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Evaluating the EU taxonomy through a lifecycle perspective

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ABSTRACT

The EU Taxonomy establishes a classification system to identify environmentally sustainable economic activities. It is guided by technical screening criteria (TSC) specified in delegated acts under the Taxonomy Regulation (TR), which mandates a scientific and lifecycle-based approach for the development of these criteria. This study examines the implementation of this lifecycle-based approach, focusing on the integration of Life Cycle Assessment (LCA) indicators. LCA serves as a robust methodology for evaluating the environmental impacts of products, processes, or services throughout their entire life cycle. This research aimed to assess the application of LCA within the TSC framework by aligning LCA impact categories with the environmental objectives (EO) delineated in the EU Taxonomy. Analysis of the TSC reveals that LCA based criteria were notably absent in more than two-thirds of the criteria examined. Among the criteria that do incorporate LCA methods, a predominant focus lies on criteria referring to the climate change mitigation objective. This assessment underscores the current adoption status of lifecycle-based methodologies within the EU Taxonomy's TSC. Furthermore, it highlights opportunities to enhance the integration of LCA by considering the mapped LCA indicators to the EOs of the EU Taxonomy.

1. Introduction

With the Paris Agreement, 196 countries, including the EU, committed to limiting global temperature rise to well below 2 °C above pre-industrial levels (*Paris Agreement.* United Nations, 2015). Article 2 (1c) of the Agreement calls for aligning financial flows with low-GHG and climate-resilient development (*Paris Agreement.* United Nations, 2015). Building on this, the EU introduced the 2019 Green Deal as a growth strategy to achieve climate neutrality by 2050 and enhance environmental sustainability (Canfora et al., 2021; Schütze and Stede, 2021).

The financial sector plays a key role in achieving those goals by mobilizing capital (Canfora et al., 2021; The European Parliament and the European Council, 2020). To support the financial sector in the green transition, the EU Taxonomy Regulation (EU TR) was introduced in 2020. It is a classification system that defines criteria for environmentally sustainable economic activities. Adopted as part of Regulation (The European Parliament and the European Council, 2020/852), it aims to align financial flows with the goals of the Green Deal and the Paris Agreement (Ahlström and Sjåfjell, 2022; Canfora et al., 2022; The European Parliament and the European Council, 2020).

The EU TR is implemented through Delegated Acts (DAs), which define criteria for environmental objectives (EO) and disclosure. The 1st DA was published in December 2021 and became legally binding on January 1, 2022, alongside a DA on disclosure requirements. An amending DA, supplementing the first, followed in June 2022. The latest, the 2nd DA, was published in November 2023 and took effect on January 1, 2024 (Canfora et al., 2021; European Commission, 2021a; Ostojic et al., 2024; The European Parliament and the European Council, 2020).

The EU Taxonomy outlines six environmental objectives (EOs) (see Fig. 1). The DAs under the EU TR define Technical Screening Criteria (TSC) to classify economic activities that: (1) make a substantial contribution (SC) to one of these objectives, (2) do no significant harm (DNSH) to the others, and (3) comply with minimum social safeguards (MSS). The 1st DA sets out the TSC for the climate objectives, while the 2nd DA, also known as the environmental DA, covers the TSC for the remaining four objectives (see Fig. 1) (Becchetti et al., 2022; Ostojic et al., 2024).

The EU Taxonomy aims to define TSC based on scientific evidence and a lifecycle approach. A life-cycle-based approach is defined as a systematic method that evaluates environmental impacts across all stages of a product, process, or service, from raw material extraction to end-of-life management (DIN German Institute for Standardization,

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2021a). In regulatory design, implementation of a life-cycle-based approach refers to the translation of conceptual life-cycle considerations into concrete, operational TSC that are technically robust and verifiable. This interpretation aligns with Article 19, paragraph 1(d), which mandates that TSC must consider the entire life cycle, drawing on existing lifecycle assessments (LCAs), and account for environmental impacts of both the economic activity and its products or services, especially during production, use, and end-of-life phases (Canfora et al., 2021; The European Parliament and the European Council, 2020).

LCA is a scientifically recognized method for evaluating the environmental impacts of products, processes, or services across their entire lifecycle (DIN German Institute for Standardization, 2021a). It is governed by international standards DIN EN ISO 14040 and 14044, which define the framework (DIN German Institute for Standardization, 2021a), requirements, and procedures (DIN German Institute for Standardization, 2021b).The primary goal of LCA is to provide transparent, science-based data to support informed, quantitative and qualitative decision-making.

In the context of the EU Taxonomy, LCA plays a key role in ensuring scientifically sound and robust sustainability criteria. It enhances the transparency and comparability of economic activities and helps prevent burden-shifting, where reducing impact at one lifecycle stage unintentionally increases it at another (Lai and Karakaya, 2024).

The research question is therefore to what extent life cycle-based approaches have been integrated into the TSCs of the DAs. In the literature the EU Taxonomy was analyzed regarding its impacts on the economy (Köppl-Turyna and Schwarzbauer, 2022) and different sectors (Koch et al., 2023; Norang et al., 2023), on climate neutrality (Schütze and Stede, 2021), regarding its applicability (Ostojic et al., 2024) or regarding its impacts on the financial sector and investments (Kirschenmann, 2022; LUCARELLI et al., 2023; Papari et al., 2024) and on ESG ratings (Dumrose et al., 2022; Zetzsche et al., 2021). A systematic investigation of LCA integration in the taxonomy is still missing. Becchetti et al., (2022), conducted a mapping of LCA impact categories to the environmental objectives, but further assessments regarding LCA approaches included in the TSC have not been performed.

Previous studies indicate that life-cycle thinking and LCA are increasingly recognized in EU policies (Sala et al., 2021). Reports published by the Platform on Sustainable Finance and by the Technical Expert Group (TEG) include methodological recommendations for the development of the TSC and highlight the relevance of life-cycle considerations. However, they do not provide a systematic or quantitative evaluation of whether, and to what extent, the lifecycle consideration are adopted and whether they explicitly refer to standardized LCA frameworks or ISO standards (EU Technical Expert Group on Sustainable Finance, 2020; Platform on Sustainable Finance, 2021).

To address this problem, the study develops a four step to operationalize implementation of the lifecycle-based approach mandated by Art. 19(1)d EU TR: (1) mapping ICs to EOs; (2) defining IC-specific keywords; (3) screening DAs; (4) qualitative verification of LCA relevance. This analysis systematically quantifies explicit lifecycle integration in 1st and 2nd DAs.

2. Methods

Impact Categories (ICs) describe specific types of environmental impacts that can be caused by the lifecycle of a product, service or process (DIN German Institute for Standardization, 2021b). In LCAs, a distinction is made among different impact assessment methods, each with their own ICs and characterization factors. In the EU, for example, the CML, RECiPe and EU Environmental Footprint (EF) methods are frequently used (PRé Sustainability, 2020). A distinction can be made between an impact-oriented (midpoint categories) and a damage-oriented approach (endpoint categories) (Guinée, 2015).

The CML method, an example of an impact-oriented approach, was developed at Leiden University in 2001 and comprises 11 ICs (PRé Sustainability, 2020). CML is used throughout Europe and is considered one of the most common methods in the EU (PRé Sustainability, 2020), which is why it serves as the standard for this work.

ReCiPe, which was developed in the Netherlands in 2008, is a method that combines both approaches (impact- and damage-oriented) (Goedkoop et al., 2009). It attempts to combine the advantages of both approaches, but faces the challenge of requiring extensive and high-quality data (Acero et al., 2016).

The EU developed the EF method to harmonize environmental assessment, using 16 standardized ICs with established scientific models, often based on sources also used in CML and ReCiPe like IPCC (for climate change) and USEtox (for toxicity) (European Commission, 2021b; Zampori and Pant, 2019).

For this study, CML 2001 baseline method (2016 update) ICs were complemented with ReCiPe 2008 midpoint-categories to broaden the range of LCA indicators (see Table A1). In addition to the eleven CML categories, particulate matter formation (PMF), ionizing radiation (IR), agricultural land occupation (ALO), urban land occupation (ULO), and water depletion (WD) - which are not covered by CML - were included from ReCiPe. In LCA, midpoint impact categories are defined at an intermediate point along the cause–effect chain, relating life cycle inventory results to specific environmental impact mechanisms (such as

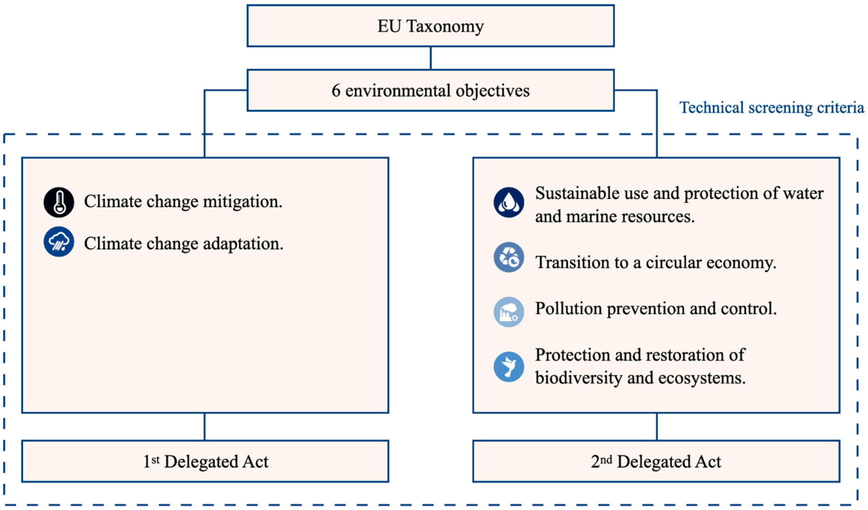

Fig. 1. Structure of the EU Taxonomy.

climate change, acidification, or eutrophication), before any optional aggregation into damage indicators at the level of broader areas of protection. In this study, we did not apply the mapping to the underlying LCIA characterization models, instead, we used the midpoint impact categories as a conceptual basis to assign each impact category to one or more EU Taxonomy EOs, according to the environmental impact mechanism it represents. Endpoint indicators, which combine several midpoint categories into a small number of generic areas of protection (e.g., human health, ecosystems, or resources) (Traverso and Backes, 2026), were not considered suitable for this purpose because their high level of aggregation does not correspond to the six differentiated EOs of the EU Taxonomy.

Additionally, the environmental Footprint (EF) 3.0 method was assessed to complete the selected set of environmental indicators with respect to EU-harmonised LCIA practice, yet comparing EF midpoint impact categories with the combined CML and ReCiPe set did not reveal additional environmental impact mechanisms relevant for the mapping, so no further indicators were added on this basis (Rybaczewska-Błażejowska and Jezierski, 2024).

2.1. *Assignment of impact categories to environmental objectives*

First, the selected ICs are assigned to the EOs of the EU Taxonomy (see Table A2). This alignment streamlines the assessment by clarifying which ICs relate to each objective and may be included in specific TSC. The assignment of ICs to EOs follows a three-criteria principle:

1. **Direct causal link**: The IC must have a clear and direct impact on the EO.
2. **Measurability and policy relevance**: The IC should provide quantifiable information on the environmental impact that is directly relevant to the EO, supporting assessment, monitoring, or policy decisions.
3. **Handling overlaps:** Some ICs affect multiple EOs and are therefore assigned to all applicable objectives If a match with such keywords is found in the following steps, a content analysis is performed to determine the relevant EO. This ensures that each occurrence is counted in the most relevant EO, while also taking into account the IC's relevance to multiple targets.

The impact category GWP is assigned to the EO of climate change mitigation. GWP describes the climate impact of GHG emissions in CO_2 equivalents. By using the GWP, the largest sources of GHG can be identified and quantified, which can promote the mitigation of climate change. In addition, it serves as a central instrument in climate policy and reporting, thereby ensuring greater transparency in climate-related topics (Neubauer, 2021; Sovacool et al., 2021).

The impact category ULO is assigned to climate change adaptation. Urban areas become very hot in the summer months due to the large number of sealed surfaces as global warming progresses. Adaptations are needed to create more green spaces and less sealed surfaces in order to achieve cooling in cities (Satterthwaite et al., 2009).

Five ICs support the objective of sustainable use and protection of water and marine resources. Nitrogen and phosphorus from fertilizers cause eutrophication. Reducing eutrophication potential (EP) protects these systems and encourages sustainable use, especially important in EU regions with year-round water shortages. Acidification potential (AP) measures acidification’s impact on water bodies, with lower AP improving water quality (Umweltbundesamt, 2024), justifying its inclusion under this objective. Marine aquatic ecotoxicity potential (MAETP) directly indicates marine ecosystem health, while freshwater aquatic ecotoxicity potential (FATEP) assesses ecotoxicity in freshwater systems (Acero et al., 2016).

The fourth EO is the transition to a circular economy, which is structured more around specific measures than ICs. However, the Abiotic Depletion Potential (ADP), which reflects the availability of mineral and metallic resources, can be linked to this objective. Establishing closed material loops through reuse and recycling enhances resource availability and positively influences ADP values (Acero et al., 2016).

Seven ICs correspond to the pollution prevention and control objective. Photochemical Ozone Creation Potential (POCP) measures ground-level ozone formation, which harms urban air quality. Human Toxicity Potential (HTP) addresses health risks from pollutants entering air, water, and soil as emissions rise. Particulate Matter Formation (PMF), mainly from industrial and traffic combustion, also significantly impacts air quality (Bölke and Witt, 2018). Chlorinated and brominated compounds deplete the stratospheric ozone layer, so reducing these emissions is crucial. While Acidification Potential (AP) is linked to water protection, most acidifying emissions are anthropogenic and airborne, making their reduction vital for pollution control, especially from fossil fuel combustion. (Crippa et al., 2021) Lowering ADP fossil reduces environmental pollution, and minimizing ionizing radiation is essential due to its long-term ecological harm (Achazi, 2010).

Ultimately, three ICs are assigned to the sixth EO, the protection and restoration of biodiversity and ecosystems. The acidification of water and soil has a direct impact on the quality of an ecosystem, which is why a reduction in the potential contributes to an improvement in ecosystems. The ALO impact category mainly considers the occupation and conversion of agricultural land. Agricultural activities are one of the main causes of biodiversity loss and unsustainable use can lead to soil degradation. (Zebisch, 2004) Additionally, Terrestrial Ecotoxicity Potential (TETP) is assigned to the EO of biodiversity. This primarily considers the toxic effects of pollutants on land-based ecosystems. If this results in damage to organisms, the FAETP can also contribute directly to the loss of biodiversity.

2.2. *Identifying LCA approaches in the delegated acts*

Having assigned the ICs to the EO of the EU Taxonomy, in the second step keywords are defined which are used to screen the DAs (step 3) and assess the extent to which the LCA method has been operationalized in the TSC, i.e., how conceptual life-cycle considerations are translated into concrete regulatory requirements (step 4). The procedure is illustrated in Fig. 2.

Keywords were selected to directly reflect the descriptions of the chosen ICs, as listed in Table A1, ensuring close alignment with EU Taxonomy objectives and LCA categories. Additional terms, such as “life cycle”, a central term of LCA, were also included. References to DIN EN ISO 14040 and 14044 signal LCA use, while DIN EN ISO 14046 and 14067 were added for their relevance: ISO 14046 defines the water footprint based on a product’s full lifecycle, and ISO 14067 outlines carbon footprint (CFP) calculation using the LCA approach. The CFP is the “sum of the quantities of GHG emitted and the quantities of GHG removed in a product system, expressed as CO_2 equivalents and based on a LCA using the single impact category of climate change.” (DIN German Institute for Standardization, 2019-02-00). Due to the direct reference of the CFP to the LCA, this standard was also included in the analysis. By combining impact-category-specific terminology with general lifecycle references and ISO norms related to LCA, the keyword set was designed to capture explicitly operationalized LCA-based requirements as comprehensively as possible. The selection of keywords is shown in Table A3.

In a next step, all selected keywords were entered into the search function of the document of the 1st and 2nd DA in order to check whether and in what form impact category keywords were integrated into the TSC.

If no results were found for the keywords, the corresponding ICs were excluded. When matches appeared, each was checked for an actual LCA reference (see Fig. 2). This qualitative screening step was conducted to distinguish between mere keyword occurrences and substantively LCA-based requirements. For each keyword match, the full criterion text was

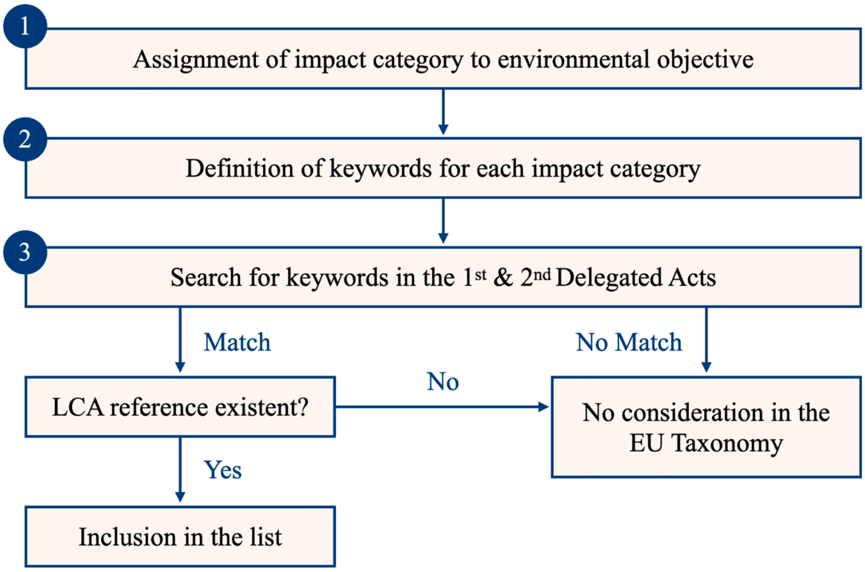

Fig. 2. Methodological approach.

manually reviewed to assess whether the reference implied a life cycle-based approach. Keyword mentions limited to general emissions reporting, efficiency improvements, or references to international agreements without lifecycle framing were not classified as LCA-based. This procedure aimed to systematically minimize false positive classifications arising from purely textual matches. For example, the keyword “ozone” appeared 15 times across both DAs, but only in relation to the Montreal Protocol, not LCA-based requirements. Thus, life cycle-based ODP mitigation is not included as a TSC requirement, and “ozone” was excluded from the LCA criteria list.

The main goal of this step was to identify keywords in the TSC that establish explicitly operationalized LCA-based approaches. While the combination of impact-category-specific terminology, general lifecycle references and ISO standards aims to minimize the risk of overlooking relevant criteria, the screening approach focuses on textually identifiable and explicitly formulated LCA-based requirements.

Nevertheless, it cannot be ruled out that certain criteria rely on implicit lifecycle reasoning without using standard LCA terminology. The approach therefore captures explicitly formalized LCA integration within regulatory criteria rather than broader or implicit environmental systems thinking.

2.3. Evaluation of LCA integration in the TSC

The evaluation process follows three steps:

- Keyword frequency: Assess keyword distribution & matches within the EU Taxonomy.
- Criteria analysis: Evaluate LCA-based requirements in SC and DNSH criteria separately.
- Integration: Combine SC/DNSH findings to identify explicit LCA integration across the TSC in the EU Taxonomy.

Matches in the SC and DNSH criteria are evaluated by total activities and by EO with SC and DNSH assessed separately. Only matches between keywords and SC or DNSH criteria descriptions, for all activities in both DAs, are considered, keywords found in activity descriptions are excluded.

Afterward, an overall evaluation examines the distribution of activities with LCA-based criteria across both DAs and all EOs. For this, the number of keywords matches in all SC and DNSH criteria per DA was determined, and keywords without matches were also identified.

To avoid double-counting activities with multiple keywords in their criteria, activities are classified as:

a. Direct LCA approach: At least one relevant keyword in SC/DNSH criteria.
b. No direct LCA approach: No keyword matches or only non-relevant matches.

Using this classification, activities with LCA-based SC criteria are identified per annex and DA. The share of these activities within each annex and DA is calculated, and their distribution across EOs is analyzed.

The evaluation of DNSH criteria is more complex, as individual activities may well have several matches in different DNSH categories. Here, a distinction must be made as to what is to be evaluated: Activities with an LCA-based approach in DNSH in general and per EO related DNSH. The following example illustrates the challenge and serves as a description of the approach:

There are several matches of keywords in the DNSH criteria of activity 1.2 Manufacture of medicinal products of Annex III (SC to pollution prevention and control) of the 2nd DA. These are the keywords GWP and CO_2, both of which can be found in the DNSH criteria for climate change mitigation, and the keywords water scarcity and ISO 14046, which can be found in the DNSH criteria for sustainable use and protection of water and marine resources. To avoid double counting in this case, the matches for the keywords GWP and CO_2 may only be counted once, as both appear in the same criterion (DNSH climate change mitigation). The same applies to the matches for water scarcity and ISO14046, which both appear in the same criterion for DNSH sustainable use and protection of water and marine resources.

When evaluating only activities with LCA-based DNSH criteria, the activity would only be counted once, based on the above definition: at least one keyword is found in the associated DNSH criteria.

However, if the DNSH criteria with an LCA-based approach are evaluated by EO, a total of two hits must be counted for activity 1.2, one for DNSH climate change mitigation and one for DNSH sustainable use and protection of water and marine resources.

Lastly, in step 3, the results of the individual assessments are combined to give an overall evaluation on SC and DNSH criteria across all DAs and all EOs, to assess the whole EU Taxonomy.

3. Results

The results are presented based on the three evaluation steps:

1. Assess keyword distribution and matches within the EU Taxonomy.
2. Evaluate LCA-based requirements in SC and DNSH criteria separately.
3. Combine SC/DNSH findings to outline LCA approaches across the taxonomy.

Each step evaluates matches by total activities of the DA and by EOs.

3.1. *Evaluation of keywords found in the EU Taxonomy*

The first step is to evaluate the allocation of keywords to impact category carried out in Table A3. Table A4 shows the results of the search for keywords in all annexes of the 1st and 2nd DA. Only a minority of keywords yielded matches that included references to LCA, most did not establish any link to LCA, and a significant proportion produced no matches at all. While every impact category had at least one keyword match, several had none that referenced LCA specifically. Only two of the sixteen ICs—GWP and WD —had LCA references based on the assigned keyword search. In the case of GWP, relevant keywords included global warming potential, GHG, and CO_2. For WD, the LCA reference stemmed from a mention of DIN EN ISO 14046 via the keyword water scarcity, which is impact-category independent.

Among the impact-category-independent keywords, all except ISO 14044 generated relevant matches with LCA references. Notably, keywords often appeared in combination. For example, ISO 14067 never appeared alone. In contrast, GHG and CO_2 were found both independently and in combination: GHG appeared alone in 24% of its matches, and CO_2 in 19%. Moreover, GHG co-occurred with CO_2 in 34% of its matches, with life-cycle and ISO 14067 in 14%, and with all three—CO_2, life-cycle, and ISO 14067—in 20% of cases.

3.2. *Substantial contribution (SC)*

Table S1 shows a detailed breakdown of the matches found per DA and annex for the criteria in SC. The table indicates the activities in which the matches with and without LCA approach (the latter marked in red and crossed out) were identified.

The use of LCA approaches in the SC criteria is limited to two EOs: climate change mitigation (1st DA) and transition to a circular economy (2nd DA). Fig. A1 shows keyword matches by DA, with the majority found in the 1st DA, particularly for the keyword GHG. CO_2 ranks second, with 28 matches in the 1st DA and one in the 2nd DA (activity 4.1).

Although ISO 14067 is mentioned in both DAs, it is the only standard referenced under the climate change mitigation objective (1st DA). DIN EN ISO 14040 appears only once, in activity 4.1 of the 2nd DA under the circular economy objective. The term global warming potential appears five times, three in climate change mitigation and two in the circular economy.

In the 1st DA, lifecycle and ISO 14067 keywords nearly always co-occur, with the exception of two activities, 4.9 (electricity transmission and distribution) and 7.1 (construction of new buildings), which mention lifecycle without referencing an ISO standard. ISO 14067 never appears alone.

Life cycle and GHG are also strongly correlated, co-occurring in 15 TSCs, all of which also include ISO 14067. Only in activities 7.1 (1st DA) and 3.1 (2nd DA, Annex II) does lifecycle appear without GHG. Fig. 3 illustrates the occurrence of LCA references found alongside the ISO number and the term "life cycle".

A total of 50 activities include TSCs for SC criteria with an LCA approach, representing 23% of all activities. As shown in Fig. 4, only 32% of these (16 activities) reference an ISO standard. Notably, whenever ISO 14067 is cited, the term lifecycle is also present. In activity 4.1 (2nd DA, Annex II), CO_2 appears alongside a reference to ISO 14040.

The distribution of activities with LCA approaches in SC criteria mirrors the EOs: only climate change mitigation (1st DA) and transition to a circular economy (2nd DA) include such approaches. Of all SC-related LCA approaches, 94% are found in the 1st DA, and just 6% in the 2nd DA.

Specifically, 26% of activities in the 1st DA and 9% in the 2nd DA feature LCA approaches in their SC criteria. Within EOs, 53% of Annex I activities (SC to climate change mitigation) and 14% of Annex II activities (SC to circular economy) contain LCA elements. No LCA approaches were identified in SC criteria for activities related to other EOs or annexes.

3.3. *Do not significant harm (DNSH)*

Table S2 shows a detailed breakdown of the matches of keywords found in the TSC for DNSH. The keywords categorized per impact category are listed in the first column. In the following columns, the DNSH to the different environmental goals are separately listed, separated by the annexes of the DAs in which the matches in the respective DNSH were found.

With two exceptions, that can be found in DNSH to the environmental goal of sustainable use and protection of water and marine resources, all matches were found in DNSH to climate change mitigation. The two matches identified in DNSH criteria to sustainable use and protection of water and marine resources, can be found in Annex III (SC to pollution prevention and control) of the 2nd DA.

Most matches involve CO_2 (28) and GHG (27) (Fig. A2), often co-

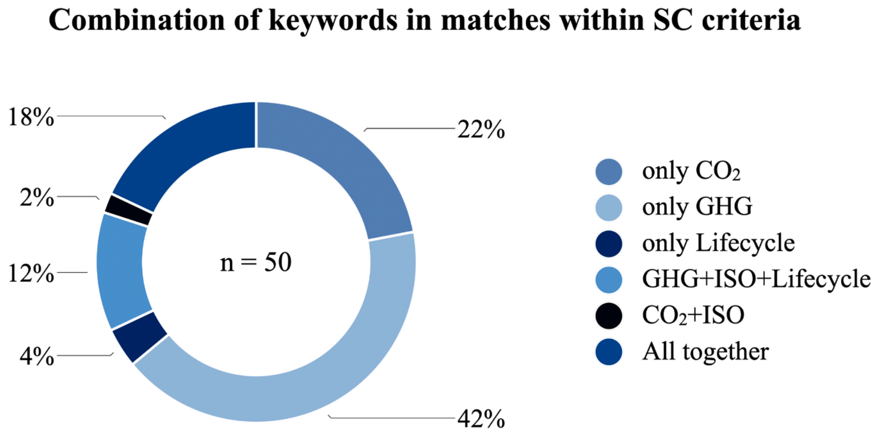

Fig. 3. Occurrence of keywords in combination in SC criteria.

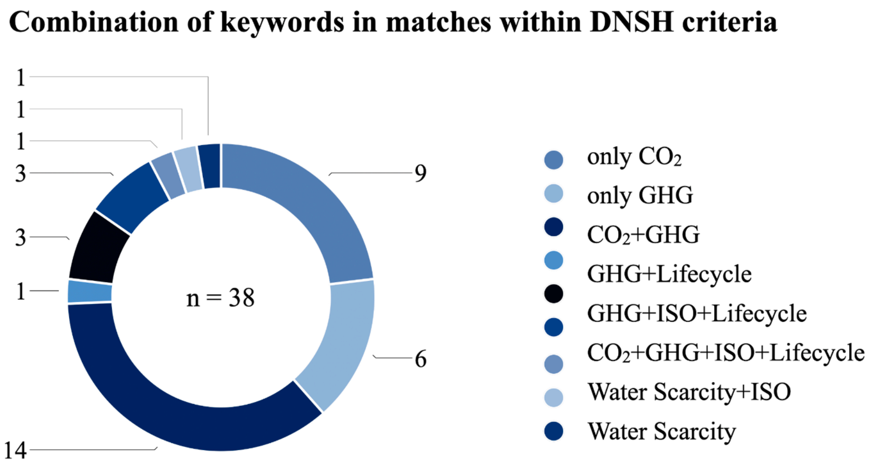

Fig. 4. Occurrence of keywords in combination in DNSH criteria.

occurring in 18 activities (Fig. 4). CO_2 appears more in the 1st DA, while ISO 14046/14067 references appear more often the 2nd DA. The distribution of LCA approaches across the legal acts is much more balanced for the DNSH criteria than for the SC criteria, independently of the EO.

Similar to SC, there is a large overlap between the terms lifecycle, ISO 14067, and GHG in DNSH climate change mitigation. Also, as shown in Fig. 4, the term GHG appears alongside CO_2, lifecycle, and a reference to ISO 14067 in three activities with LCA approach. Additionally, for three DNSH criteria, GHG was mentioned together with lifecycle and a reference to the ISO 14067 standard but without the term CO_2. Additionally, GHG occurred alongside CO_2 in 14 identified activities without further reference to an ISO norm or mentioning the term “lifecycle”. In contrast, GHG appeared alone in only six identified activities. A reference to an ISO standard was made in just seven DNSH criteria out of the 38.

Even though most of the matches were found in the 1st DA (69%), the proportion of matches in the 2nd DA is still quite high compared to SC, at just under a third (31%).

With regard to the distribution of TSC for DNSH with LCA approaches across the six EOs, it is noticeable that 95% of the matches found for the DNSH criteria, are in DNSH to climate change mitigation. Further matches were only found for DNSH to the sustainable use and protection of water and marine resources.

Taking a closer look at DNSH to climate change mitigation, 29% of the activities with DNSH to climate change mitigation contain a LCA approach. Regarding the distribution of the annexes, in total, most (24) matches were found in Annex II of the 1st DA, followed by Annex II of the 2nd DA with 9 matches. In relation to the total activities considered in the respective annexes, Annex II of the 2nd DA contains LCA approaches for the TSC for DNSH to climate change mitigation for 43% of their activities, resulting in the highest share. Followed by Annex III of the 2nd DA, with a share of 33% of DNSH climate change mitigation criteria with an LCA approach. Annex II of the 1st DA is only in 3rd place, with a share of 27%.

3.4. Overall results

By combining Tables S1 and S2, a total of 89 activities with LCA approaches are identified across both Delegated Acts (DAs), including SC and DNSH criteria. Of these, 71 activities are found in the 1st DA and 17 in the 2nd, resulting in approximately 83% of LCA-related TSCs being associated with the 1st DA.

One reason for this difference is that a total of 181 activities are listed in the 1st DA, while the 2nd DA only contains 35 activities. Taking a look at the percentual share of SC and DNSH criteria incorporating an LCA approach in relation to the total activities listed in the DAs, the following becomes evident. In relation to the total number of activities covered by the respective DAs, a larger proportion (49%) of the activities in the 2nd DA, compared to 39% of the activities in the 1st DA, include a LCA reference (Fig. 5).

In the first DA, LCA references are more common in SC criteria than in DNSH criteria, whereas in the 2nd DA, most LCA references appear in DNSH criteria, specifically for climate change mitigation. A closer look reveals that all LCA approaches in the first DA relate either to SC or DNSH criteria for climate change mitigation. Similarly, in the 2nd DA, 12 out of 14 LCA-referenced DNSH criteria also concern climate change mitigation.

Understanding the distribution of LCA-based TSCs across EOs is essential. Of the 88 identified activities with LCA approaches, 94% are linked to climate change mitigation, 53% through SC criteria and 41% through DNSH criteria. Only 3% relate to SC criteria for the circular economy, and 2% to DNSH criteria for sustainable use and protection of water and marine resources. No LCA approaches were identified for the remaining EOs.

Overall, 41% of activities in both DAs include an LCA approach, 23% in SC criteria and 19% in DNSH. This means 59% of activities contain no LCA reference. Regarding alignment with ISO standards (see Fig. 6), 16 activities reference ISO standards in SC criteria and 7 in DNSH. In total, 23 out of 88 LCA-related activities (26%) cite ISO standards.

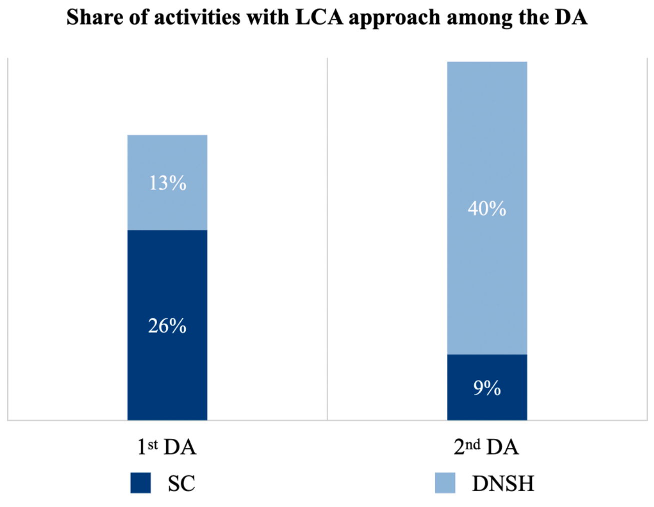

Fig. 5. Distribution of TSC with LCA approach for SC and DNSH within the DAs.

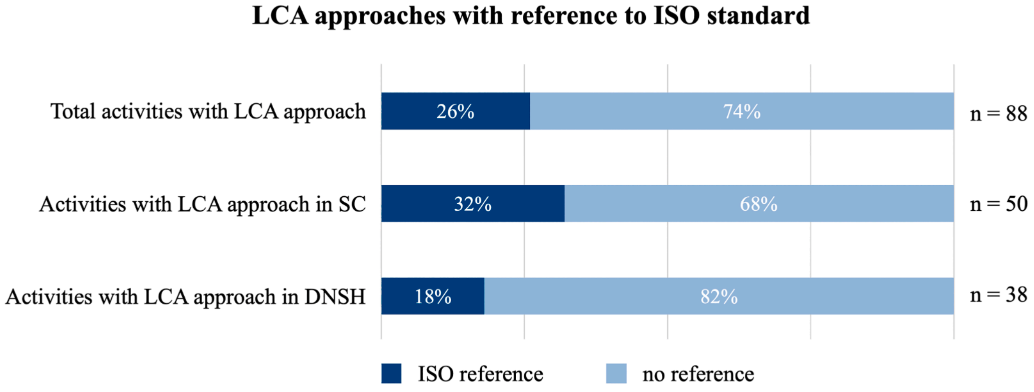

Fig. 6. Distribution of LCA approaches with reference to ISO standard.

4. Discussion

An LCA approach was identified in 88 of 216 activities (41%), meaning the majority, 128 activities, do not apply LCA-based criteria explicitly. However, this must be interpreted in light of the EU Taxonomy's methodology. Reports from the Joint Research Centre (JRC) (Canfora et al., 2021; Canfora et al., 2022) and the TEG (EU Technical Expert Group on Sustainable Finance, 2020) explain that certain activities are deemed automatically eligible. For instance, some inherently meet environmental thresholds, eliminating the need for individual assessment (Canfora et al., 2021; Canfora et al., 2022; EU Technical Expert Group on Sustainable Finance, 2020).

A key example is the 100 g CO_2e/kWh lifecycle emissions limit set for energy sector activities contributing to climate change mitigation. This threshold, reviewed every five years, exempts many renewable technologies from detailed LCA verification, as their emissions are typically well below it. For example, lifecycle emissions from wind energy range between 3.2 and 38.3 g CO_2e/kWh (Hengstler et al., 2021). As per TEG recommendations, lifecycle evidence for compliance was waived for certain activities, including: 4.1 Solar photovoltaic, 4.2 Concentrated solar power, 4.3 Wind power, 4.4 Ocean energy, 4.17 Solar cogeneration, 4.21 Solar thermal, 4.25 Heat/cool from waste heat.

Although no explicit LCA criteria are listed for these in the 1st DA, the overarching threshold applies, justifying their inclusion. If these seven are added, the total number of activities with LCA-related TSC rises to 95 of 216, raising the share to 44%.

Previous research has shown that lifecycle thinking has progressively been embedded in EU environmental policy (Sala et al., 2021). The EU Taxonomy Regulation itself requires lifecycle considerations under Article 19 (The European Parliament and the European Council, 2020), and the TEG Final Report refers to lifecycle emissions and environmental impacts as methodological foundations (EU Technical Expert Group on Sustainable Finance, 2020). However, prior studies have not systematically quantified how these conceptual commitments translate into operationalized criteria within the TSCs. Our results show that lifecycle thinking is conceptually embedded in the taxonomy framework but unevenly operationalized. While 41–44% of activities contain explicit LCA-related references or thresholds, only 23 activities (10.6%) explicitly cite ISO standards, providing formal methodological guidance. The TR emphasizes lifecycle consideration but leaves discretion regarding the methodological form of implementation. Our findings therefore suggest that lifecycle thinking is often embedded implicitly rather than through explicit methodological standardization. The observed deviations could therefore simply reflect regulatory flexibility rather than formal non-compliance. However, the absence of systematic methodological references may reduce transparency and comparability across sectors, potentially increasing interpretative flexibility and the risk of inconsistent application.

A significant majority (94% or 95% when including directly eligible energy sector activities) of LCA approaches were found in the EO of climate change mitigation (SC and DNSH). This concentration likely reflects the number of activities covered under this objective: the EU Taxonomy defines 88 activities with technical screening criteria (TSC) for SC in climate change mitigation, compared to only 6 (water and marine resources), 21 (circular economy), 6 (pollution prevention), and 2 (biodiversity and ecosystems) in the objectives introduced by the second DA. Apart from climate change mitigation, LCA is only used for DNSH in water and marine resources and for SC in the circular economy. No LCA use was identified for climate change adaptation, pollution prevention, or biodiversity-related objectives. This emphasis on LCA for climate change mitigation may partly stem from the taxonomy's roots in the EU Green Deal (Canfora et al., 2021; Canfora et al., 2022), which prioritizes achieving climate neutrality by 2050. Effective GHG emission reduction, a key element of this goal, can be better supported through LCA (Hainsch et al., 2020). This rationale extends to the Paris Agreement, where limiting global warming to below 2 °C also depends on cutting GHG emissions (*Paris Agreement.* United Nations, 2015). Consequently, political urgency around these targets likely contributed to the higher number of criteria and more frequent use of LCA in climate change mitigation. Additionally, the Global Warming Potential (GWP), linked to this objective, is the only impact category widely used in public and political discourse (Koch et al., 2022), further reinforcing its prominence in the EU Taxonomy. From a methodological perspective, climate change mitigation benefits from highly standardized LCA methods, extensive lifecycle impact assessment guidance, and broad scientific consensus (Levasseur et al., 2016; Peters et al., 2011). These indicators are widely recognized, measurable, and politically salient, making them easier to implement in regulatory screening criteria (Grubert, 2021). In contrast, biodiversity, climate change adaptation, and other environmental objectives face greater methodological challenges and data gaps (Baan et al., 2013; Soimakallio et al., 2025; Winter et al., 2017; Winter et al., 2018). Indicators for these domains are often complex, spatially specific, and lack universally accepted characterization methods. (Baan et al., 2013; Winter et al., 2017; Winter et al., 2018) Taken together, these factors suggest that the focus of LCA on climate change mitigation arises from a combination of political urgency, methodological maturity, data availability, and regulatory practicality (Grubert, 2021).

Criteria for other environmental objectives, however, generally lack comparable explicit LCA integration. However, many of these activities include quantitative or procedural requirements, such as efficiency thresholds, or mandatory assessments like environmental impact assessments (EIA), which operationalize lifecycle impacts without formally referencing LCA. The overall limited specification of explicit LCA methods and even fewer methodological standards (only 10.6% explicitly refer to ISO standards) carries risks of greenwashing and the selective choice of favourable calculation assumptions, as methodological flexibility allows for manipulation of system boundaries and allocation rules. This undermines comparability across companies and sectors, challenging the taxonomy's goal of providing standardized benchmarks for sustainable investments. Activities with explicit LCA references and clearly defined thresholds enable transparent compliance assessment and easy comparison between companies and industries. It is important to note that it remains unclear how many activities contain implicit lifecycle considerations, and further research would be needed to capture these and provide a comprehensive overview of Article 19 implementation.

Taken together, however, the results of this study suggest that while the taxonomy fundamentally incorporates lifecycle considerations into all environmental objectives, its implementation is currently inconsistent, particularly outside the area of climate change mitigation. In practice, this means that regulators, companies, and investors may need additional guidance, methodological harmonization, or case-specific assessments to ensure consistent assessment of TSC compliance across EOs where explicit LCA criteria are missing or only partially implemented. To enhance practical guidance for policymakers and regulators, our findings suggest that clearer methodological guidance could be beneficial. Specifically, harmonized LCA procedures per environmental objective, systematic reference to relevant ISO standards, or a minimum level of methodological transparency in all TSC could help reduce interpretative flexibility, improve comparability across companies and sectors, and strengthen the credibility of taxonomy-aligned investments. Such measures would assist regulators in enforcing the TSC, support businesses in compliance planning, and enhance transparency for financial market participants.

4.1. Limitations

The findings of this study must be interpreted in context: the EU Taxonomy includes enabling activities that do not directly contribute to SC for a given EO but support other activities that do. For example, LCA is not applied to manufacturing or maintaining solar PV systems, as lifecycle emissions are already addressed under their operation (activity 4.1). Additionally, some TSCs influence ICs indirectly. For instance, energy efficiency or consumption criteria in the water, wastewater, and waste sectors (SC for climate change mitigation) affect lifecycle emissions and thus impact GWP. The approach used in this study cannot capture indirect LCA considerations.

The identification of LCA integration relies predominantly on keyword searches (e.g., GHG, CO_2, life cycle, ISO standards), which may both overestimate (false positives) and underestimate (false negatives) actual LCA use. False positives were systematically minimized through manual review of all keyword matches, excluding non-LCA contexts like general emissions reporting or international agreements without lifecycle framing (e.g., "ozone" linked only to the Montreal Protocol), thereby justifying the validity of this keyword-based proxy for capturing explicitly operationalized LCA criteria. Some activities, beyond those in the energy sector (SC for climate change mitigation), may lack explicit LCA references in their SC criteria because they inherently meet thresholds. This could apply to certain activities in the 2nd DA, such as sustainable urban drainage systems or nature-based solutions for flood and drought prevention, which are directly eligible despite the absence of specific criteria. Unlike energy activities in the 1st DA, however, this is not explicitly documented in supporting materials. In addition, some SC criteria reference other activities rather than listing duplicated requirements, potentially leading to underreporting of LCA use. For instance, activity 3.15 in Annex I of the 1st DA refers to the criteria of activity 3.10, which includes an LCA approach. Since the method applied only captures keywords in the primary activity description, such cross-referenced LCA approaches may have been overlooked. Therefore, the actual number of LCA references is likely slightly higher than reported. Moreover, the methodology used to identify LCA-based criteria based on ICs may influence the results. Only ICs from the RECiPe and CML methods were considered. While these are the most widely used in Europe and align with the Product Environmental Footprint (PEF), this approach may miss LCA references linked to other methods. However, since ICs were analyzed independently of specific LCIA methods, this limitation remains acceptable. (Rybaczewska-Błażejowska and Jezierski, 2024) Another source of uncertainty lies in the assignment of ICs to EOs within the EU Taxonomy. As shown in Tables S1 and S2, most keyword-IC matches aligned with the expected EOs. However, exceptions exist, for example, keywords such as GWP and CO_2, typically linked to climate change mitigation, also appeared under the circular economy objective. Conversely, some EO-specific keywords yielded no matches. Similar classification approaches have been applied by Becchetti et al. (2022), though their study covered only a limited number of ICs. Notable differences between classifications include the assignment of eutrophication potential, attributed here to both pollution prevention and water protection, while Becchetti et al. associate it only with the former. Additionally, agricultural and urban land occupation (ALO and ULO) were grouped under “Direct land use for anthropic activities” by Becchetti et al., linked to biodiversity protection. In contrast, this study assigns ALO to biodiversity and ULO to climate adaptation. Beyond these cases, the classifications are largely consistent, with key ICs such as GWP aligned across studies, supporting the robustness of the methodological framework of this study. Finally, keyword selection significantly affects the identification of matches. Terms such as global warming potential, GHG, and CO_2 were used for GWP. Since the EU Taxonomy inconsistently uses abbreviations and full terms, relying on a single format risks missing relevant entries. This risk was mitigated by using varied keyword combinations, including impact category-independent terms like lifecycle/ life cycle or ISO 14067, to ensure comprehensive coverage. These factors collectively contribute to potential false negatives, suggesting our approach captures primarily explicit LCA integration while possibly underestimating implicit lifecycle reasoning.

Additionally, the supplementary DA to the first DA was not included in this evaluation. As a result, any LCA references in the newly added activities were not evaluated. This exclusion may introduce a bias by underrepresenting the extent of lifecycle considerations in the overall taxonomy. While the supplementary DA may include additional activities with LCA references, the majority of core activities are already covered in the first and second DAs, suggesting that the main trends observed are likely robust, though exact figures may shift as the taxonomy evolves.

Given the dynamic evolution of the taxonomy framework, our results should be interpreted as reflecting the current evaluation scope, with methodological limitations highlighting opportunities for qualitative validation of representative activity samples to better understand implicit lifecycle considerations.

4.2. Future research

Given the limitations outlined above, several important questions remain open for future research. In particular, the prevalence and operationalization of implicit lifecycle considerations within the EOs remain largely unexplored. Future studies could examine the extent to which such implicit lifecycle considerations are reflected in the DA of the TR.

Further research could also investigate how companies interpret and implement conceptual lifecycle guidance in practice, and whether greater methodological harmonization could enhance comparability, consistency, and transparency across disclosures.

Combined with the findings of this study, such research could generate valuable insights into the practical application of Article 19 and contribute to a more comprehensive assessment of the overall effectiveness of the EU Taxonomy framework.

5. Conclusion and outlook

This study demonstrates that while the EU Taxonomy was designed to promote a lifecycle-based, scientifically robust approach to sustainable investment, implementation of explicit LCA approaches remains inconsistent. LCA impact categories were mapped to the taxonomy's EOs, enabling keyword-based identification of LCA references. Our analysis shows that LCA approaches are explicitly mentioned in 41% of activities across the 1st and 2nd DAs. Including the seven energy-sector activities for which lifecycle evidence for compliance was waived increases this share slightly to 44%. However, only 10.6% of activities with LCA references explicitly cite relevant ISO standards, mainly ISO 14067, with a single mention of ISO 14040. It should be noted that some activities may incorporate lifecycle considerations implicitly, for example through overarching thresholds or cross-references, even if they do not explicitly reference LCA methods. Furthermore, LCA integration is heavily concentrated in criteria related to climate change mitigation, with significant gaps in other EOs. Most LCA approaches (67%) are found in the 1st DA, but the 2nd DA has a higher proportion of activities with LCA references (about 50% vs. 39%).

Overall, the findings suggest that lifecycle thinking is conceptually embedded across the taxonomy but operationalized inconsistently in practice. This inconsistency is particularly pronounced outside climate change mitigation. As a result, regulators, companies, and investors may face interpretative uncertainty when assessing compliance with TSC, especially in EOs where explicit LCA methodologies are absent. To enhance clarity and comparability, future revisions could benefit from clearer and more systematic methodological references. Harmonized LCA procedures tailored to each EO, consistent reference to established ISO standards, and minimum transparency requirements for methodological choices within TSC would reduce ambiguity, improve cross-sector comparability, and strengthen the credibility of taxonomy-aligned investments.

Expanding and deepening the integration of LCA within the taxonomy would also improve the transparency and scientific robustness of environmental performance assessments. Due to its standardized structure, LCA provides a well-established framework for translating environmental impacts into decision-relevant metrics. Strengthening its role within the Taxonomy would therefore support more informed policy-making and investment decisions.

Future revisions of the DAs should broaden the scope of economic activities covered and prioritize the inclusion of LCA, especially in underrepresented areas such as urban planning, agriculture or tourism, and further embed LCA, especially in EOs currently lacking such references. This would also support the integration of social sustainability indicators (S-LCA) as the social taxonomy evolves. Further research should explore the feasibility and relevance of LCA for EOs like climate change adaptation, pollution prevention, and biodiversity, where LCA is currently absent.

The assignment of ICs in this paper, could serve as a basis, which should be critically assessed and where needed extended. In addition, an LCA is always data-based, so it is very important to ensure the availability and quality of the data and to develop it further in the future. This is the only way to achieve more precise and reliable results. Ensuring high-quality, accessible data will be critical for effective LCA application. By strengthening the integration of lifecycle thinking, the EU Taxonomy can further solidify its position as a global benchmark for sustainable finance (Schütze and Stede, 2021; World Bank Group, 2020) and accelerate the transition to a truly sustainable European economy.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used Perplexity.ai for language editing and text refinement under human supervision. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Sarina Achterfeldt: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Suzana Ostojic:** Writing – review & editing, Validation, Methodology, Conceptualization. **Marzia Traverso:** Writing – review & editing, Supervision.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.horiz.2026.100190.

Appendix

Table A1, Table A2, Table A3, Table A4, Fig. A1, Fig. A2.

Table A1
Consolidated version of the impact indicators from CML and RECiPe.

Method	Impact Category	Unit	Description
	Abiotic Depletion Potential (ADP el.)	kg Sb eq.	The impact category describes the decline in the availability of mineral and metallic resources, which is promoted by unsustainable use. The value of a particular resource is linked to its availability. (Acero et al., 2016)
	Abiotic Depletion Potential (fossil) (ADP fos.)	MJ	Abiotic depletion potential (fossil) describes the decline in the availability of fossil resources, such as oil and gas, which results from unsustainable use. (Acero et al., 2016)
	Marine aquatic ecotoxicity potential (MAETP)	kg DCB eq.	The marine aquatic ecotoxicity potential assesses the toxicity of substances that can harm plants, animals and microorganisms in the marine environment. Pollutants can enter the oceans through wastewater, waste disposal or other emissions. (Acero et al. 2016)
	Photochemical Ozone Creation Potential (POCP)	kg Ethen eq.	This impact category describes a potential type of smog caused by solar radiation, heat and NMVOC and NO_x. (Acero et al. 2016)
	Eutrophication potential (EP)	kg PO_4^{-3} eq.	Eutrophication refers to the accumulation of nutrients in the environment caused by emissions of nitrogen and phosphorus into the atmosphere, water bodies and soil. The eutrophication potential is often expressed as PO4-potential. (Acero et al. 2016)

(continued on next page)

Table A1 (*continued*)

Method	Impact Category	Unit	Description
CML	Human toxicity potential (HTP)	kg DCB eq.	The human toxicity potential defines the potentially toxic hazards of chemical substances for humans. The most frequently considered products are arsenic, sodium dichromate and hydrogen fluoride. (Acero et al. 2016)
	Freshwater Aquatic Ecotoxicity Potentials (FAETP)	kg DCB eq.	The freshwater acquatic ecotoxicity potential considers the harmful effects of chemical substances on organisms and ecosystems in freshwater systems. It assesses the toxicity of pollutants and their impact on the health and biodiversity of freshwater organisms. (Acero et al. 2016)
	Ozone Depletion Potential (ODP)	kg R11 eq.	The ozone depletion potential describes the depletion of the stratospheric ozone layer due to emissions of ozone-depleting substances. These are mainly chlorinated and brominated compounds. (Acero et al. 2016)
	Terrestrial ecotoxicity potential (TETP)	kg DCB eq.	The Terrestrial Ecotoxicity Potential assesses potentially harmful effects of chemical substances on the health and diversity of soil organisms. The functionality of the soil is also considered. (Acero et al. 2016)
	Global Warming Potential (GWP)	kg CO_2 eq.	The global warming potential describes the change in global temperatures caused by greenhouse gases. The time period to be considered can be varied, with 100 years (GWP100) being the most common form. (Acero et al. 2016)
	Acidification potential (AP)	kg SO_2 eq.	The acidification potential describes the potential reduction in the pH value of water and soil due to anthropogenic emissions. Only acidification caused by SO2 and NOx is considered. (Acero et al. 2016)
	Particulate matter formation (PMF)	kg (PM_{10} to air)	Particulate matter is defined as particles with a diameter $< 10\ \mu m$. Particulate matter can have a significant impact on people and the environment. This impact category evaluates all particulate matter emissions during the life cycle. (Goedkoop et al., 2009)
	Ionizing radiation (IR)	kg (U235 to air)	This category deals with the radiation emissions of radioactive substances and their potential impact on humans and the environment. All radiation exposure occurring during the life cycle of a product or service is assessed. (Goedkoop et al. 2009)
RECiPe	Agricultural land occupation (ALO)	m^2 x Year	The use of agricultural land is assessed in this impact category. The assessment includes, in particular, the occupation of the land over a certain period of time and the conversion of the land. Both mechanisms can also occur in combination. (Goedkoop et al. 2009)
	Urban land occupation (ULO)	m^2 x Year	The same criteria apply to urban land use as to agricultural land use. Only the urban area is considered here. (Goedkoop et al. 2009)
	Water depletion (WD)	m^3	Water depletion describes the total amount of water consumed during the life cycle. It should be taken into account which types of water use result in a shortage. (Goedkoop et al. 2009)

Table A2
Assignment of impact categories to environmental objectives.

Environmental objectives	Impact category
Climate change mitigation	GWP
Climate change adaptation	ULO
Sustainable use and protection of water and marine resources	EP, WD, AP, MAETP, FAETP
Transition to a circular economy	ADP el.
Pollution prevention and control	POCP, HTP, PMF, ODP, AP, ADP fos., IR
Protection and prevention of biodiversity and ecosystems	AP, ALO, TETP

Table A3
Selected keywords for the impact categories.

Impact categories	Keywords
GWP	Global warming potential, GHG, CO_2
ODP	Ozone
EP	Eutrophication, nutrients, nitrogen, phosphate
ADP el.	Construction and demolition waste, metal, concrete
ADP fos.	Fossil, mineral oil, natural gas
POCP	Air quality, NO_x, nitrogen
AP	Acidification, sulfur, pH value
ULO	metropolitan, green, urban
WD	Water shortage, Water scarcity, Water depletion
PMF	Air pollution, particulate matter
IR	radioactive, ionizing
ALO	Fertilizer, land use, agricultural (land)
HTP	(human) health, toxic
MAETP	Ocean, fish, toxicity
TETP	Soil organisms, soil, earth
FAETP (aquatic)	Water bodies, groundwater, toxicity
Independent of impact categories	Life-cycle, DIN EN ISO 14,040/14,044/14,046/14,067

Table A4
Keywords found in the DAs.

Impact category	Keyword		
	Without matches	**Match without LCA reference**	**Match with LCA reference**
GWP	-	-	Global Warming Potential, GHG, CO_2
ODP	-	Ozone	-
EP	Eutrophication, Phosphate	Nutrient, Nitrogen	-
ADP el	-	Construction and demolition waste, Metal, Concrete	-
ADP fos	-	Fossil, Mineral Oil, Natural gas	-
POCP	-	Air quality, NO_x, Nitrogen	-
AP	Acidification, pH Value	Sulphur	-
ULO	Metropolitan	Green, Urban	-
WD	Water depletion, water shortage	-	Water Scarcity
PMF	Particular Matter	Air pollution	-
IR		Radioactive, Ionizing	-
ALO	Fertilizer, Land use	Agricultural	-
HTP	-	Health, Toxic	-
MAETP	-	Ocean, Fish, Toxicity	-
TETP	Soil Organisms, Earth	Soil	-
FAETP	-	Waterbodies, Groundwater, Toxicity	-
Independent	ISO 14,044	-	Life-cycle, ISO 14,040, ISO 14,046, ISO 14,067

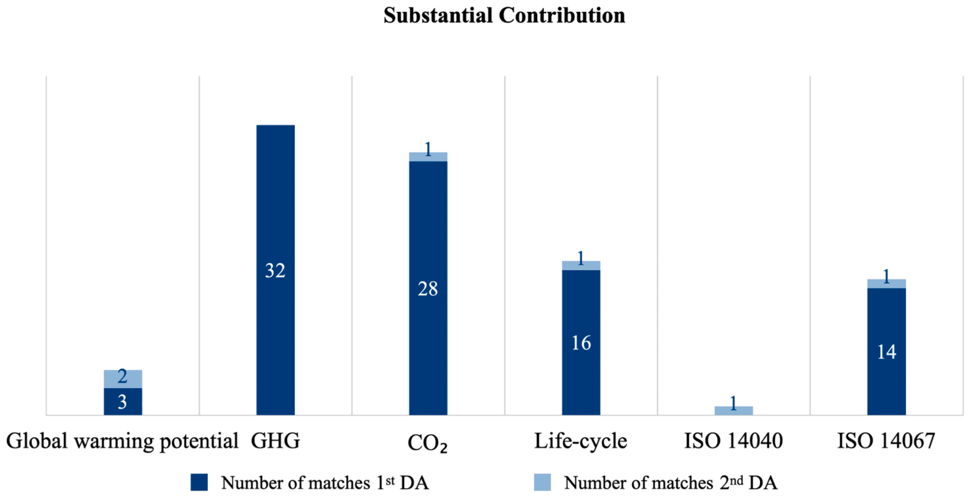

Fig. A1. Distribution of keywords with LCA references for SC among the DAs.

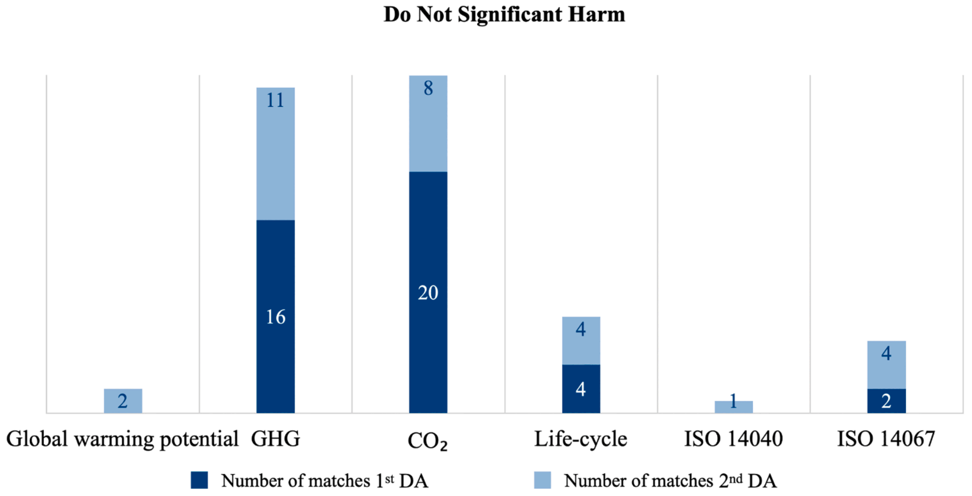

Fig. A2. Distribution of keywords with LCA references for DNSH among the DAs.

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