and end-of-life-oriented data are also referred to as downstream data, use-phase data, or end-of-life data.

(iv) Background data can be found in LCA databases, such as Ecoinvent and GaBi. The combination of background and foreground data is crucial and may require separate validation or processing to adapt to specific scenarios.

Additionally, Figure 4 in another detailed guidance document published by the European Commission, illustrates the iterative nature of data adoption across different life cycle stages [21]. This iterative process is essential for achieving the objectives of LCA. For example, in the first iteration, a combination of available specific data and easily accessible secondary data can be used. In the second iteration, better data are required for critical processes, and more specific data are needed for foreground processes. In the third iteration, higher-quality data are necessary for key processes and flows (background and foreground) [21].

In summary, clearly articulating the sources, characteristics, and iterative nature of the data used across different life cycle stages or technical process chains can significantly reduce the ambiguity in current studies regarding dataset descriptions. In turn, it enhances the comprehensibility and credibility of inventory analysis results for readers and reviewers.

3.2.4.2. Allocation

When the allocation is applied, the economic value allocation is a commonly adopted criterion (see section 3.2.2). However, according to ISO 14044, the following order of preference should be applied for allocation: physical properties (e.g., mass), economic value, and the number of subsequent uses of recycled materials [11]. Therefore, physical properties should be prioritised as the allocation criterion whenever allocation is unavoidable to depict real-world processes more accurately.

3.2.4.3. Data Quality Assessment (DQA)

ISO 14044 includes a "validation of data" step during the inventory analysis phase, emphasising the need to ensure data quality aligns with the intended application. Additionally, during the consistency check in the interpretation phase, it is necessary to confirm whether the data quality meets the requirements of the study's goal and scope [11]. This underscores the importance of DQA. However, none of the 31 existing studies have reported on the data quality they investigated.

Given the importance of data quality and the current inadequacy of DQA, this work recommends that future research conduct a formal DQA. Methods for DQA can be divided into qualitative and semi-quantitative approaches [71]. The qualitative approach is represented by the US Department of Agriculture's LCA Digital Commons [72], while the semi-quantitative approach is exemplified by the Data Quality Rating (DQR) used in ILCD [21], and the PEF and the OEF [59, 73], and the Pedigree Matrix approach employed by ecoinvent in 2013 [74], which proposed in 1996 [75]. It should be noted that although the PEF and the OEF maintain the fundamental principles of ILCD's DQA methodology, such as the six Data Quality Indicators (DQIs) and five-level rating scale (Excellent, Very Good, Good, Fair, and Poor) [59], whilst exhibiting slight variations in the stringency of methodological approach and data quality requirement [76]. Recently, Carlesso et al. have integrated DQR and Pedigree Matrix into one hybrid DQA approach [77]; the complementary nature of the hybrid approach is also demonstrated in Salemdeeb et al.'s study, and a two-tiered assessment method was developed [78]. Since data quality significantly influences the results of LCIA, this work suggests conducting DQA prior to the impact assessment phase, specifically during the inventory analysis phase, rather than during the interpretation phase.

3.2.4.4. Inventory visibility

As noted in Section 3.2.3, six studies have yet to disclose their inventory analysis results, which might affect the transparency and credibility of the research. Therefore, it is recommended that at least the activity data (foreground data) of the inventory analysis results be published in the paper (either in the main text or as supplementary materials).

3.3. Impact Assessment

3.3.1. Impact assessment Method

Figure 11 illustrates the frequency with which various LCIA methods have been applied in CO_2 adsorption LCA studies. Analysis of 31 publications reveals that ReCiPe was used in 17 instances—substantially more than IMPACT and CML, each applied 4 times—with other methods (e.g., TRACI, IPCC, EF) being used less frequently. This pattern could be attributed to ReCiPe's ability to provide both detailed evaluations through its 18 midpoint and 3 endpoint categories—offering comprehensive environmental impact capture, which is consistent with Rybaczewska-Błażejowska and Jezierski's finding [79].

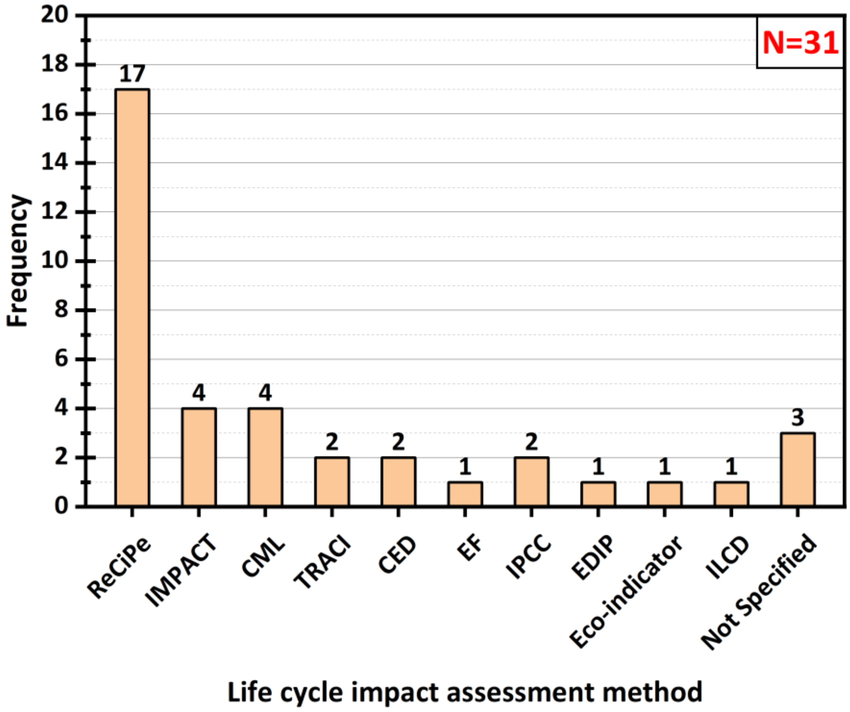

Figure 11. Types, frequency and percentage of impact assessment methods in LCA studies of CO_2 adsorption

3.3.2. Type and quantity of impact category

Figure 12 presents the types and quantities of impact categories corresponding to different LCIA methods in CO_2 adsorption LCA studies. Black dots represent midpoint categories, while red stars represent endpoint categories. The analysis indicates that the types and numbers of impact categories selected vary across studies. Overall, the majority (23 studies) employed only midpoint category indicators, such as [34, 51], while eight studies incorporated both midpoint and endpoint categories, such as [37, 38].

In terms of the number of impact categories, significant variation exists among studies. For midpoint categories, the range is broad: some studies focus on core environmental impact indicators, with fewer than ten categories, while others consider a more comprehensive set, exceeding ten categories and even covering all 18 impact indicators. For endpoint categories, the variation is smaller due to the limitation to 3 endpoint categories; IMPACT methodology reduces the number of endpoint categories from 4 to 3 because while climate change was historically classified as an endpoint category [80], but is now considered a midpoint category [81].

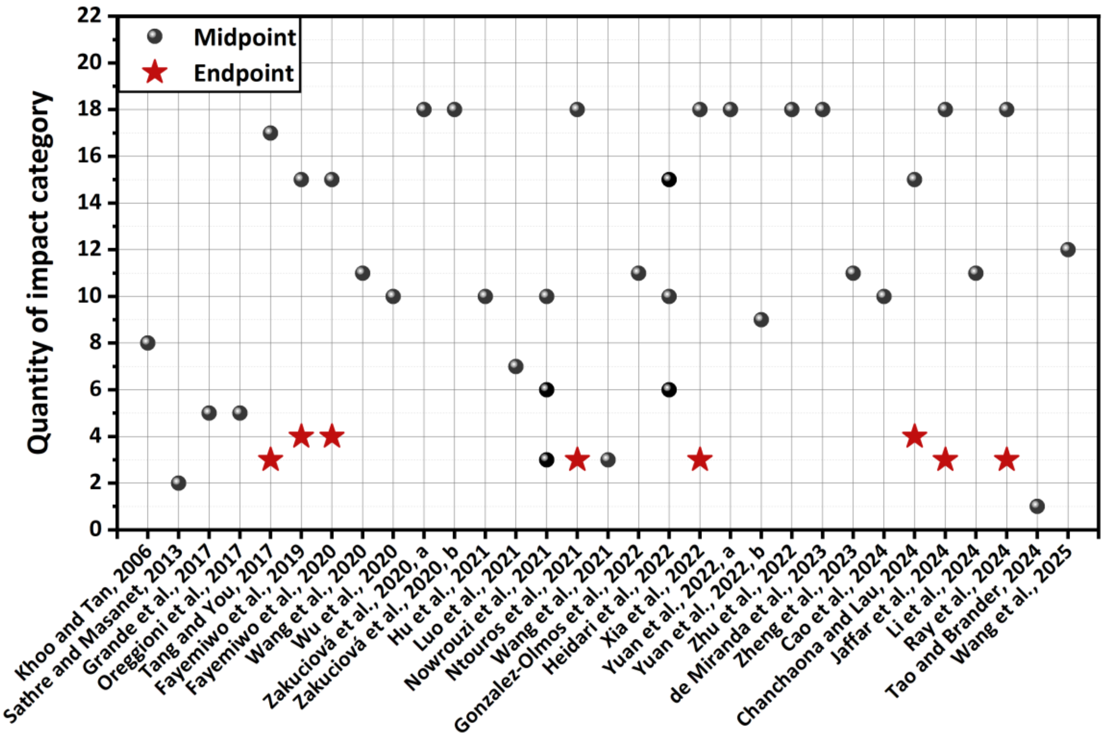

Figure 12. Types and quantity of impact assessment categories in LCA studies of CO_2 adsorption

3.3.3. Final score

Weighting to obtain an aggregate final score is an optional step in impact assessment [11, 12]. Seven studies (27%) provided final scores for impact categories, facilitating the ranking of different options and decision-making. For instance, Chanchaona and Lau proposed a Total Endpoint Impacts metric based on four endpoint indicators and normalised the results, enabling a straightforward comparison of different adsorbent synthesis routes [50].

3.3.4. Gaps and opportunities

3.3.4.1. Impact assessment Method

Regarding the impact assessment method, diverse methods have been used in previous studies. However, following LCA4CCU recommendations, the CML method—employing 11 impact categories (basic version)—is endorsed as it harmonises assessments with the Environmental Product Declaration (EPD) system to enhance comparability [70]. Additionally, the Environmental Footprint (EF) method—adopted and recommended by the European Commission [59], which spans 16 impact categories and has been notably refined in its update from EF3.0 to EF3.1, with major updates made to key indicators such as Climate Change, Human Toxicity (non-carcinogenic) and Freshwater Ecotoxicity, and the weighted impact categories can be summed to obtain the EF single overall score [82]. Overall, we recommend following the latest EU EF method in the future, as its official promotion by European institutions ensures broader international coverage, ongoing updates and enhancements, and ultimately, a robust, transparent, and common approach to assessing the environmental performance of CO_2 adsorption technologies.

3.3.4.2. Quantity of Impact Assessment Categories

As discussed in 3.3.2, Type and Quantity of Impact Categories, most studies still consider fewer than ten impact categories. Since a key value of LCA is the identification of trade-offs between categories, and since the environmental impacts of current adsorption technologies are not completely clear, it is recommended that all impact category types be used. If specific categories are excluded, justifications should be provided [70]. Although the core environmental impacts of CO_2 adsorption are often associated with GHG reduction effects (e.g., global warming potential or climate change), it is crucial to identify potential environmental trade-offs arising from CO_2 adsorption implementation to support informed decision-making.

3.3.4.3. Final score

Seven studies briefly discussed the results of weighting to obtain a final score. However, weighting is based on value choices rather than scientific principles, and different individuals, organisations, and populations may have varying preferences. The currently published studies still lack sufficient explanation of weighting factors and methods. According to ISO 14044, it is recommended to provide both the unweighted data and parameter results (or normalised results) alongside the weighted results [11]. Additionally, this paper suggests that future research should include detailed explanations of the selection criteria, values, and methodologies for normalisation benchmarks, weighting factors, and weighting methods to enhance the transparency and credibility of the analysis.

3.4. Interpretation

3.4.1. Significant analysis

Significance analysis aids in identifying critical issues in the LCI and LCIA phases. According to the European Commission's "Guide for Interpreting Life Cycle Assessment Results", the objects of significance analysis can be classified as (i) Elementary flow, (ii) Process, (iii) Life cycle stage, and (iv) Impact category [83]. This study adheres to this classification framework while also identifying two additional categories from 31 studies, namely: (v) Material and (vi) Mixed (process & material). The frequency of these six types of significance analysis is illustrated in Figure 13. More than half of the reviewed studies (18 papers) conducted significance analysis at the process stage, followed by (vi) Mixed (process & material) and (v) Material, both are 6 studies, respectively. Other types of significance analysis are relatively rare.

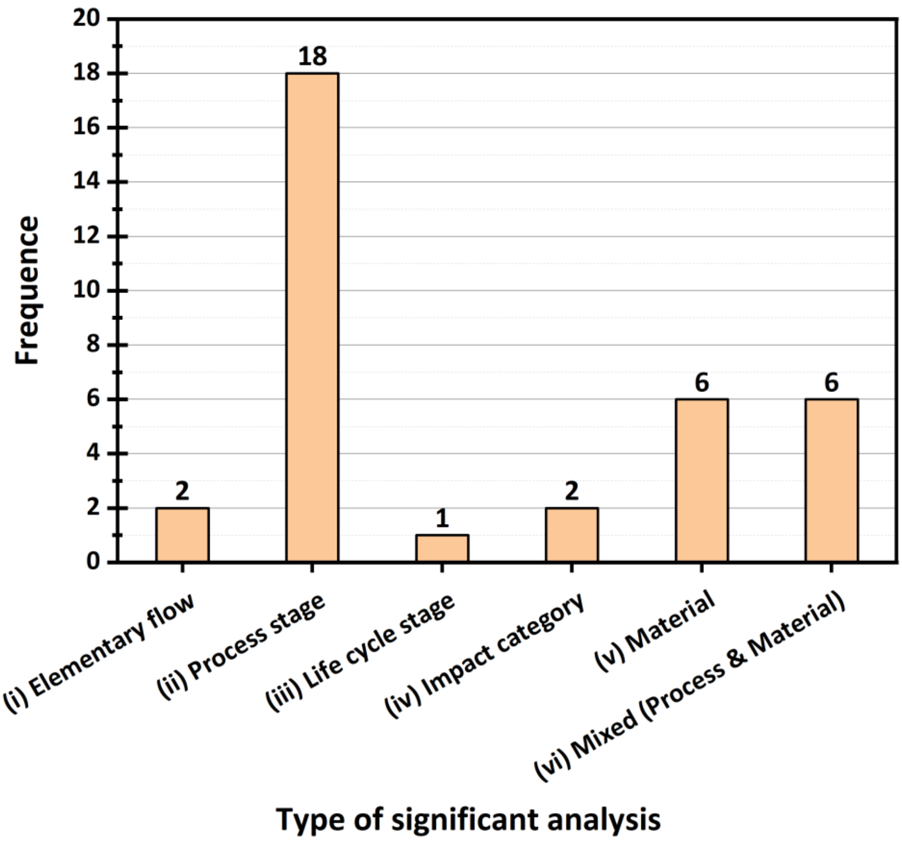

Figure 13. Types and frequency of significance analysis in LCA studies of CO_2 adsorption

3.4.2. Uncertainty analysis

It is important to emphasise that sensitivity analysis is not entirely equivalent to uncertainty analysis; these two terms are often used interchangeably but incorrectly [84]. Uncertainty analysis generally consists of four nested and progressive steps: (i) Identification and characterisation of uncertainty, (ii) Uncertainty propagation analysis, (iii) Sensitivity analysis, and (iv) Communication. For a detailed discussion, refer to the work of Igos et al. [67]. Here, we briefly outline the core questions addressed by each step:

(i) Identification and characterisation of uncertainty answer: Where are the sources (locations) of uncertainty in the system, and what is their magnitude (qualitative or quantitative)?

(ii) Uncertainty propagation analysis answers: How does system uncertainty affect the results (confidence level)?

(iii) Sensitivity analysis answers: Which part of the uncertainty is more critical (influential)?

(iv) Communication answers: How should the uncertainty content be conveyed to the audience?

Thus, uncertainty analysis encompasses sensitivity analysis. Moreover, the methods used for uncertainty and sensitivity analyses are not identical; for further details, see [67].

Uncertainty in LCA can be categorised into three types: Context, quantity (inputs and parameters), and model [67]. Among the 31 studies reviewed, the majority (24 studies, 77%) did not conduct uncertainty analysis, while only a minority (7 studies, 23%) performed such analysis. As shown in Figure 14, five studies focused on quantity uncertainty, one on context uncertainty, and one did not specify the type of uncertainty. Among the five studies addressing quantity uncertainty, two tried to analyse it but did not specify the methods used; the other three employed Monte Carlo sampling to address quantity uncertainty. Additionally, the study that did not specify the type of uncertainty also used Monte Carlo sampling as an analytical tool. The only study addressing context uncertainty adopted scenario analysis as its method.

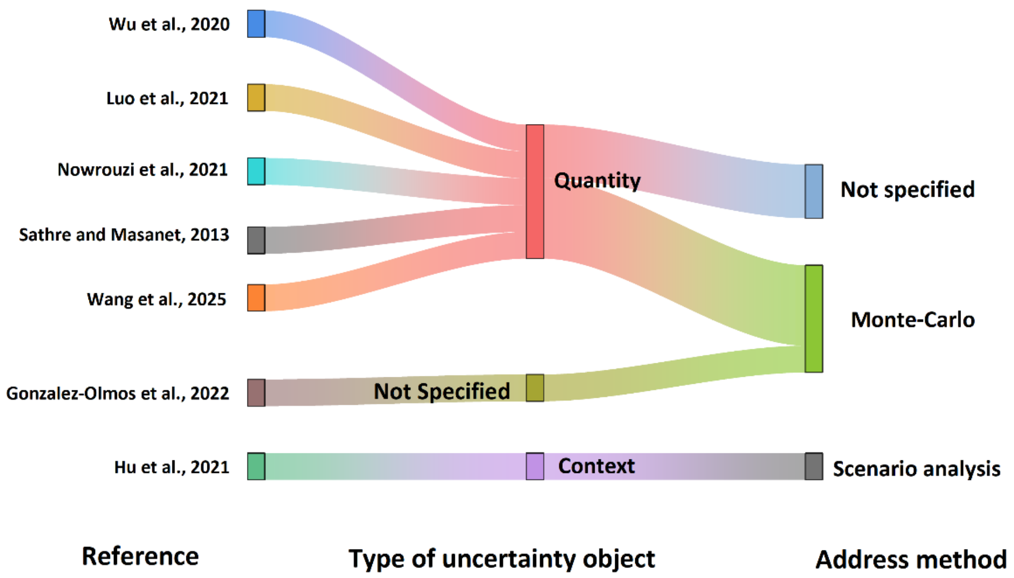

Figure 14. Types of uncertainty objects and analysis methods in LCA studies of CO_2 adsorption

3.4.3. Sensitivity analysis

Sensitivity analysis identifies which uncertainties have a significant or negligible impact on the results, thereby enhancing the understanding of result robustness (credibility) [67]. As shown in Figure 15, nearly half (14 studies, 45%) of the 31 studies conducted sensitivity analysis. Among these, the number of investigations targeting quantity and context uncertainties were 11 and 7, respectively. Sensitivity analysis for quantity was uniformly conducted using the one-at-a-time (OAT) method, though the range of variation differed slightly. Most studies set the percentage fluctuation range within ±20%, such as in [34]; one study, however, adopted a more extensive fluctuation range of ±40% [45]; and Wang et al. set two ranges, i.e. ±10% and ±30%, according to the nature of parameters [49]. For context sensitivity, most studies employed scenario analysis, with only one study using marginal analysis [42].

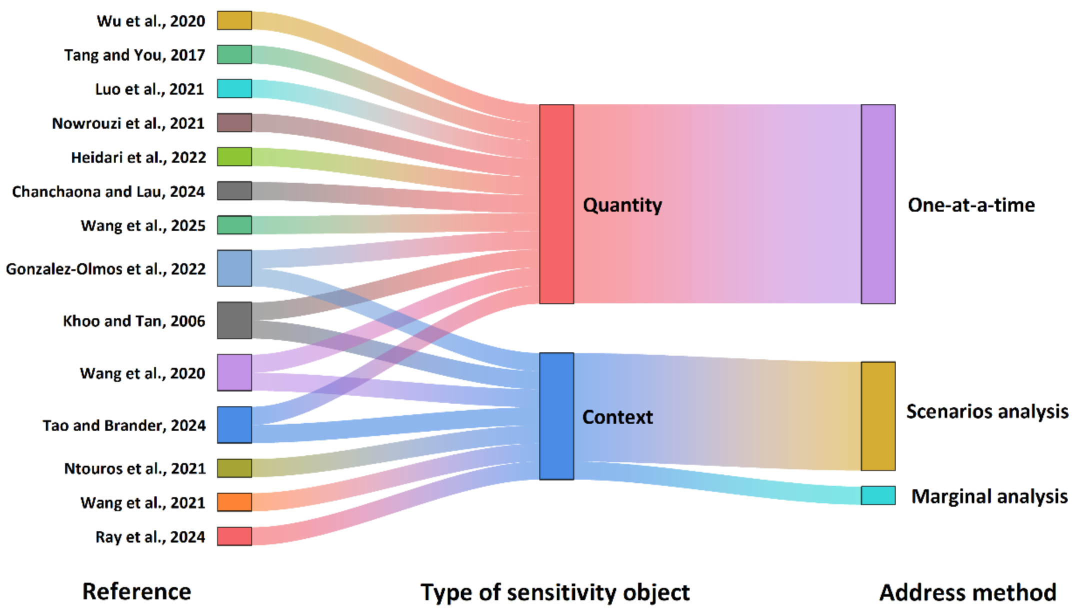

Figure 15. Types of sensitivity objects and analysis methods in LCA studies of CO_2 adsorption

3.4.4. Gaps and opportunities

3.4.4.1. Significant analysis of contributor

Section 3.4.1 on significant analysis shows that most studies focused on (ii) process stages as the object of analysis. Additionally, two new variants have emerged: (v) material and (vi) mixed (process & material). While these new forms provide fresh insights into the environmental impacts of CO_2 adsorption from different perspectives, they are not entirely based on an entire life-cycle perspective, particularly true for (vi) mixed (process & material), where the intersection of contributors with different natures makes it challenging to assess whether the consideration of contributors is comprehensive or if omissions exist.

In contrast, the approaches recommended by the European Commission—(i) elementary flow, (iii) life cycle stages, and (iv) impact category—have not been widely adopted despite being more standardised and reliable. Conducting significant analysis on these aspects allows for careful consideration of all contributors of the exact nature from an entire life-cycle perspective, ensuring no omissions and enabling the determination of their respective contribution rates.

Another notable deficiency in the significant analysis of the 31 reviewed studies is the lack of criteria for determining significance levels. Appendix 2 of ISO 14044 provides guidelines for ranking significance and their reference thresholds, as follows:

- ✧ A: Most important, significant influence, i.e., contribution > 50%.
- ✧ B: Very important, relevant influence, i.e., 25% < contribution < 50%.
- ✧ C: Fairly important, some influence, i.e., 10% < contribution < 25%.
- ✧ D: Little importance, minor influence, i.e., 2.5% < contribution < 10%.
- ✧ E: Not important, negligible influence, i.e., contribution < 2.5% [11].

Additionally, the European Commission advocates for the "most relevant" threshold conditions for (i) elementary flow, (ii) process stages, and (iii) life cycle stages, defined as all elementary flows/process stages/life cycle stages cumulatively contributing more than 80% to any impact category [83].

Therefore, future research is recommended to strengthen significant analysis for (i) elementary flow, (iii) life cycle stages, and (iv) impact category. On the other hand, clear criteria for contribution levels should be established, and the contribution rates of all significant analyses should be delineated.

3.4.4.2. Uncertainty analysis and sensitivity analysis

Most studies did not conduct uncertainty propagation analysis, and more than half did not perform sensitivity analysis, which may undermine the credibility of the LCA results. For uncertainty propagation analysis, the focus has primarily been on quantity uncertainty, while propagation analysis for context and model uncertainties remains severely lacking. Similarly, sensitivity analysis for model-related aspects (e.g., characterisation models for impact categories) is also absent.

For quantity sensitivity analysis, the OAT method was universally applied. However, OAT is a local sensitivity analysis method that does not account for interactions between two or more variables [85]. For instance, CO_2 capture rate and regeneration energy consumption are strongly correlated [6]. When the CO_2 capture rate is adjusted upward to a certain level, regeneration energy consumption may increase significantly. If sensitivity analysis only considers the CO_2 capture rate without accounting for the correlated changes in regeneration energy consumption, the value of the analysis results is limited.

In summary, as far as possible, future research could:

(i) Promote the adoption of uncertainty and sensitivity analyses while distinguishing their respective roles.

(ii) Address the gaps in context and model uncertainty and sensitivity analyses.

(iii) For quantity uncertainty, consider global sensitivity analysis methods (e.g., variance-based methods) to better understand the interactions among strongly correlated uncertainty factors.

3.4.4.3. Uncertainty of impact categories and their role in comparative LCA judgments

In comparative LCA of different CO_2 adsorption options, discussions often revolve around comparative judgments, i.e., evaluating the advantages and disadvantages of different options based on impact category scores. However, the 31 reviewed studies almost universally neglected the differences in uncertainty across impact categories.

The European Commission classifies impact categories by quality [70, 86]:

- ✧ Quality level I: Global warming, Climate change, Ozone depletion, Particulate matter/respiratory inorganics.
- ✧ Quality level II: Ionising radiation (human health and ecosystems), Photochemical ozone formation, Acidification, Eutrophication (terrestrial, freshwater, and marine), Resource depletion (mineral and fossil), Human toxicity (cancer and non-cancer effects), Ecotoxicity (freshwater).
- ✧ Quality level III: Cancer human health effects, Non-cancer human health effects, Ecotoxicity freshwater, Land use, water use, Resource use (water, mineral, metals, and energy carriers).

The quality levels are defined as:

- ✧ Quality level I: Recommended and satisfactory.
- ✧ Quality level II: Recommended but in need of some improvements.

- ✧ Quality level III: Recommended but to be used with caution.

Jolliet et al. also discussed default rules for determining the significance of differences in impact categories across scenarios. For the full version, refer to the original book [25]. Two examples are briefly summarised below:

- ✧ For energy and CO_2, any difference of at least 10% can be considered as significant.
- ✧ For toxicity characterisation, impact calculations often involve greater uncertainty, requiring a difference of at least one to two orders of magnitude between scenarios to be considered significant.

In general, the magnitude of uncertainty varies significantly across impact categories, sometimes differing by orders of magnitude. No universal rule exists for determining the significance of differences across all impact categories.

Although no universally precise criteria have been established, a cautious and conservative approach is advisable when addressing differences across impact categories in various scenarios. When the differences between two options may fall within the range of uncertainty, it is prudent to avoid making definitive statements that one option is categorically superior to the other in certain impact categories, as such assertions risk leading to overly speculative conclusions. For example, in one study, Gonzalez - Olmos et al. stated in their abstract that "All the key performance indicators studied had better values with 13X-APG than CMS-330" [44], while Jaffar et al. claimed that "The novel SPEI-based CCS process showed superior environmental performance compared to the conventional MEA-based CCS process." [40]. However, a more detailed examination of their LCIA results reveals that the scores for some impact categories between the alternatives are very close, even with only negligible differences. Consequently, if impact category uncertainty is not adequately considered, drawing definitive conclusions from LCIA results may be somewhat overoptimistic. Given that some decision-makers are not specialists in LCA, basing decisions solely on such findings could lead to biased outcomes, insufficient robustness, and even erroneous decisions.

Generally, two strategies can be adopted to mitigate the challenges posed by impact category uncertainty in comparative LCA:

(i) Cross-validation using multiple LCIA methods: By employing several LCIA methods for cross-validation, one can reduce the influence of uncertainty inherent to any single method. This approach enhances the robustness of the comparative LCIA results, the subsequent LCA conclusions, and the reliability of subsequent decisions. For example, Coppola et al. not only utilised the ReCiPe 2016 method but also confirmed their findings using ILCD 2011, with both approaches yielding consistent results [87]. Another study employed ReCiPe 2016, ILCD 2011, CML-IA baseline and IMPACT 2002+ to compare the environmental impacts of the electricity consumption structures across the EU27, Norway, Switzerland and the UK, demonstrating that the ranking of environmental profiles was largely consistent across methods, with discrepancies only in a few impact categories [79].

(ii) Sensitivity and uncertainty analysis of characterisation factors and models: given that the uncertainties in LCIA results stem primarily from the underlying characterisation factors and models, and they vary in different LCIA methods [79, 88], performing sensitivity and uncertainty analyses on these components is crucial to establishing the confidence intervals for the results. This way, in turn, provides a robust basis for comparing different scenarios. In addition, if the study needs to draw out the endpoint impact categories score, normally, their uncertainty level is higher than mid-point impact categories [59, 89]; the normalisation factor and weighting factor could also be considered in sensitivity and uncertainty analysis.

In summary, both strategies contribute to a deeper understanding of how impact category uncertainty affects comparative LCA outcomes. Strategy (i) is more straightforward to implement, whereas strategy (ii) demands a comprehensive understanding of the underlying mechanisms of LCIA methods. The inherent uncertainty in impact categories should not be overlooked, as it can be as significant as the parameter uncertainty that is typically emphasised [88]. Although issues such as the common significance grade of LCIA result differences remain unresolved in the LCA industry, when the differences in certain impact categories between alternatives are minimal, a more cautious approach is warranted to avoid conclusions of insufficient robustness that could adversely affect subsequent decision-making.

3.4.4.4. Differential coping with independent and shared uncertainty in comparative LCA

According to existing 31 surveys, when conducting comparative LCA, although some studies have conducted uncertainty analysis, whether the uncertainties in the comparison options are exclusive (or common) has not been particularly emphasised. However, they are quite different and even determine how to compare different options [25, 85].

The above discussion is based on the situation that the uncertainties are independent between different options. However, in the field of CO_2 adsorption, different options may share some of the same uncertainties. For example, when comparing different regeneration processes of the same CO_2 adsorbent, the uncertainty of the yield in the adsorbent synthesis stage is consistent because they are in the same production background. It should be noted that if two or more scenarios share common uncertainty, simply comparing through the independent confidence intervals of LCIA results could lead to misleading conclusions; at this time, the researcher should directly co-analyse the probability that option A is higher (or lower) than option B in a certain impact category under the same uncertainty.

When addressing shared uncertainties in multi-system analyses, the robustness of joint analysis methods requires consideration of significance levels in comparative LCIA results (as previously discussed). A threshold (e.g., 10%) can be established to determine significant differences: if Option A's result in a given impact category exceeds (or falls below) Option B's result by this fixed percentage (e.g., 10%), the difference is deemed significant. Note that under such stringent criteria, the probability of observing 'significant differences' will inherently be lower than that of detecting 'any numerical differences' between systems.

3.4.4.5. Section Summary

This subsection outlines key uncertainty-related challenges in comparative LCA:

(i) Distinguishing uncertainty analysis from sensitivity analysis.

(ii) Assessing the significance of LCIA result differences (impact category-specific uncertainties).

(iii) Differentiating independent vs. shared uncertainties in compared systems

These issues are notoriously complex and error-prone. To mitigate common pitfalls systematically consulting the following progressive checklist after completing a comparative LCA may help mitigate common pitfalls:

(i) Is this truly a comparative LCA study?

(ii) Was uncertainty analysis explicitly conducted? (Characterisation, propagation, sensitivity analysis, reporting).

(iii) Are uncertainty analysis and sensitivity analysis clearly distinguished?

(iv) Were impact category uncertainties accounted for? (i.e., is the observed LCIA difference significant?)

(v) Do the compared systems share any common uncertainty sources?

3.5. A Suggested Methodological Framework

Building upon the research gaps and opportunities identified in the preceding sections, this part proposes the core elements and develops a hierarchical methodological framework for the LCA of CO_2 adsorption technologies, as illustrated in Figure 16. This framework is based on the baseline of current state-of-the-art identified in this study and aspires towards best practices outlined in ISO 14040, ISO 14044, and the ILCD Handbook. It delineates a suggested pathway from the current status to the aspirational state.

The framework qualitatively classifies methodological enhancement efforts into three hierarchical levels, using two progressive discriminative statements based on the degree of additional effort required:

(i) Does the current baseline require further analysis? If not, it is classified as a minor effort, typically involving supplementary or improved reporting on existing work, especially aiming to reduce textual ambiguity. If yes, then proceed to the second criterion:

(ii) Does the new analysis require interdisciplinary knowledge? If not, it constitutes moderate effort, usually implying that while partial or similar LCA analyses have been conducted, there is room for methodological refinement, achievable using conventional LCA expertise. If interdisciplinary knowledge is indeed necessary, it is classified as a major effort, typically addressing significant methodological gaps or misapplications that demand mastery of fundamental LCA architecture and supporting interdisciplinary insights.

The methodological steps described within the framework are not exhaustive; a complete methodological execution must still conform to the latest ISO 14040 and ISO 14044 standards. Rather, this framework serves as an "opportunity checklist", focusing on key points across the four phases of LCA that could significantly enhance comparability and reliability.

Specifically, the detailed methodological elements mapped to the three hierarchical levels are shown in Figure 16, while concrete examples supporting these methodologies can be found in "Supplementary Document 2 - Examples".

It is crucial to emphasise that this framework is not intended to replace the ISO 14040 standard methodology but acts as a complementary extension tailored to the context of CO_2 adsorption. It offers a conceptual solution for bridging the considerable gap between the current application of LCA methods and the ideal standards in the CO_2 adsorption field.

Compared with standalone ISO 14040 & ISO 14044, this framework offers several potential advantages:

(i) Field-specific gap identification: ISO 14040 & 14044 provide the overarching standards and guidelines for LCA research, treating all four phases with almost equal importance without explicitly emphasising any specific challenges in a given field. By contrast, this framework identifies field-specific shortcomings in applying LCA on CO_2 adsorption, treating these as an "opportunity checklist" and offering a strategy for progressive alignment with ISO 14040 & ISO 14044 expectations based on additional effort levels.

(ii) Focused enhancement of comparability and reliability: While ISO 14040 & ISO 14044 cover broad aspects such as transparency, comparability, reliability, communicability, and verifiability, this framework particularly targets the comparability and reliability issues pertinent to the CO_2 adsorption domain, e.g., establishing consensus comparability tiers and addressing uncertainty in comparative impact categories.

(iii) Tailored applicability to CO_2 adsorption: ISO 14040 & ISO 14044 offer a generic framework applicable to all products and services without considering the specific characteristics of individual study objects. Conversely, this framework is custom-designed for CO_2 adsorption, incorporating field-specific elements like setting functional units for adsorbents and CCS, and proposing consensus-based comparability baselines, thus reducing the trial-and-error process in practice and ensuring a basic quality standard.

(iv) Methodological tool recommendations: ISO 14040 & ISO 14044 present general principles without specifying preferred methodological tools, thus allowing diversity but also causing methodological heterogeneity. In contrast, this framework recommends specific methods and tools, such as using the EF 3.1 method for LCIA and global sensitivity analysis for uncertainty assessments.

(v) Provision of practical examples: ISO 14040 & ISO 14044 do not provide case-specific methodological examples, which can leave practitioners struggling with implementation despite adhering to theoretical principles. This framework is supported by practical examples of methodological elements, offering actionable guidance to practitioners.

However, despite aiming to narrow the gap between practical and ideal LCA applications and being underpinned by scientific references, the proposed framework still has several limitations:

(i) Limitations in literature review methodology: Some relevant publications may have been missed because they did not use standard LCA terms like "life cycle assessment" but broader descriptors such as "ecological" or "sustainable". Expanding the search terms would compromise search precision. Thus, a balance between precision and comprehensiveness inevitably leaves room for omissions.

(ii) Cognitive limitations: Some decisions, such as constructing the comparability framework or setting consensus-based baselines for CO_2 adsorption, necessarily relied on the professional judgment of the research team, which might introduce cognitive biases and require further validation or expert evaluation in future work.

(iii) Tension between standardisation and flexibility: While standardisation promotes comparability and credibility, it may also reduce methodological diversity. For example, recommending the EF 3.1 method could discourage using alternative LCIA methodologies. Conversely, despite efforts to refine key elements such as functional units for CO_2 adsorption, some space for methodological variation remains, preserving flexibility but also potentially introducing heterogeneity in LCA approaches and results.

In summary, balancing the precision and breadth of the literature review, overcoming cognitive limitations, and managing the tension between standardisation and diversity will require ongoing iteration and refinement in future research.

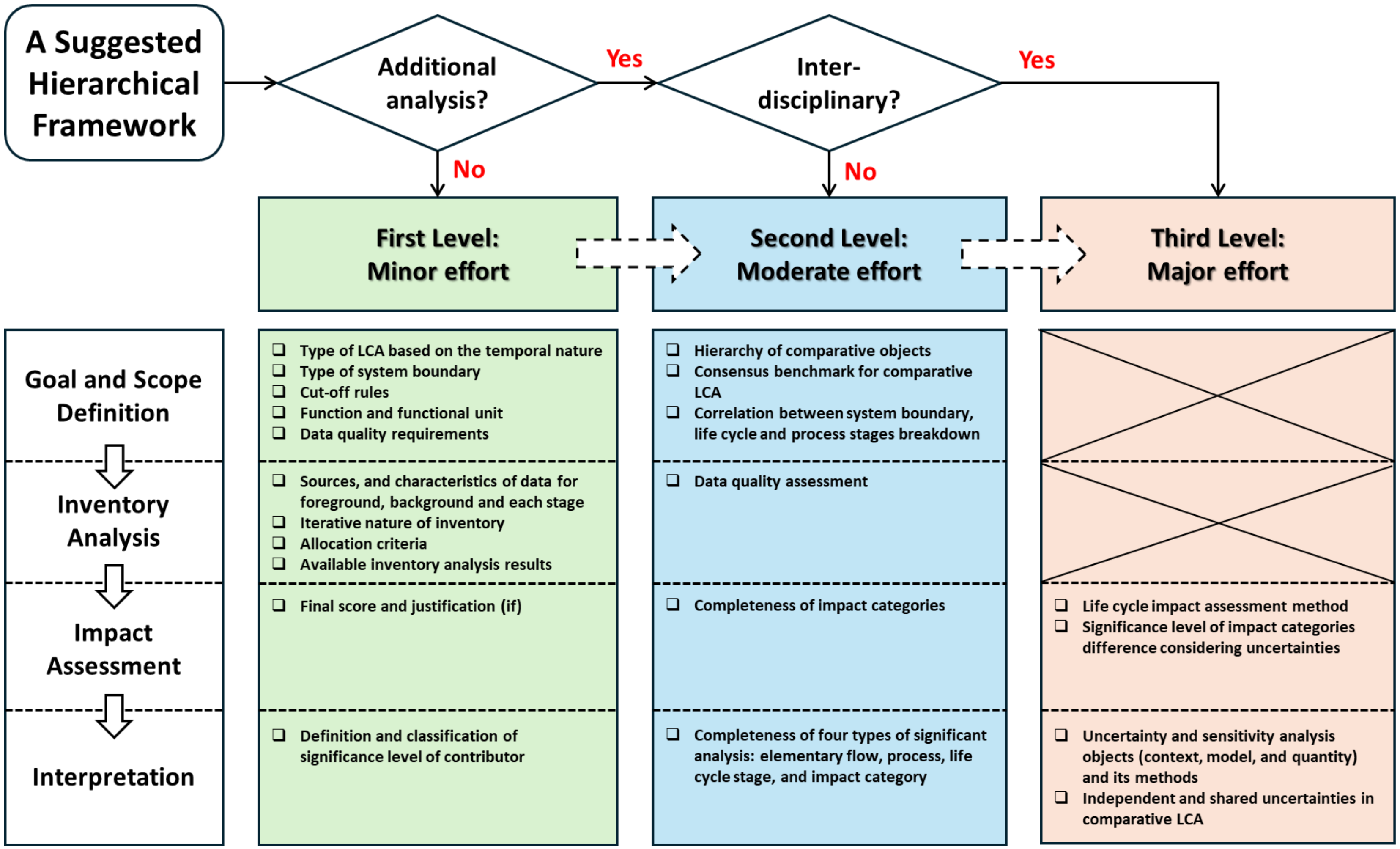

Figure 16. **A suggested hierarchical methodological framework to enhance the comparability and reliability for LCA of CO_2 adsorption**

4. Conclusion

This study addresses the methodological ambiguity and inconsistency in conducting LCA for CO_2 adsorption technologies in energy-intensive industries by systematically identifying the commonalities and differences in the methodological elements of 31 existing studies published from 2006 to 2025. It also highlights the gaps and opportunities for improvement compared to the latest ISO standards, ILCD guidelines, and other normative documents. Based on these findings, this paper proposes an LCA methodological framework that considers comparability and reliability, with the main conclusions summarised as follows:

(i) Existing literature demonstrates certain commonalities in applying LCA methodologies across the four phases, such as the definition of system boundaries and functional units. However, certain differences exist simultaneously, such as the correlation of the system boundary, life cycle stages and processes, and the number of impact categories considered.

(ii) There remain methodological gaps that require further attention, including data quality analysis, reporting on the characteristics and iterative nature of inventory data, consideration of uncertainties in impact categories when making comparative judgments, and the classification of significance levels in significance analysis results.

(iii) The proposed methodological framework in this paper may enhance the credibility and comparability of LCA results. The implementation of the framework is categorised into three Levels of effort:

- ✧ First Level: Minor effort, based on the existing analysis, but adjustments to the format and precision of reporting are needed, such as explicitly defining the hierarchical level of the comparative objects.
- ✧ Second Level: Moderate effort, such as completing data quality analysis and adopting a more comprehensive impact assessment categories.
- ✧ Third Level: Major effort, such as conducting uncertainty and sensitivity analyses for context and models.

Standardised and comparable LCA results for CO_2 adsorption technologies are a critical research objective for LCA practitioners. This study makes a unique contribution to the field by improving the consistency and comparability of LCA methodologies. The findings provide methodological references for subsequent related studies, reducing uncertainty and ambiguity in LCA methodologies applications and encouraging more researchers to explore the standardisation of LCA methodologies in greater depth.

Credit authorship contribution statement

Yipeng Yao: Conceptualisation, Methodology, Visualisation, Writing – original draft.
Marie-Eve Duprez: Writing – review & editing, Supervision.
Guy De Weireld: Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that there is no conflict of interest.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, Yipeng Yao used ChatGPT to improve the manuscript's readability and language. After using this service, Yipeng YAO reviewed and edited the content as needed and took full responsibility for the content of the published article.

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