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Life cycle assessment in energy-intensive industries: Cement, steel, glass, plastic

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ABSTRACT

The cement, steel, glass, and plastics sectors are at the forefront of industrial decarbonization and must make effective, evidence-based strategic choices. For the first time, this work analyzes current implementation of life cycle assessment (LCA) methodology, as a key decision lever, across the aforementioned sectors through a critical, systematic literature review of 256 studies. Results reveal differences in how LCA studies are conducted, and that implementation is fragmented. Many studies did not consider functionality when defining a functional unit, and most do not objectively assess data quality. Significant differences also exist regarding the definition of scope and selection of impact categories and interpretations. Therefore, this work provides recommendations for 'best practice' in LCA applied to global industrial sectors, aiding in the development of a consistent and transparent approach to cross-sector LCA implementation. Specifically, functional unit types must be properly defined, cross-sector allocation procedures should be intrinsically linked, a 'cradle-to-cradle' system boundary should be used where possible, and these aspects should be synergistically implemented across sectors where possible. Data quality should be assessed objectively, with greater uniformity in impact assessment methodologies, impact assessment categories, and reporting methods. Sensitivity and uncertainty assessments should be completed and reported in line with International Standard Organization (ISO) 14040 and 14044, and a greater focus should be placed on future production processes and technology. This will improve LCA applications and outcomes, allow effective cross-sector comparison, and enhance decision making towards net zero.

1. Introduction

Since the Industrial Revolution, the increasing demand for infrastructure and products has resulted in the formation of, and reliance on, several key global industrial sectors that have greatly contributed to the growth of modern society, including: cement, steel, glass, chemicals, paper, and aluminum. In the past two decades, these industries have seen unprecedented growth that will only continue as a rising global population further increases consumer demand [1]. However, this growth has come at the expense of adverse environmental impacts due to the energy intensive nature of these industrial processes [2].

In 2022, it was reported that the global industrial sector accounted for nine gigatons, equivalent to 25 %, of all carbon dioxide emissions [1]. Ensuring that all global greenhouse gas emissions decline by 43 % by 2030 to reach net zero by 2050 has become an international priority as outlined by United Nations Sustainable Development Goal 13 [3]. A lack of incentive to implement innovative, sustainable solutions in energy intensive industries has until recently been slow due to the absence of new competition for incumbents, and the requirement for large capital expenditure. Furthermore, their position in the supply chain has until recently shielded them from the consumer pressure which drives the environmental and social performance of more publicly visible businesses. However, as a result of recent shifts in expectations of

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Abbreviations

BFS - blast furnace slag
BF-BOF – blast furnace-basic oxygen furnace
CML - Centrum voor Milieukunde Leiden
E-IO - economic input-output
GGBS - ground granulated blast furnace slag
GWP - global warming potential
IPCC - Intergovernmental Panel on Climate Change
ISO - International Standards Organization
LCA - life cycle assessment
PCR - Product Category Rules
SCM - supplementary cementitious materials
SLR - systematic literature review
UK - United Kingdom
WOS - Web of Science

consumers and policy makers, these sectors are now facing profound pressures to reduce their carbon emissions [4]. Several approaches have been adopted to tackle these issues including addressing the need for responsible consumption, production, and innovative sustainable technologies by applying the concept of a circular economy across all industrial sectors, whilst also retrofitting existing infrastructure with cleaner, greener, and more efficient industrial processes; aligning with United Nations Sustainable Development Goals 9 and 12 [5,6].

An example of this is seen in the United Kingdom (UK), where the UK Research & Innovation council identified six industrial sectors that contribute most to the UK's carbon footprint, with 50 million metric tons of carbon dioxide being emitted annually: cement, metals, glass, paper, ceramics, and chemicals [4]. To bring further attention to carbon emission reductions required in these economically vital industries, which together account for 2.5 % of the UK's gross domestic product, these sectors were termed the UK's 'Foundation Industries' [4,7]. Although the industries that are considered 'foundational' differ between countries, once they are identified, a greater focus can be placed on finding innovative and sustainable solutions to decarbonize while also ensuring economic stability and growth.

There are several standardized methodologies for evaluating the feasibility of decarbonization including environmental impact assessment [8], environmental management system [9], and carbon footprint of a product [10]. Life cycle assessment (LCA), however, is the most widely used method to provide a general perspective for a given product by evaluating a wide range of environmental impacts throughout its whole life cycle [11]. LCA has also become an increasingly critical lever within industrial product development as a strategic decision making tool, where solutions to address environmental impacts can be prioritized to best optimize a system given current financial, technological, and human resources [12].

The International Standard Organization (ISO) 14040 and 14044 define the LCA framework in the four distinct stages as seen in Fig. 1 [11,13]. The first stage, 'goal and scope', defines and establishes the rules and depth of a study. This includes selecting a functional unit, system boundary, and allocation procedure for a selected product. Stage two, 'inventory analysis', encompasses data collection and data quality evaluation. The third stage, 'impact assessment', aims to calculate the environmental impacts of the defined product using environmental indicators. Stage four, 'interpretation', requires the assessor to draw conclusions based on the analysis and to carry out checks to ensure robust results. While interpretation is often listed as the last step in conducting an LCA, it should occur at every step of the LCA methodology.

The technological, economic, and social importance of 'foundational' sectors means that they have been extensively studied in isolation through detailed environmental impact analysis of specific processes and technologies as well as individual sector literature review studies [14–17]. However, by assessing existing peer-reviewed LCA studies across multiple sectors, current trends and practices at both a sector and cross-sector level can be identified. Within existing subject studies, this type of cross-sectoral review has not previously been completed. Given the multitude of interconnections and interdependencies between these sectors, each respective industry would benefit from understanding how their counterparts are approaching the challenge of decarbonization. There are a number of well-established literature review methodologies including narrative, meta-analysis, and meta-synthesis [18]. In this study a systematic literature review (SLR) methodology was selected, as described by Tranfield et al. [19]. This technique adopts a repeatable, replicable, and transparent methodology which captures key studies related to a specific research question. When completed correctly, the study is able to produce reliable findings and conclusions [20].

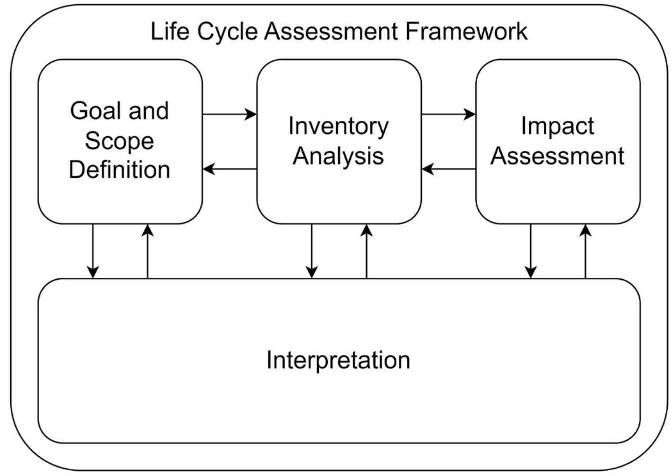

Fig. 1. LCA Framework, adapted from [11].

The goal of this review is to assess and understand how LCA studies are conducted in four global industrial sectors (cement, steel, glass, plastics), analyze the findings to ascertain how standardized LCA methodology is implemented, and generate recommendations for future LCA studies across these industries. Importantly, by analyzing current implementation practices of LCA methodology across the aforementioned sectors through a critical, systematic literature review, new insight is obtained regarding wide scale cross-sector implementation in these energy intensive industries. This is the first study that applies SLR methodology to distil a vast array of research regarding LCA implementation in cement, steel, glass, and plastic sectors holistically, generates a set of overarching conclusions applicable across each of these energy-intensive sectors, and develops a set of key recommendations for 'best practice' in LCA applied to such global industrial sectors. This will improve LCA practice, allow effective cross-sector comparison, and enhance decision making towards net zero.

This study is divided into five sections as follows: section two describes the SLR methodology used to retrieve journal articles, section three reports the bibliometric analysis of the retrieved articles, section four details the findings of the review, section five summarizes the similarities and differences in application of the LCA methodology between each sector, and section six summarizes the key findings and provides recommendations for future LCA implementation.

2. Methodology

2.1. Overall approach

Due to its prevalence, the process-based approach described by Tranfield et al. [19] and Atansovska et al. [21] was adopted as the overarching strategy for performing this SLR. The process of completing this review consists of the following three stages: planning (section 2.2), conducting (sections 2.3 and 2.4), and reporting. The approach is shown by a flowchart in Fig. 2.

2.2. Step 1: article collection

2.2.1. Review scope

This review focused solely on english language, peer-reviewed journal articles. Modern methods of LCA were standardized by ISO 14040 in 1997 [22], but did not become commonplace until 2000 with the publication of impact assessment methodologies [23]. Therefore, to capture the best quality environmental LCA articles which utilize standard methods and terminology, only work published within the last twenty years (2003 until 2023) is reviewed. The key focus of this research is the environmental impact of production and manufacture of feedstock materials within four energy intensive sectors as discussed in section one. Therefore, studies which primarily addressed life cycle costing and social impacts were excluded unless the LCA portion was significant enough to review.

2.2.2. Keyword and database selection

The databases that were used to conduct the review were SCOPUS, EBSCO, and Web of Science (WOS). These are considered to be the largest databases that can provide a sufficient number of articles to conduct a systematic review [21]. Several different keyword strings were trialed but ultimately a generic string, sector specific keywords, and associated search parameters were used as shown in Table 1. Sector specific keywords were added to further specify search results in sectors that utilize specific terminology; however, due to the comprehensive array of plastic materials that are considered part of the plastic industry, no specific terminology was required.

2.3. Step 2: descriptive analysis

Bibliometric analysis, a type of descriptive analysis, is defined as both a quantitative and qualitative research method which is utilized to evaluate the impact of individual researchers, research clusters, journals, countries, or institutions [21]. It is also a useful method for systematically identifying research trends within different fields of study [24]. To perform this bibliometric analysis, VOSviewer, a software package, was used to visualize and analyze keyword co-occurrence [25].

Table 1
Keyword string, sector specific terms, and search parameters used.

Keyword String			
("Life Cycle Assessment" OR "Life Cycle Analysis" OR "LCA" OR "Life Cycle Impact Assessment") AND ("*Sector Name* Industry" OR "*Sector Name* Production" OR "*Sector Name* Manufactur*" OR "*Sector Specific Terms*")			
Sector Specific Terms			
Cement	**Steel**	**Glass**	**Plastics**
"Portland Cement Production" OR "Portland Cement Manufactur*"	"Iron Industry" OR "Iron Production"	"Glass Furnace" OR "Glass Melting"	*Not applicable*
Search Parameters			
Database(s)		SCOPUS, EBSCO, WOS	
Publication Year		2003–2023	
Article Type		Journal	
Language		English	

2.4. Step 3: article evaluation

The retrieved articles were reviewed according to review criteria adapted from Atansovska et al. [21] and Bisinella et al. [26]. For this study, the broad groups were refined into three main categories: general, sectoral, and LCA characteristics. The general characteristics section notes information relating to the study's publication and scope. The sectoral characteristics section was included as a customizable review criteria block by which unique aspects of material production for each sector could be captured. The LCA characteristics section highlights how the LCA methodology was implemented in each study by assessing each category of the LCA framework illustrated in Fig. 1. In addition, the standards followed in each study were noted as a quality proxy. This exhaustive, predefined set of review criteria for each criteria group is summarized in Table 2. As required by Tranfield et al. [19], this will keep the review as objective as possible whilst retaining maximum comparative value in the study.

3. Descriptive analysis results

3.1. Articles retrieved

The SLR process resulted in a total of 1164 articles across all sectors over the last twenty years, as shown in Table 3.

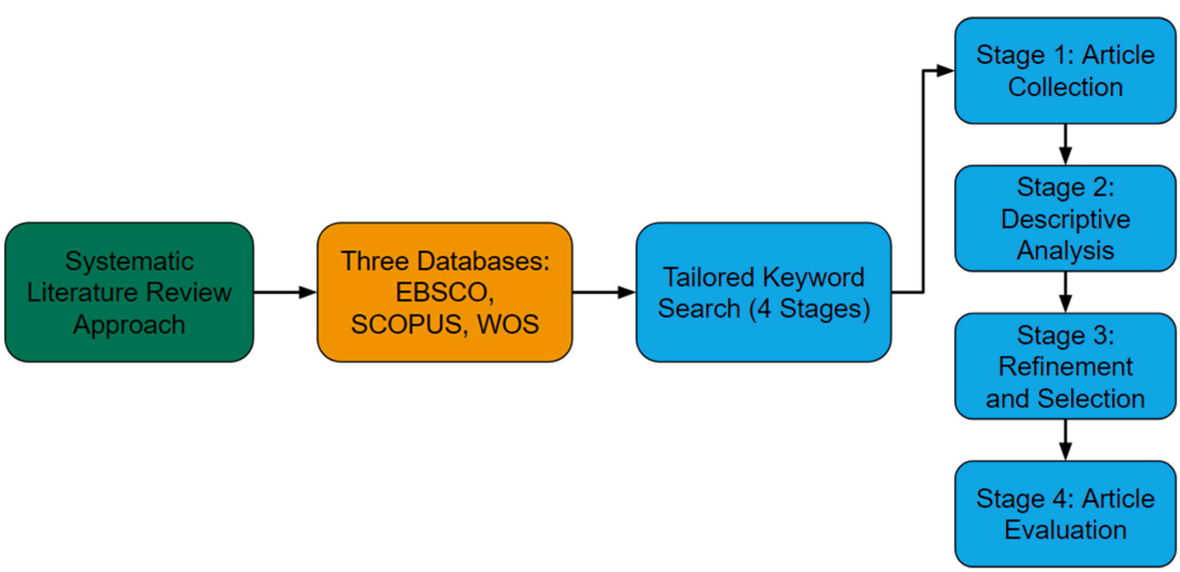

Fig. 2. SLR process flowchart.

Table 2
Review Criteria used Organized by Criteria Groups.

Criteria Groups	Review Criteria			
General Characteristics	• Author(s) • Journal		• Geographic Location(s) • Year	
Sectoral Characteristics	**Cement** • Type of Cement • Alternative Fuel Types • Supplementary Cementitious Material/Precursor • Alkali Activators	**Steel** • Production Route • Final Product	**Glass** • Type of Glass • Manufacturing • Processes • Glass Application • Recyclability	**Plastics** • Inventory • Type of Polymer • Type of Plastic
General Characteristics	• Author(s) • Journal		• Geographic Location(s) • Year	
Goal and Scope	• Number of Scenarios • Comparative LCA • Functional Unit Type • Functional Unit		• System Boundary • Substages Considered • Allocation Procedure • Type of LCA	
Inventory Analysis	• Data Type • Data Quality Mention/Assessment • Foreground Data Source		• Background Data Source • Data Sources • Databases	
Impact Assessment	• LCA Software Used • Impact Assessment Method		• Midpoint Environmental Indicators • Endpoint Environmental Indicators	
Interpretation	• Sensitivity Analysis Conducted • Uncertainty Analysis Conducted • Predictive LCA Conducted			
Quality Proxy	• Standards Followed			

Table 3
Numerical summary of articles collected following SLR process.

Database/Sector	Cement	Steel	Glass	Plastics	Total
SCOPUS	182	193	38	190	**603**
EBSCO	51	63	23	18	**155**
Web of Science	159	187	19	41	**406**
Total	**392**	**443**	**80**	**249**	**1164**

3.2. Bibliometric analysis and keyword evaluation of retrieved articles

In line with the developed SLR process, a bibliometric analysis was performed on the retrieved articles to ensure consistency across each sector of study as well as identify key meta-insights into each sector. Following guidelines established by Van Eck et al. [25] as well as experimentation, the author keyword co-occurrence parameter was set to a minimum of three and five occurrences per keyword as shown in Figs. 3 and 4 respectively. The color codes indicate clusters of keywords which are utilized together (i.e., the same keywords are used in different papers). Broadly, these are split into each sector of interest but there are some common clusters which are cross-sector. These two maps denote a good alignment between the keywords returned from the SLR, and the subject areas of interest. Important keywords associated with the production of cement (concrete, Portland cement, and compression strength), steel (blast furnace, electric arc furnace, and iron and steel industry), glass (life cycle assessment, energy, and recycling), and plastics (plastics waste, bioplastics, and recycling) are seen. There is also good alignment with keywords emerging from circular economy and sustainable manufacturing practices (circular economy, sustainable innovation, waste management, and recycling). Furthermore, there are several keywords which have significant cross sector overlap including ‘life cycle assessment’, ‘environmental impact’, and ‘sustainability’.

3.3. Final taxonomy

Following the bibliometric analysis and keyword evaluation in section 3.2, a large number of duplicate, off-topic, non-compliant, and non-accessible articles were identified and removed. For this study, off-topic papers encompassed all articles that did not perform an LCA or were not relevant to the topic of sustainability studies. Non-compliant studies include studies that:

1. Do not relate to the sector being considered.
2. Do not evaluate production of the main product of the sector.
3. Do not use LCA as the primary methodology to assess environmental impacts.
4. Are literature review studies that evaluate existing LCAs.

Non-accessible articles include studies that could not be accessed or downloaded from their respective databases. This results in 256 unique articles for analysis which were compliant with the criteria and goals of this SLR. The article identification and retrieval flow chart is illustrated in Fig. 5.

4. Results

4.1. General characteristics of studies

Year of Publication: As shown in Fig. 6, the application of LCA methodology has been increasing since 2015. There has been a further sharp increase since 2020 which represents 46.5 % of the total collected publications since 2003. This phenomenon is particularly visible in the cement and plastics sectors.

Geographic Location of Study: Fig. 7 highlights the geographic locations evaluated in the studies assessed. It was determined that China is the country with the greatest number of LCA evaluations in the cement, plastics, and steel sectors, likely due to the large economic and industrial growth seen in recent decades [27]. However, glass LCA articles were more focused in Italy due to the importance of glass to the country’s economy [28]. The region with the largest number of scenario evaluations was Europe. Excluding studies in Europe that specified a specific country, 33 assessed studies opted to perform an LCA considering Europe as a generalized region; making use of Eurocentric databases such as Ecoinvent. This value includes studies that looked at European Union nations only, Europe, and Europe without Switzerland. In addition to regional evaluations, 11 assessed studies utilized general global data.

4.2. Sectoral characteristics

Cement Sector: As the most commonly used construction binder, Portland cement was evaluated as a scenario in roughly 70 % of evaluated studies. While this is the case, only 35 % of studies assessed opted to exclusively evaluate Portland cement manufacturing by evaluating

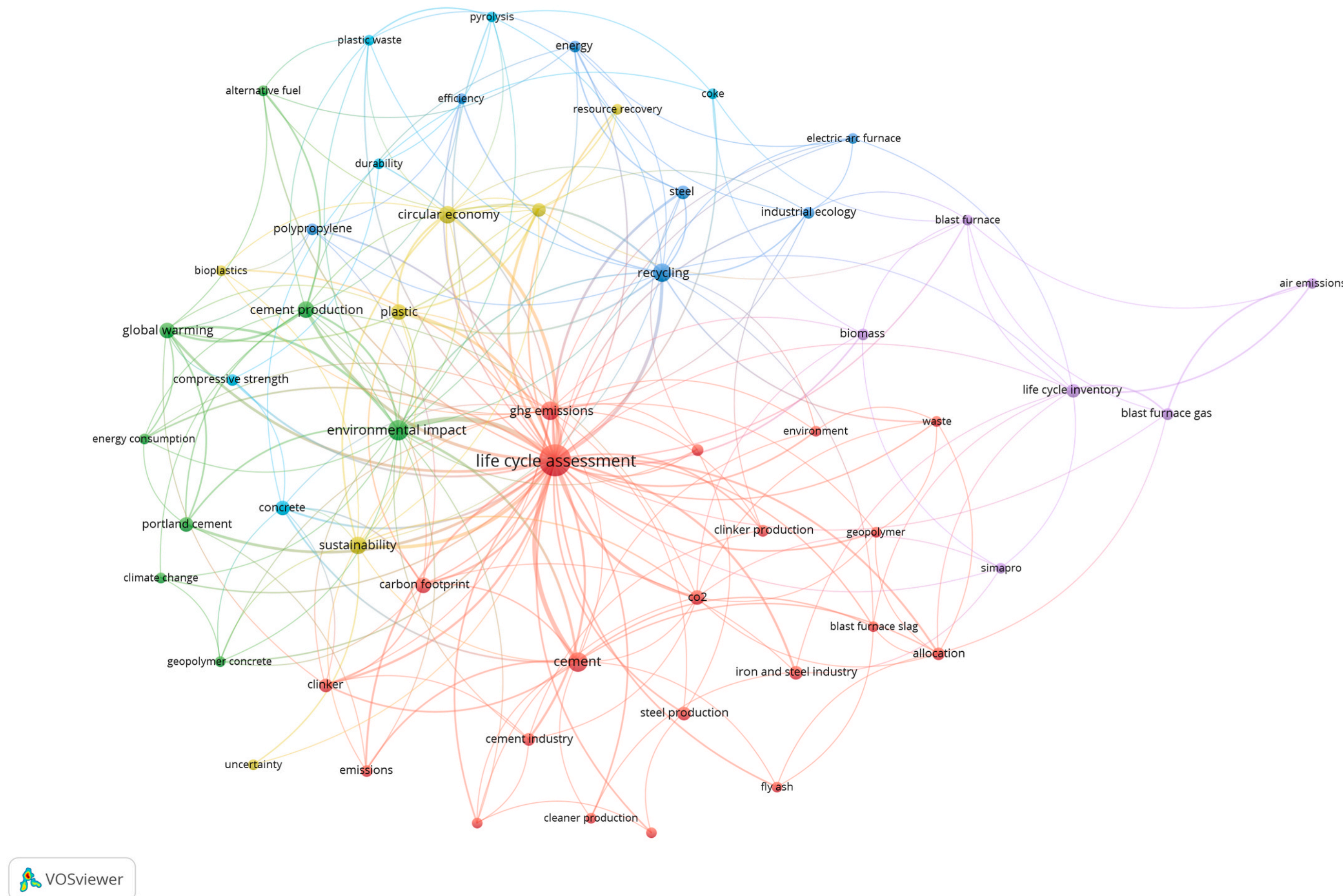

Fig. 3. Author keyword co-occurrence map (minimum of 3), with cleaned keywords.

current 'business as usual' production processes utilizing region specific data [29,30]. Portland cement was often used as a base scenario to compare alternative cement types such as blended cements or alkali activated cements. Roughly 47 % of studies assessed evaluated supplementary cementitious materials (SCMs) for use in blended cements at various substitution levels with fly ash, ground granulated blast furnace slags (GGBS), and other natural pozzolans the being most assessed SCMs. Three of the selected studies opted to evaluate limestone calcined clay cement (LC^3), as an alternative to blended cements using industrial wastes [31–33]. Approximately 10 % of retrieved studies evaluated alkali activated cements, with sodium silicate being the alkali activator that was most selected. In addition to evaluating alternative low carbon cement alternatives, it was found that roughly 20 % of studies opted to conduct a comparative LCA to assess the environmental impacts of utilizing alternative fuel types including solid recovered fuel and liquid hazardous waste [34,35]. With the calcination process requiring the largest fuel input, 22 of the studies assessed opted to evaluate the production of clinker as a scenario [36,37]. In contrast, nine of the selected studies evaluated concrete production by furthering the system boundary to include aggregate and water consumption [38,39].

Steel Sector: As the dominant steel production route, roughly 75 % of assessed studies focused at least partially on blast furnace - basic oxygen furnace (BF-BOF) production. Of these assessed studies, 63 % focused exclusively on the BF-BOF production route [40–42]. The remainder conducted a comparative study on multiple routes, including electric arc furnace production [43,44]. The remaining assessed studies focused on the electric arc production route only [45]. A variety of iron and steel products were selected for the scope. Approximately 28 % of all retrieved studies chose to focus on semi-finished products including crude steel [46], slab [47], and liquid steel [48]. The majority of assessed studies evaluated finished steel products including cold rolled coil [49], hot rolled coil [50], rebar [51], and hot rolled beams [52]. A number of retrieved studies focused specifically on intermediate products used within the BF-BOF production route including coke [53], cast iron [54], sinter [55], and iron ore pellets [56]. Whilst others chose to expand the system boundary further and study specialist types of steel products including stainless [57] and galvanized [58] steel. More recent studies tend to include additional scenarios which focus on reducing the environmental impact of production by using innovative technologies. This is across all production routes and includes the use of biomass [59], wood pellet fuel [60], scrap [48], carbon capture technologies [61,62], and hydrogen fuel [63].

Glass Sector: Out of the seven papers retrieved, four papers focused exclusively on glass production [28,64–66]. The remaining articles included a glass production LCA as part of a wider system boundary [67–69]. Hollow glass was researched in three papers, with two considering its production [28,66] and one evaluating production and recycling [69]. Crystal glass was studied in two papers, and mainly focused on the production process [64,65]. The remainder considered specialist glass including high pressure [67] and borosilicate [68] glass.

Plastics Sector: More than 60 % of assessed studies performed an LCA on fossil fuel-based plastics, whilst the remaining focused on understanding the potential of bioplastics as an alternative. Meanwhile, 10 % of studies analyzed recycled polymers [70] and other recycling technologies [71]. The most common applications were found to be as feedstock (40 %) [72], packaging material (30 %) [73], and within modes of transportation (12 %) [74]. Certain applications in agriculture [75], household appliances [76], and fashion [77], have received

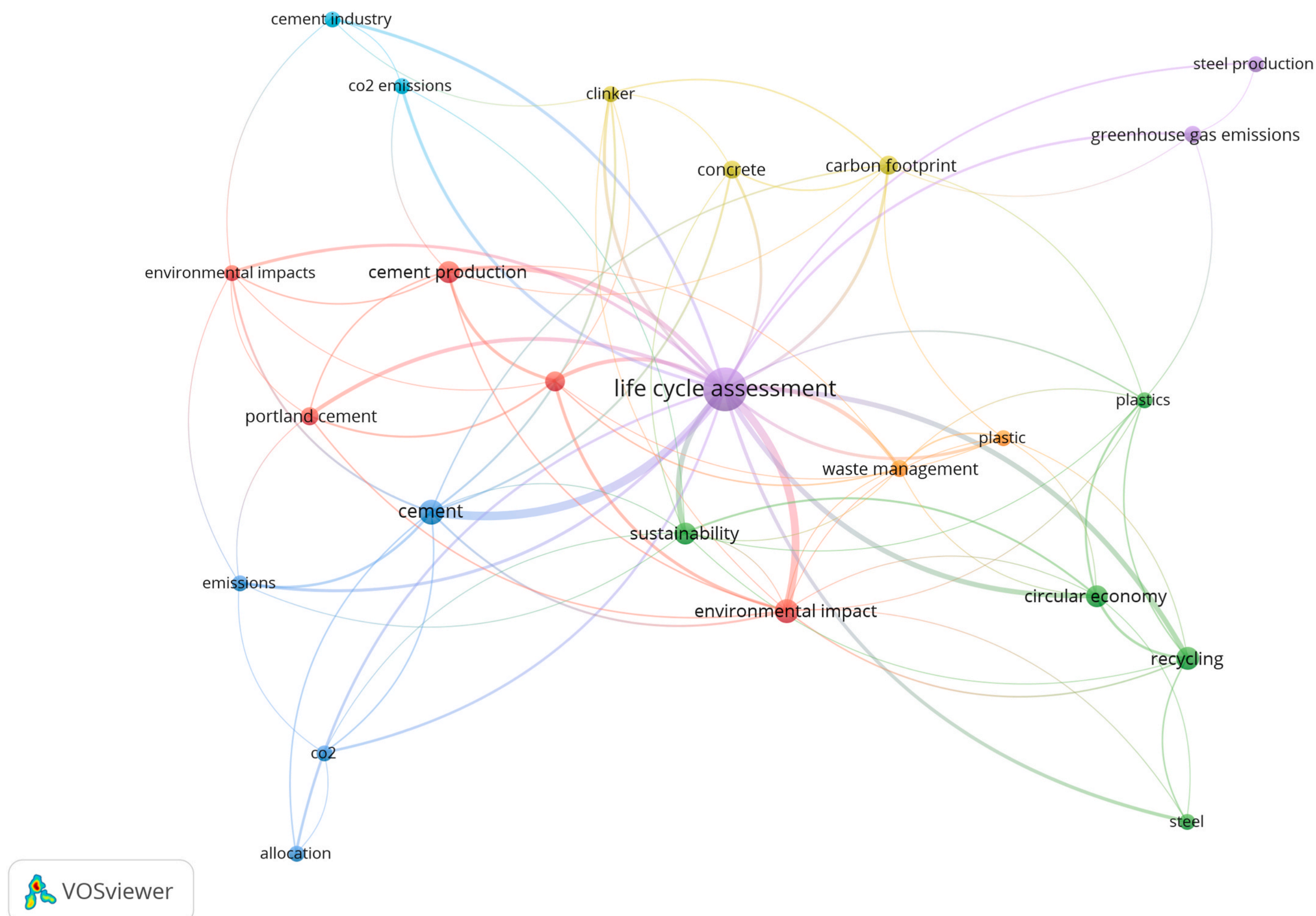

Fig. 4. Author keyword co-occurrence map (minimum of 5), with cleaned keywords.

comparatively limited attention. Within Europe, it has been identified that polyethylene terephthalate and polypropylene are the most commonly used polymers despite their known adverse environmental impacts [78]. Therefore, these materials have become a focal point for LCA research with nearly half of assessed studies evaluating them. Limited investigations have been carried out into novel fiber reinforced plastics [74,79]. Roughly 68 % of assessed studies performed a comparative analysis to evaluate environmental impact differences between virgin and sustainable plastic alternatives [75,78].

4.3. LCA characteristics

4.3.1. Goal and scope

4.3.1.1. Functional unit. A functional unit is defined as a “quantification of identified functions of a product” where the unit “provide(s) a reference to which the inputs and outputs are related” [11]. A properly defined functional unit is key when assessing the environmental impacts of a product throughout its whole life cycle. Alternatively, a declared unit can be used instead when the precise function of the material is unknown. A declared unit is defined as “a reference by which product, material, and energy flows are normalized to produce data expressed on a common basis” [80]. As noted in Product Category Rules (PCR) 2019:14, a declared unit can be utilized instead of a functional unit for ‘cradle-to-gate’ studies if “the product or material is physically integrated with other products during installation so they cannot be physically separated from them at end of life, the product or material is no longer identifiable at end of life as a result of a physical or chemical transformation process, and the product or material does not contain biogenic carbon” [81].

Cement Sector: The most selected functional unit type was found to be a mass-based unit. Over 60 % of assessed studies opted for this unit type, with roughly half selecting ‘one metric ton of clinker’ [82] or ‘one metric ton of cement or cement product’ [83,84]. Studies that opted to evaluate the production of concrete typically selected a volume-based unit [85,86]. These units, however, should be classified as declared units because the precise function of the cement product was not defined. In the retrieved studies, 50 % reported using a functional unit despite the material’s function not being defined. Only 42 % of assessed studies accounted for performance in comparative assessments evaluating more than one cement type [31,87–89].

Steel Sector: A mass-based unit was the most selected functional unit type, with approximately two thirds of assessed studies selecting ‘one metric ton of steel product’ (regardless of the eventual product) as the common unit of mass [60,90,91]. A number of assessed studies defined their functional unit specific to their data inventory [92,93]. A single study selected a functional unit type relating to energy [94], whilst another selected a functional unit type relating to volume [95]. These studies have goals which are specifically related to understanding the environmental impact of energy and water consumption respectively. However, these units (mass, volume, and energy) should be classified as declared units because the precise function of the steel product was not defined. As a result, over 80 % of retrieved studies reported using a functional unit despite not defining the material’s function.

Glass Sector: The most common functional unit selected was a mass-based unit, with most selecting ‘1 kg’ of glass produced as the unit of

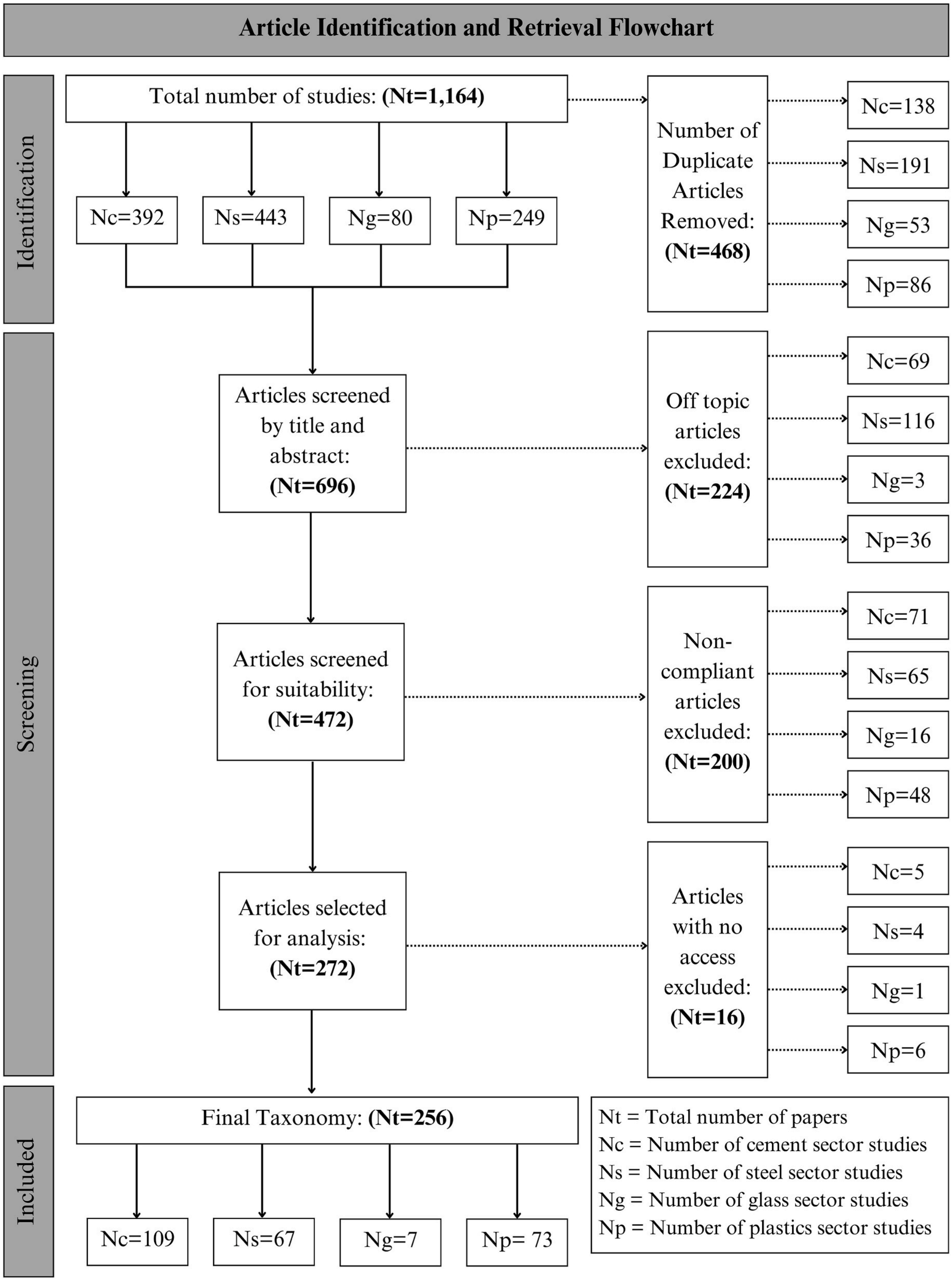

Fig. 5. Numerical summary of articles collected following descriptive analysis process (dotted arrows represent number of papers removed during retrieval).

mass. Vinci et al. [28] opted to include a time variable. The remaining two articles did not directly define glass as the assessed product, but still primarily focused on glass production [67,68].

Plastics Sector: More than 65 % of the retrieved studies were found to use mass-based units, choosing either '1 kg' or 'one metric ton of polymer product(s)' [96]. Additionally, of the retrieved studies, 14 % selected a length unit [97] and 11 % selected a volume unit [98]. Furthermore, 10 % evaluated mechanical performance, such as carrying capacity, as their functional unit [99]. However, one study chose three different declared units due to the challenges of determining a functional unit for their multifunctional product [71]. It was observed that declared units were often selected but were frequently regarded as

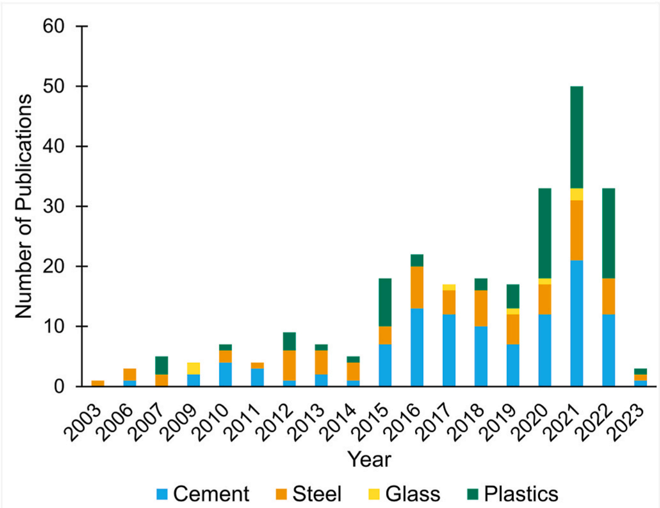

Fig. 6. Temporal Assessment summarizing LCA Publications from 2003 to 2023.

functional units [100].

4.3.1.2. System boundary. A system boundary defines which aspects of a product's life cycle will be included and excluded in the analysis [11]. There are four main system boundaries that can be considered. The first is 'cradle-to-gate', which considers the extraction of any raw materials, the manufacturing process of the product, and any material or product transportation. PCR 2019:14 defines 'cradle-to-gate' as five distinct stages which includes extraction of raw materials [A1], transportation to manufacturing [A2], product manufacturing [A3], transportation to building site [A4] and construction site process [A5] [81]. The second is 'gate-to-gate', which assesses the environmental impacts at the product manufacturing stage (denoted as [A3] for construction products). The third is 'cradle-to-grave', which extends the system boundary to also include the use ([B1-B7] for construction products) and end of life ([C1-C4] for construction products) of a given product. The last is 'cradle-to-cradle' which defines the system boundary as a complete circle by reusing material at the 'end-of-life' stage.

Cement Sector: The most commonly selected system boundary is 'cradle-to-gate', as selected by 95 % of assessed studies. This is likely due the material's product stage accounting for the largest environmental impact [101]. Some studies provide justification for this system boundary selection by assuming that the 'use' and 'end-of-life' phase would be similar for any cement mixes analyzed [102]. However, the definition of 'cradle-to-gate' changed based on the scope of the study. Most retrieved studies opted to evaluate the [A1-A3] stages of 'cradle-to-gate' but some did not include the product packaging stage found in [A3] [103,104], and others opted to not include [A2] [105]. Even fewer considered the final two 'cradle-to-gate' stages, [A4] and [A5]. Two of the retrieved studies that did evaluate these stages assessed the impacts of concrete production [39,106]. By including all stages of the 'cradle-to-gate' system boundary, a more holistic view can be presented. 'Cradle-to-grave' or 'cradle-to-cradle' is typically not considered due to the complexity of determining the 'use' and 'end-of-life' as reflected in less than 4 % of the assessed studies.

Steel Sector: Approximately 75 % of retrieved studies selected a 'cradle-to-gate' system boundary, with most opting to evaluate the [A1-A3] stages [41,107]. Others chose not to include [A2] to avoid double counting within their model [108] and due to the effects of regionalization [109]. Furthermore, one study chose to exclude both [A1] and [A2] due to the type of LCA model utilized [110]. None of the retrieved studies elected to evaluate the [A4] and [A5] stages of 'cradle-to-gate', likely due to the site specific nature of these stages [59] and the perceived relatively low impact [108]. Roughly 15 % of evaluated studies selected the 'gate-to-gate' boundary type. This was often chosen when the study had a goal related to a specific aspect of the production process [48,111]. Only 6 % of assessed studies elected to evaluate a 'cradle-to-grave' or 'cradle-to-cradle' boundary type, often to explore novel solutions to reduce environmental impact through increased scrap inclusion [112] and carbon capture technologies [113].

Glass Sector: Three studies selected a 'cradle-to-gate' system boundary [64,67,68], however only one study explicitly included transportation of raw materials to the manufacturing location [64]. Two studies opted to extend the system boundary to include the 'use' and 'end-of-life' stages [65,66]. Another study extended this boundary further by including recycling and an analysis of the circular economy [69]. The remaining study did not specify a system boundary, but the study scope implies that a strict 'gate-to-gate' analysis was selected [28].

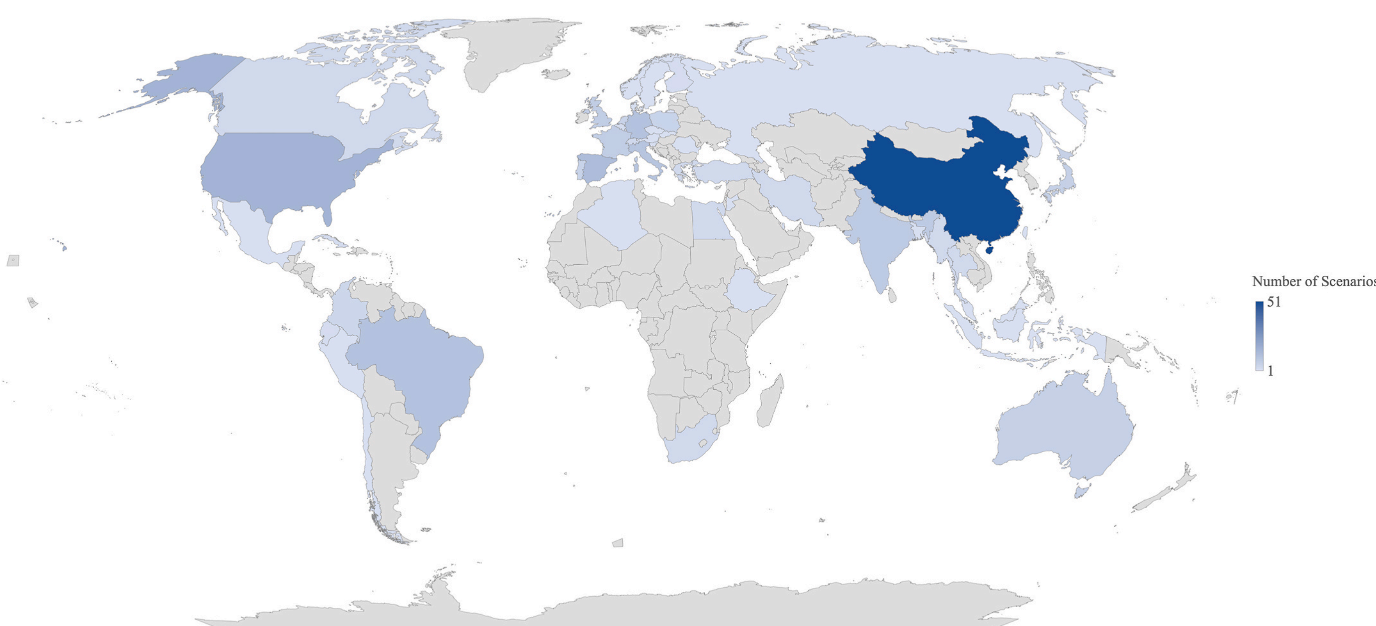

Fig. 7. Geographical locations considered for retrieved LCA studies.

Plastics Sector: Roughly 47 % of retrieved studies adopted a 'cradle-to-gate' system boundary [114,115], while 40 % selected the extended 'cradle-to-grave' boundary [116,117]. Only one study explored the 'cradle-to-cradle' perspective, emphasizing the potential for recycling and waste valorization [78]. In contrast, five studies selected a 'gate-to-gate' system boundary to examine specific manufacturing phases [71,118]. Six other studies employed a 'gate-to-grave' boundary, which includes manufacturing and disposal phases [119,120]. Additionally, three studies left the system boundary unspecified [121–123]. Four studies explored more than a single system boundary (e.g., 'cradle-to-gate' and 'cradle-to-grave') [71,78,124,125].

4.3.1.3. Allocation. Allocation is defined as "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" [11]. Although ISO 14040 does not specify a specific procedure for allocation, it does note that allocation through system expansion and avoided burden should be avoided when possible. Instead, it is best to allocate based on physical (e.g., mass) or non-physical (e.g., economic) relationships [13]. The benefit of using a mass allocation procedure is that the value typically remains constant over time, with change only occurring if the product's production process is significantly improved due to technological changes. However, problems may occur if the mass of the by-product being considered is greater than that of the main product. While an economic allocation procedure can take into account the value and therefore the demand of the product being considered, price fluctuations may render the results inaccurate in the future [126].

Cement Sector: Careful consideration must be made for the allocation of SCMs such as GGBS, fly ash, and other industrial waste materials. Traditionally, these materials have been classified as waste products despite their increased demand within the cement sector. Since 2008 however, BFS has been considered a by-product within the European region [127,128]. If an industrial waste material is no longer considered a waste product, the environmental impacts associated with it must be considered. It was found that out of the 48 retrieved studies that examined the use of industrial waste materials for use in low carbon cements, over half did not specify an allocation procedure to account for the environmental impacts to the material's production. When an allocation procedure was specified, economic allocation was most often used [129,130]. The same number of studies opted to evaluate both mass and economic allocation procedures [131,132]. Additional allocation procedures that were considered for industrial wastes include avoided burden [85], energy [39], and impacts [133].

Steel Sector: The majority of retrieved studies did not specify an allocation procedure used [90,134,135] despite the importance of correctly allocating the impact of the several intermediate products produced during the steel production process (e.g., BFS) [136]. Five different allocation procedures were used by the remaining studies: system expansion [94], avoided burden [137], mass [51], energy [138], and economic [138]. The allocation procedure selected varies significantly between studies but is typically influenced by the goal of the study. There appears to be no consensus on which allocation procedure to use, and this can have an impact on the study result.

Glass Sector: Despite the production of potential by-products, allocation procedures were not applied in any of the retrieved studies.

Plastics Sector: More than half of all retrieved studies did not specify the use of any allocation procedure. When used however, it was found that allocation based on physical relationships (e.g., energy and mass) was selected in 30 % of studies [71,139]. Other allocation procedures were used including system expansion [140,141] and economic [142].

4.3.2. Inventory analysis

The inventory analysis step of an LCA evaluates the flow of energy, emissions, and matter across a defined system boundary by creating a life cycle inventory [12]. There are three main LCA methodologies that influence how a life cycle inventory is created: process-based, economic input-output (E-IO), and hybrid [143]. The process-based methodology is based on the physical flows present within a system boundary. The E-IO method evaluates a material's environmental impacts based on economic flows between sectors within a product's supply chain. The hybrid LCA methodology is a combination of the process-based and E-IO methodologies [144].

4.3.2.1. Type of LCA. Cement Sector: The process-based methodology was found to be the most commonly used [130]. Three of the assessed studies selected the E-IO method [27,145,146]. The hybrid methodology was conducted in two of the retrieved studies, with one evaluating production in China [147] and the other in Australia [129]. The implementation of the process-based approach across most papers is in line with the research questions presented which focus on process specific evaluations.

Steel Sector: Roughly 88 % of studies assessed selected the process-based method [148], with a small number taking a E-IO [95] or hybrid approach [149]. Given the focus on material production, this is to be expected. However, it does highlight that it is uncommon for material level analysis to be conducted using novel LCA methodologies.

Glass Sector: All retrieved studies utilized a process-based methodology, highlighting a potential research gap to utilize novel LCA methodologies [66].

Plastics Sector: The process-based methodology was predominantly selected in the retrieved studies [150,151]. Two studies performed a hybrid LCA to evaluate the wider environmental impacts of the assessed product [152,153].

4.3.2.2. Data source. Data sources for LCA studies can be split into two different categories: primary and secondary. Primary data is data collected by the LCA practitioner from either industry or laboratory testing. Secondary data is obtained through publicly available databases, existing publications, or other sources.

Cement Sector: It was found that approximately 43 % of retrieved studies utilized primary data sources. A majority of these studies were transparent about where the primary data was obtained, but some noted that the data was confidential and therefore could not be detailed [30,154,155]. Only a small number of retrieved studies utilized primary data exclusively [82,104], with most opting to use a combination of both primary and secondary data sources [156,157]. Secondary data sources were used in some form in over half of all assessed studies, with roughly 57 % relying on solely secondary data [158,159]. Some of the most widely used databases were found to be Ecoinvent [160], GaBi [86], European Reference Life Cycle Database [161], United States Life Cycle Inventory [35], and Chinese Life Cycle Database [130].

Steel Sector: Approximately half of retrieved studies utilized primary data sources. A small number of these have detailed the source, which includes major manufacturers such as Corus [53], ArcelorMittal [93], and ThyssenKrupp [136]. However, most studies that reported using a primary data source do not specify the supplier. Most of the assessed studies supplement their foreground data with secondary data, typically from studies or publicly accessible database sources [55,108,138]. The remaining studies made use of this secondary data only [162]. A wide range of databases have been used including Ecoinvent [51], WorldSteel [163], GaBi [164], and DEAM [137].

Glass Sector: Only one study relied solely on primary data due its specific 'gate-to-gate' system boundary selection [28]. Five studies supplemented the collected primary data with secondary data sources [64–68], while the remaining study opted to use only secondary data [69]. The transparency of primary data collected varied across the retrieved studies, with Pulselli et al. [65] providing the most detailed primary data inventory despite the study's need to exclude certain data values for confidentiality reasons. A number of databases were utilized including Ecoinvent [66], Environmental Development of Industrial

Products [64], and European Reference Life Cycle Database [69].

Plastics Sector: Approximately 60 % of the retrieved studies utilized primary data obtained from experimental works [118] or directly from plastic industries [165]. A number of these studies supplemented this data with secondary data from databases such as Ecoinvent [166], GaBi [122], European Reference Life Cycle Database [167], and Chinese Life Cycle Database [168]. A third of assessed studies relied solely on secondary data [169].

4.3.2.3. Software. Cement Sector: SimaPro was found to be the most utilized software package with nearly half of all retrieved studies opting to use it [170,171]. The second and third most used software were found to be GaBi [172,173] and OpenLCA [174,175]. Roughly a quarter of studies did not specify a specific software package [147,176], however it is likely that many of these studies opted to perform calculations in Excel or in custom software [160,177].

Steel Sector: Approximately 45 % of retrieved studies utilized either SimaPro [41,107] or GaBi [61,178]. However, a similar number used an unspecified software package [44]. How the results were presented in some assessed studies means that the software used could be deduced, but this finding would also suggest a significant number used custom solutions. The remainder of studies used a variety of software packages including OpenLCA [56,179].

Glass Sector: In six of the seven retrieved studies, there was an even split between the GaBi [64–66] and SimaPro [28,67,68] software packages. The remaining article opted to select OpenLCA for their analysis [69].

Plastics Sector: SimaPro was found to be the most utilized software package with 35 % opting to use it [180]. The second and third most commonly used software packages were found to be GaBi [79] and OpenLCA [181]. Other software selections include Excel [182] and Thinkstep Professional [183]. About 10 % of retrieved studies did not specify a specific software package [184].

4.3.3. Impact assessment

Life cycle impact assessment is defined as the stage at which the "magnitude and significance of the potential environmental impacts for a product system" are evaluated throughout the entire life cycle of a product [11]. At this step, the impact categories, category indicators, and characterization models are selected.

Cement Sector: It was determined that Centrum voor Milieukunde Leiden (CML) was the most often selected impact assessment methodology, with 33 of the retrieved studies selecting this method [83,131,155]. The second and third most utilized methodologies were found to be Intergovernmental Panel on Climate Change (IPCC) [32,185] and ReCiPe [29,186]. A number of studies opted to select more than one impact assessment methodology to consider a wider range of impact categories [187] or for sensitivity analysis purposes [147]. Less than 13 % of retrieved studies did not specify an impact assessment methodology [174,188]. The most common midpoint indicator reported was global warming potential (GWP), with nearly every study reporting this indicator. The second most reported midpoint indicator was found to be ozone depletion potential with over half of all retrieved studies evaluating this category. Other common midpoint categories that were reported include acidification potential, photochemical oxidation potential, eutrophication potential, and terrestrial ecotoxicity. Endpoint indicators were reported in only a fifth of all retrieved studies, with human health, resources, and ecosystem quality being the most reported categories. To assess endpoint categories, it was concluded that Eco-Indicator [36,132] and IMPACT [189,190] were most commonly selected.

Steel Sector: There is a near-even (approximately 20 % each) split between the ReCiPe [54], IPCC [191], and CML [45] impact methodologies in the retrieved studies. These were occasionally used in combination with each other [40,178,192]. Other impact methodologies utilized include International Reference Life Cycle Database [41], IMPACT [47], Eco-indicator [52], cumulative energy demand [193], and water footprint [194]. However, nearly a quarter of all retrieved studies did not specify an impact methodology [109,113,195]. Studies which used the IPCC and CML methodologies tend to focus heavily on GWP, with over 70 % reporting this. In contrast, a majority of assessed studies which used the ReCiPe methodology reported all of the midpoint indicators available [196]. Aside from GWP, the most common midpoint indicators reported were particulate matter formation, eutrophication potential, and acidification potential. Regardless of impact methodology, only 12 % of retrieved studies reported an endpoint indicator result [58,60,179]. The most common endpoint indicators reported were human health, ecosystem quality, and resources. All but two of these studies used the ReCiPe methodology to do this [49,51].

Glass Sector: The CML impact assessment methodology was selected in five of the seven retrieved studies. In addition to CML, one study opted to also use the ecological scarcity method [69]. The remaining studies selected other methodologies including ReCiPe [28], IPCC [67], and cumulative energy demand [67]. The most frequently assessed midpoint indicators were GWP, acidification potential, eutrophication potential, ozone depletion potential, and photochemical oxidation potential. Only one article opted to calculate endpoint indicators, with human health, ecosystem quality, resources, and climate change being assessed [28].

Plastics Sector: Among the retrieved studies, ReCiPe was found to be the most often selected impact assessment method with approximately 19 % of the studies utilizing this method [152,197]. CML was found to be the second most used method [72]. However, around 14 % of assessed studies employed a mixed-methodology approach, indicating a preference for combining various methods to comprehensively evaluate environmental impacts [114,142]. Less than 5 % of retrieved studies did not specify the impact methodology [198,199]. The most commonly assessed impact indicator was found to be GWP [167,200]. Other reported indicators include freshwater ecotoxicity, particulate matter formation, terrestrial acidification potential. Only 20 % of evaluated studies considered endpoint indicators, with the most evaluated categories being human health, ecosystem quality, and resources. To calculate these indicators, ReCiPe was found to be the impact assessment method typically selected [201].

4.3.4. Interpretation

ISO 14044 standard specifies two main interpretation checks that should be conducted [13]. The first check is a sensitivity analysis which is used to test the accuracy of a result by altering assumptions defined in the goal and scope. A second check is an uncertainty analysis which verifies if the data collected is relevant and accurate. This is typically done using a Monte Carlo analysis method. The Monte Carlo method is a probabilistic method to model intricate systems and assess uncertainties by simulating numerous scenario analysis [202]. A third analysis type that can be considered to evaluate possible future scenarios for a given material process is a scenario analysis. This can be done through the theoretical implementation of novel changes to a product's manufacturing processes [26]. Once the interpretation step is completed, conclusions from the results can be drawn and recommendations can be made.

Cement Sector: It was found that roughly 40 % of the retrieved studies opted to conduct a sensitivity analysis. The most common sensitivity analysis performed in these studies involved altering key input data parameters (most notably transportation distance) by 5–20 % [173,203]. Altering the allocation procedure was also a common sensitivity analysis check for studies that evaluated by-products for use in low carbon cements [131,204]. Only 11 studies opted to perform an uncertainty analysis [89], with Monte Carlo simulation being the most used evaluation method [205,206]. Only eight studies conducted both a sensitivity and uncertainty analysis as part of the study [129,187,206].

Steel Sector: Only a quarter of retrieved studies reported completing a sensitivity analysis. The most common method of completing this was by altering the input parameters and reporting the effects on the results. There is no consensus for a standard approach to this, with studies altering parameters by 5 % [58], 10 % [51], and 20 % [207]. Roughly 20 % of assessed studies completed an uncertainty analysis, with Monte Carlo simulations being the most common method [192,208]. Less than 8 % of retrieved studies elected to complete both interpretation checks, with frequency increasing in more recent studies [58,209].

Glass Sector: Three of the seven studies opted to perform a sensitivity analysis, despite the studies not referring to it as such. Methods included changing input parameters such as the amount of recycled glass present in a batch [66,69] and transportation distance [69]. One study provided the most comprehensive sensitivity analysis by evaluating geographical, economic, and technological parameters such as the amount of energy consumed, process efficiency, and plant life span [67]. None of the retrieved studies performed an uncertainty analysis.

Plastics Sector: It was found that more than half of the retrieved studies conducted a sensitivity analysis [97,210]. Approximately 26 % of studies performed an uncertainty analysis with Monte Carlo simulation being the most commonly selected method [211]. Roughly 19 % of the retrieved studies conducted both a sensitivity and uncertainty analysis [169,212].

5. Discussion

5.1. LCA cross sector comparisons

5.1.1. Goal and scope

Across the sectors investigated, in the majority of cases, the terminology relating to functional and declared units is being inconsistently used. This means that the performance of materials is not being accounted for when the functional unit is defined. In the retrieved studies, over two thirds reported using a functional unit without considering the mechanical properties that affect a product's function. As such, a declared unit should be used to describe the assessed product more accurately. While the use of either unit type can be justified, it is important to distinguish the difference between these terms as it can have a direct impact on the results of a study. This is particularly true in cases where functional equivalence must be taken into consideration when conducting a comparative analysis between two or more products [172]. Ultimately, differences between studies, even at this fundamental level, may limit the understanding gained by conducting an LCA. Thus, greater focus needs to be placed on how the units are identified and defined. This can only be done through an objective comparison on the basis of functionality by the use of a properly defined functional unit. As noted, alternatively, a declared unit can be implemented when the material properties or the function is not affected or known.

A good example of the challenge that comes with defining material functionality is found within the cement sector. Using a blended cement mix or an alkali activated cement can result in performance differences (most notably compressive strength) when compared to Portland cement alone [213,214]. This illustrates the clear mechanical property differences that should be accounted for when conducting an LCA. When considering compressive strength differences in comparative assessments, most studies opted to use a strength ratio modification based on measured compressive strength to normalize environmental impacts [158,189]. Aside from compressive strength, other parameters that have been selected to evaluate cement functionality include rapid chloride permeability and service life [215]. Some studies opted to define their functional unit by using a combination of parameters to provide a more holistic definition of cement functionality [172,216]. This type of functional unit is particularly relevant when evaluating the environmental impact of a specific structural element that requires a certain mechanical strength and defined service life [217]. An approach like this is not seen in any of the other sectors, despite an intrinsic link between material function and properties. Within the steel sector, this could be defined by the mechanical properties or by considering a specific product function, such as the wear resistance of rail steels. Similarly, in the glass sector, the mechanical properties of specific products are critical depending on application, and therefore must be considered within the functional unit. Likewise, defining a functional unit for plastic products is a complex task due to the wide range of potential applications. As a result, declared units are typically favored over more complex functional units that define performance. Ultimately, this highlights that environmental impact is influenced by material function, which could produce different environmental impact results when assessed beyond a 'cradle-to-gate' system boundary.

It was found in all retrieved studies the most commonly selected system boundary was 'cradle-to-gate'. Typically, data availability for 'cradle-to-gate' is more abundant and reliable compared to data in downstream stages such as 'use' and 'end-of-life'. Furthermore, this system boundary enables a direct comparison of the environmental impact of different products or materials at the manufacturing phase. This is valuable for industries seeking to identify hotspots, trade-offs, and opportunities for improvement to make informed decisions about their processes and materials. While this is the case, there is a notable lack of studies that extend the system boundary. However, within the plastics industry, the 'cradle-to-grave' boundary is often evaluated due to more prevalent circular economy practices. Despite this, there is a clear need for studies that provide a greater holistic view across the entirety of a material's life cycle to understand the full environmental impacts of a product. Evaluating a product that is ultimately used in a variety of applications with different requirements is challenging unless the study scope and functional unit is very specific [84,204]. For example, with the primary function of cement being the main ingredient in concrete, carbon uptake of concrete structures due to carbonation would need to be assessed in the 'use' and 'end-of-life' stages. While this aspect can be used to reduce concrete's carbon footprint, the life span, concrete strength, and post demolition time all have to be considered as they directly impact the amount of carbon dioxide uptake that can occur [218]. Similarly, it is difficult to generalize the use of steel as a product due to the variety of potential downstream uses (either as a feedstock, semi-finished, or finished product). This results in a complex boundary that is difficult to define unless a specific product is being evaluated.

There is also a clear challenge on how to tackle allocation, with a variety of procedures used within each sector. The most interesting exponent of this, despite the intrinsic link between them, is in the steel and cement sectors through the production of BFS as a by-product and the use of GGBS to create blended cements respectively. There is no clear consensus on how BFS (as well as other by-products) should be allocated. This means that both sectors are sometimes allocating environmental impacts within their system boundary, and sometimes outside of it. When allocation was considered, it was found that the cement sector most often utilized economic allocation and the steel sector utilized mass allocation. However, in the glass and plastics sectors, allocation of by-products is rarely considered. This makes current cross-sector comparison challenging and means technological advances cannot be properly assessed. This contradicts the core principles of LCA.

5.1.2. Inventory analysis

A common thread between studies across each sector is the frequent utilization of the same two basic methodologies: process-based and E-IO. These are both common but have known limitations. Process-based LCAs can be conducted using a process flow, or through a matrix method [219]. This works well for a simple product system, but industrial processes tend to have multiple input and output streams. In this case, the allocation of material flow becomes a challenge due to the large amount of data required to fully satisfy the system boundary. Consequently, the method is known to suffer from error truncation, which can hamper long term decisions for policy making or comparative assessments [143]. E-IO was devised to counter these issues by considering the whole product supply chain within an economy [220]. However, this can suffer from detail limitations due to the scale of data [221] required and the fact that E-IO datasets are not regularly updated [143]. A small number of studies within each sector have understood these limitations and made use of more novel techniques such as hybrid methodology. These may provide a more holistic view on the material's environmental impacts through the evaluation of a wider system boundary. The reasons for this limited uptake could be numerous but is likely due to a lack of method standardization beyond detailed academic studies and limitations presented by the software found to be most commonly used [144,222].

Across all retrieved studies, there is a mixture of reported data sources. Less than half reported using primary data, with only a small group reporting the data supplier. However, the majority did not include this information, often citing data security concerns. It was also found that raw data is often not published; however, this trend is reversing in recent years with a move toward open access publication [223]. This means there is a concerning lack of transparent primary data being used in studies which are important levers for decision making toward industrial decarbonization. As noted, many studies also utilize secondary data. However, it is a known issue that large databases are not kept up to date which could create additional issues with study comparison and validation [224].

The quality and accuracy of an LCA is directly related to the quality of the data collected. However, most of the retrieved studies struggled to demonstrate sufficient, objective quality checks on their data; and in most cases, do not mention it at all. In ISO 14044, specific requirements are outlined in regard to data quality, particularly studies that are publicly released and used in comparative assertions. Quality checks are designed to classify data sources based on the relevance and reliability of data and to better understand the uncertainty created by using certain types of data. This includes assessing the time period, geographical coverage, technological coverage, consistency, and reproducibility of the data used in an LCA study among other data quality checks [13,141]. In the cement sector, only a fifth of the evaluated studies explicitly mentioned the importance of data quality or conducted a qualitative data quality assessment. A small number opted to extend this evaluation further by conducting a quantitative data quality assessment such as conducting a pedigree matrix evaluation [172,206]. Similarly, in the steel sector, a quarter of studies mentioned the issue of data quality [42,162]. However, only a fifth of these studies opted to complete a full data quality assessment but typically only using qualitative techniques [40]. Despite the noted importance, a data quality assessment was not conducted in any retrieved glass sector studies. In the plastics sector, roughly 18 % of retrieved studies explicitly mentioned data quality, with a small percentage performing a formal data quality assessment utilizing a pedigree matrix [116,141,169]. As a result, the majority of data is being left unscrutinized. Inevitably, this leaves uncertainty over the reliability of some data (both primary and secondary). This is particularly true within studies which focus exclusively on production sites [41,65,104] that should otherwise be the example case for the open publication of data. This issue limits how LCA methods can be used to make informed decisions about the impacts of different technologies and processes. It is important for studies to prioritize data transparency when possible and assess the reliability and credibility of all data sources to ensure accurate findings.

5.1.3. Impact assessment

Across the retrieved studies, the most utilized impact assessment methodologies were CML, IPCC, and ReCiPe. Some studies elected to use a combination of methodologies to satisfy their study goals. However, there are technical differences between each methodology [23,225]. One study opted to directly compare different methodologies and assess the outcomes as part of a sensitivity analysis, and found that the results were very similar across all categories included [147]. This suggests that the reason behind choosing a particular methodology is often practitioner driven, and typically only down to meeting study goals. There were also a wide variety of midpoint impact assessment categories evaluated, the most common being GWP. A number of retrieved studies chose to only report categories directly related to climate change, which could be down to an absence standardization [226]. Other common categories varied depending on the sector; for example, the cement, steel, and glass sectors often assessed acidification potential and eutrophication potential, whereas the plastics sector typically assessed freshwater ecotoxicity potential and terrestrial acidification potential. Furthermore, there are two distinct methods of reporting these results: through graphs or numerical values. The latter of these is much clearer but is less common. There is also discussion about how each methodology employs distinct characterization factors to convert emissions or resource use into single scores [227]. These factors are often derived from different scientific models, databases, and assumptions, which leads to differences in single score values for the same processes [228]. Although each of these issues is often down to the sector and study goals, this level of variation in category and reporting choice can make comparative assertions between studies challenging. Furthermore, only a fifth of retrieved studies reported an endpoint impact assessment category. Although midpoint categories are typically more detailed and therefore have a lower overall uncertainty associated with them [229,230], endpoint categories are crucial to making long-term decisions about product processes. The most common methodologies used to report endpoint categories were Eco-Indicator, IMPACT, and ReCiPe; meaning that some studies changed methodologies between midpoint and endpoint.

5.1.4. Interpretation

Most retrieved studies only completed a variation of qualitative interpretation. That is, making comments on the results found without the associated statistical error and uncertainty. Less than half of all retrieved studies completed a sensitivity analysis which is critical in understanding the accuracy of the results. Even fewer completed an uncertainty analysis which should be used to understand the potential errors in input data. The lack of implementation of these key requirements is concerning. This stage is critical to not only verify that the results align with the defined goal and scope, but also to identify and correct any mistakes. The limited implementation of this stage across all sectors suggests that all sectors are facing the same challenges with fully implementing the interpretation step. In addition, it was determined that only a fifth of all retrieved studies opted to evaluate future scenarios by conducting a predictive LCA [148,182,231]. This LCA approach should be examined more thoroughly as industrial decarbonization becomes critical.

5.1.5. Standards

Many retrieved studies reported using an LCA related standard; typically, either ISO 14040 [11] and/or ISO 14044 [13]. As mentioned, despite this good level of 'on the surface' compliance with the existing framework, a significant number of these studies do not fully follow the standardized methodology. Concerningly, a quarter of all retrieved studies reported using either an unnamed standard or do not mention a standard at all. This mixture of standard compliance, standard use, and underreporting of standard utilization means that cross-sector comparison is stifled at a fundamental level.

Observing how LCAs are conducted in academia compared to industry further highlights key differences in the implementation of the standardized methodology. LCAs created for industry are required to follow a strict set of guidelines to publish the findings as an Environmental Product Declaration, which are published in accordance with ISO 14040 [11] in addition to PCRs [81] which provide guidelines for each product category. A rigorous third-party review by experts is also required for certification. These requirements, which are notably absent in academically published LCAs, illustrate the lack of robustness present in established practices. Only two retrieved studies followed PCR guidelines [66,232]. There are efforts to harmonize academic and industrial frameworks. For example, the Partnership for Carbon

Transparency Pathfinder Framework attempts to integrate existing standards and guidelines to enhance several key criteria including data quality indicators, emission calculation methods, allocation procedures, and decarbonization incentives [233]. It is critical that harmonized approaches continue to be pursued within the LCA community to enable effective and transparent LCA studies.

5.2. Study limitations

Whilst the retrieved articles provide a comprehensive review of the energy-intensive sectors of interest, there are limitations within the methodology which may influence the outcome of the study. Achieving a keyword string which is both general yet specific is challenging, and the boundaries chosen may have artificially limited study retrieval; however, the large number of relevant studies accessed would suggest that any artificial limitation on study retrieval is not substantial. While this is the case, it should be noted that there were significantly fewer studies retrieved from Africa and some parts of Asia, likely due to a lack of accessible literature available from those regions that focused on the chosen energy-intensive sectors. As a result, a bias towards studies conducted on western, industrialized nations is apparent. Similarly, the search criteria deliberately limited results to only peer-reviewed journal articles given the large quantity of studies available, and the need to focus on high quality, peer-reviewed research. However, this was observed to be a particular limitation in regard to retrieval of studies focused on the glass sector, and had this criterion not been included, the resulting search criteria may have resulted in more studies for analysis. Furthermore, analysis of the chemical sector was restricted to studies related to plastics. Although a significant portion of the chemical sector is dedicated to plastic production, there are several other product areas which would benefit from detailed analysis. Future research can expand on not just these sectors but also other energy intensive sectors such as paper, ceramics, and other metals. As noted within the methodology, this study deliberately excludes the analysis of impact category values. Although outside the scope of this research, analysis of impact category values would allow future studies to be benchmarked against a wide selection of literature from each energy-intensive industry.

6. Conclusion

This study investigated the implementation of LCA methodology across four, key global energy intensive industries: cement, steel, glass, and plastics. An SLR methodology was implemented using a novel keyword string. The challenge of generating a string that captured a wide range of keywords was solved through the use of sector specific terms. This string enabled cross-sector retrieval of studies specifically focused on production of materials within the aforementioned sectors. Following this, studies were objectively inspected through a bibliometric analysis using VOSviewer. Studies that were duplicate, off topic, non-compliant, and non-accessible were removed. The final taxonomy yielded 256 unique journal articles for further analysis.

The findings revealed significant contrast across the four sectors and the implementation of the standardized LCA methodology:

- Goal and Scope: A declared unit of mass was most commonly selected; however, this unit was often incorrectly labeled as a functional unit. Despite being a key aspect of material performance, functionality was rarely defined as part of the functional unit. ‘Cradle-to-gate’ was the most commonly used type of system boundary. When an allocation procedure was selected for a by-product, it was found that the steel sector most often used mass allocation and the cement sector frequently selected economic allocation. In the remaining sectors, an allocation procedure was typically not specified.
- Inventory Analysis: The process-based method was the most commonly employed LCA type to create an life cycle inventory. Several retrieved studies in each sector did elect to use alternative methodologies including E-IO and hybrid. Primary data sources were used by approximately half of all retrieved studies. However, most either wholly or partially relied on secondary data. Nearly all assessed studies utilized an industry standard software package, typically SimaPro or GaBi. The number of retrieved studies that carried out data quality checks were significantly limited. Among the few that did assess the quality of their data, the pedigree matrix emerged as the preferred method.
- Impact Assessment: Impact assessments were completed by all assessed studies. A range of methodologies were used to report midpoint indicators, such as CML, IPCC, and ReCiPe. A diverse range of impact assessment categories have been reported within the retrieved studies. Only a fifth of assessed studies calculated an endpoint indicator. The lack of uniform reporting (in terms of methodology, category, and style) makes comparative assertions difficult.
- Interpretation: Less than half of retrieved studies elected to conduct a sensitivity or uncertainty analysis. Many qualitative and quantitative approaches were taken, with no clear consensus on how to complete either interpretation stage.

Ultimately these findings show that a consistent approach to meet the existing LCA standards is lacking. While this study focused on the cement, steel, glass, and plastics sectors, it is expected that this lack of consistency will be similar in other industrial sectors. Therefore, key recommendations are outlined which will allow for greater transparency and comparative value for future LCA studies across all industrial sectors and products:

1. Although different functional unit types are appropriate under the right circumstances, they must be properly defined. This is imperative in comparative assertions; therefore, this aspect of ISO 14040 should be very rigorously observed when conducting a study.
2. It has been identified that allocation procedures for by-products used in two or more sectors should be intrinsically linked. This influences how and where some product impacts are attributed. Therefore, LCA practitioners must seek to properly allocate by-products in a consistent manner; particularly where products enter the life cycle of another product.
3. The majority of studies in energy intensive industries are likely to be focusing on a production site, therefore making use of the ‘cradle-to-gate’ boundary. As the importance of the circular economy principle grows, a ‘cradle-to-cradle’ system boundary would provide a more holistic view of a product’s life cycle.
4. It is clear that energy intensive industries have not always worked synergistically, despite the benefits of systems symbiosis; likely due to the complexity of modern supply chains. To allow for this approach, the system boundary and functional unit of a study must be defined with this in mind. This will allow for cross-sector analysis by combining studies to build a wider system boundary (e.g., using steelmaking BFS to create low carbon cements and glass flux), whilst retaining the accuracy of single product studies.
5. A high quality LCA can only be completed with high quality data, which is typically from a primary source. However, there is a clear challenge with allowing open access to sensitive industrial data. Therefore, the academic and industrial LCA community must work together to find a solution.
6. Data quality should be assessed objectively. This is paramount to understanding how confident a reader can be in the result of an LCA study. At a minimum, this should be done in line with ISO 14044 by assessing data on factors such as temporal, geographical, and technological relevance qualitatively. However, to be as effective as possible, this should be done using a quantitative

technique such as a matrix evaluation. Assessing data in this way enhances effective comparative assertions and helps build public confidence in studies.

7. Greater uniformity in impact assessment methodologies, impact assessment categories. and reporting methods would be highly beneficial. There is no standard approach to selecting either a methodology or reporting categories which stifles comparison on a fundamental level.
8. Interpretation is the most critical step in the LCA framework. Sensitivity and uncertainty assessments should be completed and reported as stated in ISO 14040 and ISO 14044. Confidence in results should be reported to enable transparent decision making.
9. The implementation of LCA methodology by academic and industrial practitioners should seek to converge through the improved selection of system boundaries, impact categories, and interpretation methods. This should be done using stringent guidelines taking inspiration from industrial PCRs.
10. A greater focus should be placed on future production processes and technology.

This research has generated several recommendations for improvements on current LCA practice, particularly in energy-intensive industries. While these are only recommendations, effective implementation of current and future LCA methodologies will offer the opportunity to carry out these suggestions. Further work should seek to address limitations and build upon this research by assessing impact category values within each sector to establish benchmark values. This will pave the way for an integrated research direction towards net zero, through effective cross-sector comparison and using the LCA technique as a critical decision lever.

CRediT authorship contribution statement

Madeline C.S. Rihner: Conceptualization, (lead), Data curation, (equal), Formal analysis, (cement sector, Methodology, supporting, Writing – original draft, equal. **Jacob W. Whittle:** Conceptualization, supporting, Data curation, (equal, Formal analysis, steel sector, Methodology, lead, Writing – original draft, equal. **Mahmoud H.A. Gadelhaq:** Conceptualization, supporting, Data curation, equal, Formal analysis, glass sector, Methodology, supporting, Writing – original draft, equal. **Su Natasha Mohamad:** Conceptualization, supporting, Data curation, equal, Formal analysis, plastics sector, Methodology, (supporting), Writing – original draft, equal. **Ruoyang Yuan:** Writing – review & editing. **Rachael Rothman:** Writing – review & editing. **David I. Fletcher:** Supervision, Writing – review & editing. **Brant Walkley:** Supervision, Writing- Review and Editing. **Lenny S.C. Koh:** Project administration, Supervision, Writing- Review and Editing.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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