A survey of the life cycle assessment of food supply chains

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ARTICLE INFO

ABSTRACT

Food supply chains have substantial impacts on our environment, using large amounts of fossil fuel and other non-renewable resources, as well as water and land. Food supply chains are also complex systems, and their evaluation thus requires a study of the entire system, from primary production to end-of-life food-waste solutions. This paper examines the current state-of-the-art of the published food supply chains Life Cycle Assessment studies and their quality and coherency with the existing standards from the methodological perspective. In particular, we have followed the framework of the International Organization for Standardization, and considered the standard's requirements, emphasising goal and scope, inventory, life cycle impact assessment and interpretation. We have surveyed forty-nine research and review papers, sourced from the Web of Science. Additionally, we have carried out a content analysis, identifying research areas and existing research trends. The results identified possible improvements in terms of goals and scope, as well as inventory and life cycle impact assessment, to increase the consistency and reliability of studies. These studies, in turn, affect a transparent and sustainability-oriented decision-making process, which is essential at various levels — company, stakeholders, national and global. Concept maps reveal the most dominant research directions, which are production, use, system and packaging. Missing is a role of socio-economic effects, as food life-cycles include societal and economic functions as well as circular economy options, during production or end-of-life processes.

1. Introduction

The food sector is an intensive primary resource user, and we cannot ignore its impacts on sustainability. Food production is one of the primary drivers of global environmental concerns (Egilmez et al., 2014). Around 70% of the European Union's agricultural yield is destinated to the food sector, which employs over four million people. Moreover, the food market is valued over €215 billion, positioning it in the top ten largest world markets (McCarthy et al., 2015). Due to its diversity and complexity, moving towards a sustainable food system is challenging (Miah et al., 2018). Existing food supply systems depend on fossil fuels and non-renewable resources (Markussen et al., 2014) and cause the depletion of groundwater and soil loss (Holden et al., 2018). The food-processing sector is responsible for around 20% of greenhouse emissions, and it will expand to satisfy the world's food demand in the upcoming years (Biswas et al., 2016). According to the EU Commission, the food sector contributes to 23% of global resource use and to 31% of acidifying emissions (Bengtsson and Seddon, 2013). In parallel to resource consumption, an enormous quantity of waste is generated along the food supply chains (Noya et al., 2018). The food sector is exceptionally varied: different sub-sectors result in environmental impacts with other extensions. For instance, chicken production has the lowest resources consumption per live weight, generating 8% of greenhouse gas emissions (MacLeod et al., 2013), while beef production generates 29% and pork production 72% (López-Andrés et al., 2018). Dairy sector significantly contributes to global warming by producing 2,7% of worldwide anthropogenic greenhouse gas emissions (Milani et al., 2011). Environmental burdens are often overlooked: the increased production of field-grown salads and vegetables in the Mediterranean area is responsible for water supply damages, soil salination increase and water quality decrease (Webb et al., 2013).

The main challenge is how to decrease environmental impacts

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while increasing food production (Putman et al., 2017). Moreover, a transition from fossil fuel to sustainable resources in the food system is necessary (Holden et al., 2018). To achieve these goals, an understanding of energy consumption and resources contribution to environmental burdens is fundamental (Keyes et al., 2015). Thus, in-depth knowledge of the entire supply chain is of utmost importance, from primary production to consumption (Hessle et al., 2017), also considering circular economy principles. In response to food systems complexity, different research tools have been developed for analysing life cycles to measure their related impacts (Ruviaro et al., 2012). Life cycle assessment (LCA) has been commonly used for defining food supply chains impacts, taking into consideration food waste, global food industry environmental impacts and shipping distances to satisfy consumers demands all over the world (Park et al., 2016). It is considered to be one of the most informative tools to quantitatively compare the environmental performances of multiple food consumption strategies (McAuliffe et al., 2018), including raw materials consumption and emissions for energy generation (Zhao et al., 2018). LCA also identifies life cycle phases responsible for most relevant environmental impacts, aiming to determine highly specific solutions for all technologies adopted (McDevitt and Milà i Canals, 2011). Furthermore, LCA indicates the most critical processes and materials in the supply chain, improving food production environmental performances and suggesting better alternatives to minimise adverse environmental impacts (Park et al., 2016). Also, the European Parliament mentioned the LCA in the Green Deal (European Commission, 2020), calling on the Commission to develop life cycle assessment methodologies.

During the past decade, an increase in the popularity of LCA studies focusing on the food sector has been perceived (Biswas et al., 2016). These studies often represent low comparability, inventory data limitations, variability in food production processes, boundaries and functional units (Holden et al., 2018). However, final LCA results usually have an influence on the decision-making process in policy, consumer or producer perspective. Unreliable or non-transparent studies can bring confusions into the decision-making process, especially when considering resource usage and related impacts. Furthermore, Weidema (1997) argued that critical reviews of LCA studies have never been used. Also, van der Berg et al. (1999) claims that a consensus method for establishing the level of confidence in the LCA results is currently missing, as quality assessments usually cover only the quality of input data.

Inspired by these challenges in the food supply sector, an in-depth discussion on LCA is of utmost importance. Thus, our research questions were:

RQ1: How well the published LCA food supply chain studies comply (considering the quality) with the existing standardised methodology?

RQ2: What are the dominant research areas covered within the studies as well as future trends from the content perspective?

Recently, some review papers were published. Web of Science identifies eight review papers related to food sectors. For example, supply chain issues in SME food sector (Arun and PrasannaVenkatesan, 2020), LCA studies of dining out (Dai et al., 2020), achieving a sustainable performance of data-driven agriculture supply chain (Kamble et al., 2020) or a systematic review of life-cycle based approaches in the foodservice sector to improve sustainability (Takacs and Borrion, 2020). To our knowledge, a critical elaboration of food supply chain LCA studies has never been performed, nor the research trends in the field, based on the concept maps.

A systematic review of scientific literature was carried out to examine current state-of-the-art in the field, directions of LCA in food supply chains, and quality of the studies, which consequently

influences a decision-making process. We gave a focus to a holistic methodological approach to assure the reliability of the studies. Emphasis is given to all the phases, following the methodology in ISO 14040 and ISO 14044 (ISO 2006a; 2006b). The focus was given to the quality of functional units, inventory data, life−cycle impact assessment and impacts categories considered, taking into account spatial and temporal variability, which are extremely difficult to measure. This paper aims to scientometrically analyse LCA in the food supply chains, using the textual analysis tool Leximancer for interpreting and visualising complex data (Campbell et al., 2011) to explore dominant themes in the research field and propose future research directions.

We have systematically reviewed forty-nine scientific papers to identify challenges, knowledge gaps, research areas and topics. Besides, we suggest improvement options to existing barriers, to improve the LCA studies quality and to increase the reliability and confidence, consequently enhance decision-making processes in the field.

This paper develops in four sections, as follows: Materials and Methods describes data collection, descriptive and structural analysis, data evaluation with Leximancer software. Results represent scientometrics outcomes. Discussion elaborates the findings. Finally, Conclusions reports insights from the study.

2. Materials and Methods

Our research covers forty-nine scientific papers, published from 2009 to 2019, in which authors performed an LCA for a specific food product or product group. We have obtained the documents via the Web of Science (WoS), which represents the global dominant citation database. It includes Journal Citation Reports (JCR), comprehending high impact journals (Clarivate Analytics, 2019). In our research, we have considered only scientific papers and review papers, not containing monographs and conference proceedings. The period considered is suggested by the results obtained from the WoS. With the specified keywords we have found studies from 2009 on. The ten years could be considered to be valid for research according to the work of Albertí et al. (2019). In fact, LCA studies performed more than 15−20 years ago are incomparable, because of several issues, such as an update of assessment methodologies and characterisation factors, databases as well as improvements of environmental policies.

The research methodology follows a process proposed by Mayring (2003) and includes four steps:

1. Material collection − collecting material and determining one unit (single paper)
2. Descriptive analysis − providing background for a theoretical analysis
3. Structural dimensions − assessing the crucial topics of analysis, following the structure and issues listed in ISO 14040 and ISO 14044 (ISO 2006a; 2006b).
4. Data evaluation − analysing papers according to the structural dimensions, enabling identification and interpretation

Each step is further described hereinafter:

2.1. Step 1 and step 2: data collection and descriptive analysis

A total of 987 scientific papers were extracted from WoS, using the keywords "life cycle assessment" and "food supply chain". The review was carried out in January 2019. A single paper was determined to be one study unit. After extraction from WoS, conference papers, proceedings, and monographs were discharged, reducing the number of study units to 244. An in-depth investigation of the

papers revealed that not all were suitable for our study. Many were not including life cycle assessment as such, but only covering un-related topics: e.g. focusing exclusively on carbon footprint, water supply, biofuels or food packaging. The in-depth review process (Fig. 1) led to the selection of 49 papers (5% of the papers extracted from WoS).

2.2. Step 3: structural dimensions

The structure of LCA studies of each paper was characterised in terms of its components, following ISO 14040 and 14044 (ISO 2006a; 2006b). Thus, we have identified characteristics:

a) goal and scope of the study, including functional unit and system boundaries.
b) inventory data, and processes, including data acquisition, primary and/or generic data, databases, the relevance of the life cycle assessment links to the quality of the data.
c) life cycle impact assessment (LCIA), including impact categories selection, classification, and characterisation.
d) the interpretation of results.

2.3. Step 4: data evaluation

For performing contents analysis (conceptualisation) we have used Leximancer software, version 4.5. Leximancer determines the main concepts and correlations, conducting thematic and semantic investigations by using two co-occurrence information − semantic and relational (Smith, 2003). Thus, offering a deeper understanding for LCA and food supply chain narrative inquiry. The algorithms used in this software are statistical, integrating nonlinear dynamics and machine learning, determining the presence of concepts and forming categories and relationships (Angus et al., 2013). In the conceptual analysis, documents are examined for the concepts' presence and frequency, such as words, phrases, definitions, where a concepts list and relationships are visualised via a concept map (Hyndman and Pill, 2018). The themes importance is expressed by the circles colour and its size (a size indicates concepts clustered together). Concepts are connected to the theme in which they are positioned. The concepts distance indicates thier relationships (Biesenthal and Wilden, 2014). Thus, semantically weak associated concepts are mapped far from each other, whereas overlapping indicates very close concepts (Campbell et al., 2011). As explained by Baldauf and Kaplan (2010), the software is appropriate for exploratory research as it produces high concept extractions and thematic clustering reliability and reproducibility, avoiding possible biases that are typical of manually coded text analysis techniques.

3. Results

In this section, we represent the results of the in-depth analysis, including publishing frequency in the previous ten years, followed
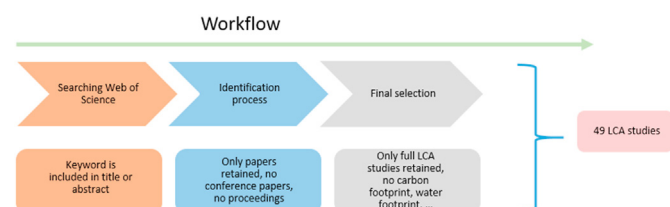

Fig. 1. Workflow followed in selecting papers of interest.

by analyses according to the LCA phases as a framework, and finally Leximancer thematic and semantic results. All variables describing LCA studies were reported in a specific supplementary material (Table 5). In details, it lists goal, target, functional unit, observed system boundaries, type of LCI data, database, software for calculation, LCIA method, impact categories and reference for each LCA study. Moreover, food type (e.g. tomato) and group (e.g. vegetables) are added to simply eventual searches.

3.1. Publishing frequency

Fig. 2 illustrates the distribution of papers per year. They increased from 2009 to 2019, showing the growing interest and need for LCA studies in the food sector. It can be observed that the trend over the years is positive, thus indicating that this line of research is becoming a hot topic with many implications for a more sustainable future. Studies are mostly conducted at food product level such as eggs (Pelletier, 2017), milk (Cecchini et al., 2016), cheese (Palmieri et al., 2017; Kim et al., 2013), oil (Salomone and Ioppolo, 2012; Tsarouhas et al., 2015), wine (Pattara et al., 2012; Neto et al., 2013), tomatoes (Neira et al., 2018; Bosona and Gebresenbet, 2018), or chocolate (Recanati et al., 2018; Konstantas et al., 2018). Furthermore, broader studies were perceived, covering food groups such as diaries, (Hessle et al., 2017); livestock, e.g. McAuliffe et al. (2018); fruits and vegetables, e.g. Stoessel et al. (2012); agri-food system, (Tasca et al., 2017); fisheries (Farmery et al., 2015; Fréon et al., 2017) and comparing home-made and ready meals (Rivera et al., 2014). Several papers also focused on meat supply chains (Lamnatou et al., 2016; Noya et al., 2017; López-Andrés et al., 2018; Wiedemann et al., 2015b).

Fig. 3 shows an overview of journals, published LCA studies of food supply chains. As represented, researchers mostly published their studies in the Journal of Cleaner Production (over 40%), followed by The International Journal of Life Cycle Assessment (12%). Researchers published 22% of studies in other journals, such as Journal of Food Engineering, Environmental Science and Policy, Food Research International, International Journal of Agricultural Sustainability, etc.

3.2. Goal and scope

The ISO standard 14040 (ISO 2006a) determines LCA goal and scope, including the aim, target audience, and observed system description. The reviewed LCA studies have various goals and scopes, which focus on identifying environmental impacts within food supply chains, e.g. (Neira et al., 2018). As all the studies defined
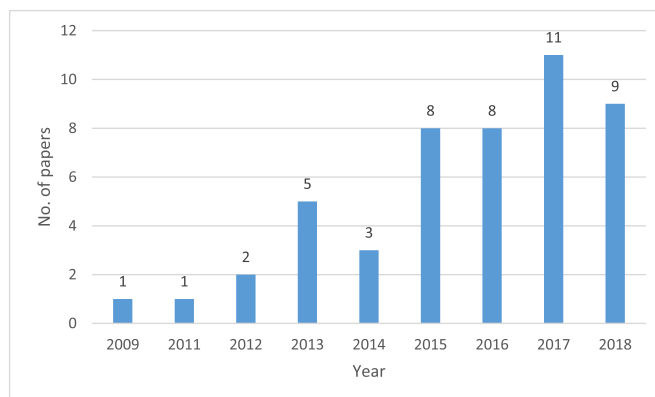

Fig. 2. The distribution of research and review papers included in this study according to their publication years.
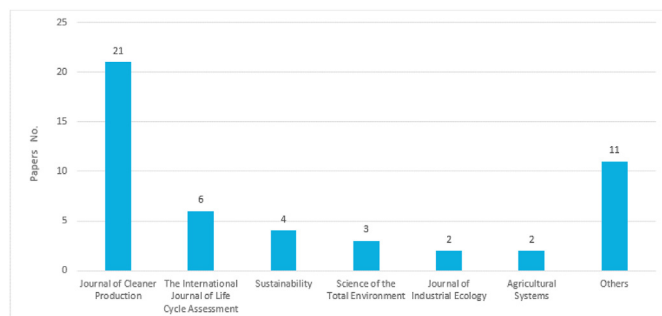
Fig. 3. Overview of leading journals, publishing LCA studies of the food supply chain.

their goals, only 10% papers considered the intended application in the goal and scope section, despite the fact, that this is determined by the ISO 14040 (ISO 2006a).

Target groups in the studies were mostly food consumers and producers to raise their knowledge and awareness about food's environmental impacts. However, 64% of the studies defined their target audience.

To sum up, most of the studies determined their goal and scope as quantifying environmental impacts and defining critical processes within supply chains. At the same time, a gap appears in clearly describing the intended application, which should be consistent with the goal and scope (according to ISO 14040). However, the intended audience is in the majority of papers clearly stated.

3.2.1. Functional unit and system boundaries

ISO 14040 (ISO 2006a) defines a functional unit (FU) as a quantified performance of a product system for use as a reference unit. A system boundary defines the unit processes included in the system, referring to raw material extraction, inputs and outputs in the central processing sequence, transport, disposal, material recovery, and additional operations (ISO 2006a).

In 85% of the reviewed papers, functional units are expressed in weight units such as grams (g), kilograms (Kg) or tonnes (t). For liquid food products (15% of the papers), e.g. milk, oil, or wine, the units are expressed litres (L) or millilitres (mL), often considering one bottle. Functional units are usually defined in detail with observed physical characteristics, e.g. dry, cooked, chilled or skimmed, live or dead animal, highlighting a product weight difference in various processes steps. All the studies defined the functional unit. However, the quality and specifcness of definitions vary. Most of the authors described a functional unit by quantifying product weight and form for commerce (raw, frozen, baked, packed, consumed), as food weight varies significantly through processes.

ISO 14044 (ISO 2006b) further determines that the LCA addresses environmental aspects through the product's whole life cycle from raw material to production, use, end-of-life treatment, recycling and final disposal, i.e. "cradle-to-grave". It explains that a partial LCA could be carried out with proper justification, for example, "cradle-to-gate", "gate-to-gate", or studies of specific supply chain parts. System boundaries identification is one of the essential steps in an LCA and relies on the particular challenge and question (Klöpffer and Grahl, 2014). When defining system boundaries, the objective must be to include in the system the activities relevant to the purpose of the study. Thus, the choice of system boundaries is closely related to the goal definition (Tillman et al., 1994). Supplementary material (Table 5) indicates that 74% of studies considered "cradle-to-gate", covering production (from raw materials) and transport to the consumer, while only 26%

considered "cradle-to-grave". Besides, 55% of the studies included diagrams of system boundaries.

To outline, all of the empirical studies defined their system boundaries, but the quality and basis for chosen system boundaries are poorly represented. Köpfer in Grahl (2014) explained a necessity for cut-off criteria, regulating the exclusion of insignificant inputs into the system. The proportion of 1% (mass, energy, etc.) of the overall system is chosen as the cut-off criterion and that the portion to be cut off shall not exceed 5% per unit process (Köpfer in Grahl, 2014). 90% of the studies do not explicitly state, on which basis or rule their system boundary was determined. We can claim that all the studies considered system boundaries, which were consistent with their goal and scope, as they mostly focused on analysing a part of their observed supply chain. Surprisingly, information about the cut-off criteria, especially on how and which processes were included in the evaluation, how in-depth they embraced the processes in the supply chain, where not perceived or explained. Weidema et al. (2004) states that the functional unit should relate to the function of the product rather than the physical product. PEF Guide (European Commission, 2013, 2016) proposes requirements to define the functional unit properly. These requirements are to follow the questions: what (the function/service provided), how much (extend of the function or service), how well (level of quality), how long (the duration or lifetime of a product). Besides, Weidema (2017) suggests a three-step procedure for defining a functional unit, which is: identifying a market segment and obligatory product properties, and expressing the functional unit as a quantity of the product, as defined by the compulsory product properties.

3.3. Inventory analysis

The inventory analysis consists in inputs and outputs compilation, qualification and quantification, which are represented via resources, materials, emissions in the observed supply chains (ISO 2006a; Ingrao et al., 2018). Thus, LCA relevance is directly connected to the inventory data (Wiedemann et al., 2015). Considering that food supply chains are very complex, dynamic, and involve many various stakeholders, data unavailability, is likely to occur. Furthermore, ISO 14040 (ISO 2006a) states that such issues may be identified in this phase, and that goal or scope revision is sometimes required.

In the reviewed papers, most authors firstly determined primary (i.e. directly collected from the analysed system) and generic data (i.e. from existing databases). Product environmental footprint (PEF) guides specify for which processes primary (i.e. specific) or secondary (i.e. average or proxy) data are used. Primary data are site-specific, company-specific or supply-chain-specific. Using generic data is acceptable if a specific raw material origin is not known (Klöpffer and Grahl, 2014). Primary data were usually obtained from companies, farms, or organisations via different forms. Secondary data were mostly collected in other international databases, representing information about raw materials and energy eco-inventories. In Table 1, the databases used for generic data are shown, including both literature data usage and existing secondary databases. The most common database to determine environment consequences was Ecoinvent, usually used with SimaPro or GaBi software, following the Intergovernmental Panel on Climate Change (IPCC). It can be observed that 16 papers also used data from previous publications in the field.

As studied by Lasvaux et al. (2015), choosing generic or product-specific LCA databases is of major importance, influencing LCIA results. Current generic databases can present very different values, which depend on the type of environmental indicator or category. For example, in LCA of buildings sector can influence on POCP

Table 1
Secondary databases used in numbers.

Secondary database	Papers No.
Ecoinvent	39
IPCC database	18
Existing published literature	13
Agri-footprint	2
Australian Government's National Pollution Inventory (NPI, 2002)	1
World food LCA base	2
AustLCI database	2
Swiss Agricultural Life Cycle Assessment Model	1
Danish LCA food database	1
Department for Environment, Food and Rural Affairs (DEFRA, 2012),	1
National Resources Defence Council (NRDC, 2014)	1
World resources institute (WRI, 2004)	1
2014 Baseline Emission Factor for Regional Power Grids in China	1
GaBi professional database	1
European life cycle database	1
LCA food database	1
OEF Sector Rules Retail database	1
World resources institute	1
US LCI database	1

(photochemical ozone creation potential) or ADP (abiotic depletion potential) elements significantly, where results sometimes deviate for more than 100% (Lasvaux et al., 2015). When only secondary data are used, e.g. for material acquisition, these processes cannot reflect credibility in the modelling, because it means that real high environmental impacts might be hidden by average data coming from existing databases (Bach et al., 2018). Thus, a minimum processes list (called mandatory processes) shall always be covered by company-specific data. The purpose is to avoid that study is performed without access to the relevant site-specific primary data and that its results communicated following only the application of default data. Especially in the food industry, circumstances, energy inputs and material usage, locations (even in the same country or region) differ. Data sets usually do not include detailed specifications, and obtained results can be misleading even for the same product.

3.4. Impact assessment and interpretation

ISO standards describe the LCIA framework, consisting of mandatory (characterisation) and optional (normalisation and weighting) elements. Selection of impact categories depends on the authors choice, and it is based on data availability and the goal of the study (Klöpffer and Grahl, 2014). Table 2 shows different LCIA methods used in the studies, categorised into midpoint, end-point, and combined methodologies. Problem-oriented methods have midpoint impact categories and model problems at an early stage in the cause-effect chain. End-point methods are damage-oriented and have a narrowed set of categories, which address damage to humans and ecosystems. In contrast, combined methods include both approaches: problem and damage orientation (Monteiro and Freire, 2012). Table 2 indicates that most frequently used LCIA were as follows: ReCiPe (20%), CML (16%), and IPCC (12%). Less frequently used methods in food supply were TRACI and BP LCI. Authors also often combined two or more methods, e.g. CML and EDIP, CML and Eco indicator 99, etc., where CML was the most frequently used.

Different LCIA adopted in the papers result in different sets of impact categories assessed. Specific impact categories, such as human toxicities and ecotoxicity, are susceptible to LCIA methods. Various methods may produce different results (Dreyer et al., 2003). The selection of impact categories shall reflect a comprehensive set of environmental issues related to the system studied

Table 2
LCIA methods used in numbers.

LCIA	Papers No.
Midpoint methodologies	
- CML	8
- ILCD	4
- TRACI	1
Combined mid and end-point	
- ReCiPe	10
- IMPACT 2002+	2
Other LCIA	
- IPCC	6
Ecological footprints	4
- BP LCI	1
Combined methods	
- CML + EDIP	1
- Eco indicator 99	1
- CML + IPCC	4
- CML + ReCiPe	1
- CML + IPCC + EDIP	1
- ReCiPe + TRACI	1
- Australian indicator set, IPCC	1
- IPCC + ReCiPe	1

and the impact categories are environmentally relevant, internationally accepted and avoid double counting Stranddorf et al. (2005). LCA study is more comprehensive when a broad set of impact categories is considered.

Tables 3 and 4 represent the impact categories of selected papers. Only a few authors used all the impact categories defined by the selected LCIA method. Table 3 indicates the considered impact categories using the CML method. Most frequently and equally employed were GWP, acidification, and eutrophication. These impact categories were followed by terrestrial ecotoxicity, human toxicity, ozone depletion, photochemical ozone formation, aquatic ecotoxicity, and freshwater aquatic ecotoxicity.

Table 4 shows that within the ReCiPe method authors most frequently considered climate change, followed by terrestrial ecotoxicity, ozone layer, photochemical ozone formation, etc. Only in two cases reviewed urban land occupation, metal and fossil depletion were emphasised.

IPCC methodology focuses only on climate change, and it was used in 26% of papers. Its results are expressed in terms of global warming potential (GWP) within a frame of 100 years (Bastianoni et al., 2014). TRACI was the less frequently employed LCIA

Table 3
Impact categories within the CML method used in numbers.

Impact category	Papers No.
Global warming potential	13
Acidification	10
Eutrophication	10
Terrestrial ecotoxicity	7
Human toxicity	6
Ozone depletion	6
Photochemical ozone formation	5
Abiotic depletion	5
Aquatic ecotoxicity	4
Freshwater aquatic ecotoxicity	4

method, where authors considered impact categories such as global warming, followed by ozone depletion, climate change, eutrophication, ozone layer depletion, and land occupation. 28% of studies represented within the impact categories energy-related indicators, such as Cumulative Fossil Energy Demand (CED), characterising a screening impact indicator via energy demand within the product life-cycle (Huijbregts et al., 2006). It is usually calculated as the energy utilisation of non-renewable and renewable energy sources Ingrao et al. (2018). CED can serve as a screening indicator for environmental performance, but its usefulness as a stand-alone indicator for environmental impact is limited. The PEF Guide European Commission (2018) further suggests that the identification of the most relevant impact categories shall be based on the normalised and weighted results, and at last three relevant impact categories shall be considered.

The high variability of impact categories investigated and the lack of explanation for their decisions might suggest that they were selected without following any precise predefined scheme. Only a few authors, e.g. Miah et al. (2018) or Noya et al. (2017), explained the impact category selection process, as well as Burek et al. (2018) and van Putten et al. (2016), refer to previously published literature as an impact category selection argument. However, a selection of the impact categories requires a precise selection as results obtained have an impact on the decision-making process, leading to improvements and strategic actions.

Interpretation consists of analysing findings from the inventory analysis, and impact assessment, and is considered to identify significant impacts and evaluate results through completeness, sensitivity, and consistency. All the authors carried out an interpretation of results, identifying processes, with substantial

Table 4
Impact categories within the ReCiPe method used in numbers.

Impact category	Papers No.
Climate change	9
Terrestrial ecotoxicity	9
Ozone layer depletion	8
Photochemical ozone formation	8
Human toxicity	7
Freshwater ecotoxicity	7
Terrestrial acidification	6
Water depletion	6
Freshwater eutrophication	5
Marine ecotoxicity	5
Marine eutrophication	5
Natural land transformation	4
Ionising radiation	4
Agricultural land occupation	3
Particulate matter formation	3
Urban land occupation	2
Metal depletion	2
Fossil depletion	2

contributions to the selected impact categories. ISO 14044 (ISO 2006b) also requires a data quality assessment. Thus, it is necessary to make any potential data weakness transparent. 41% studies contained sensitivity analysis, but only 14% uncertainty analysis, which due to Konstantas et al. (2018) assess the robustness of the results against a plausible range of variations in different LCI parameters. Consequently, other parameters influencing the results could be considered and discussed in the study.

Within our study, we were also trying to identify patterns regarding methodological flaws and useful examples. From the development perspective regarding the time perspective there were no patterns, showing that the recent studies were better considering compliance with the ISO standards. However, we might find patterns between good examples of LCA studies and journals with high impact factors. In the majority, we have perceived good examples in the International Journal of LCA and the Science of the Total Environment. Also, Journal of Cleaner Production published some papers, which are almost entirely compliant with the methodological issues.

3.5. Content analysis

Forty-nine papers were examined using Leximancer software to identify the main concepts related to LCA and food supply chains. The concepts were then grouped into high-level themes, which were identified by the software. Fig. 4 illustrates the results of the content analysis: each black dot represents a concept, and each circle represents a theme. All dots within the theme are clustered together.

The contents analysis indicated that the most dominant themes are the following, from the most relevant to less significate: *production*, *use*, *system* and *packaging*. In the *production* theme, the concepts of 'environment', 'product', and 'impacts' are closely related, which reminds the main LCA goal. Moreover, other recurring relevant concepts are 'systems', and 'industry', 'global', which might testify the perspective of the approach of the LCA studies. In
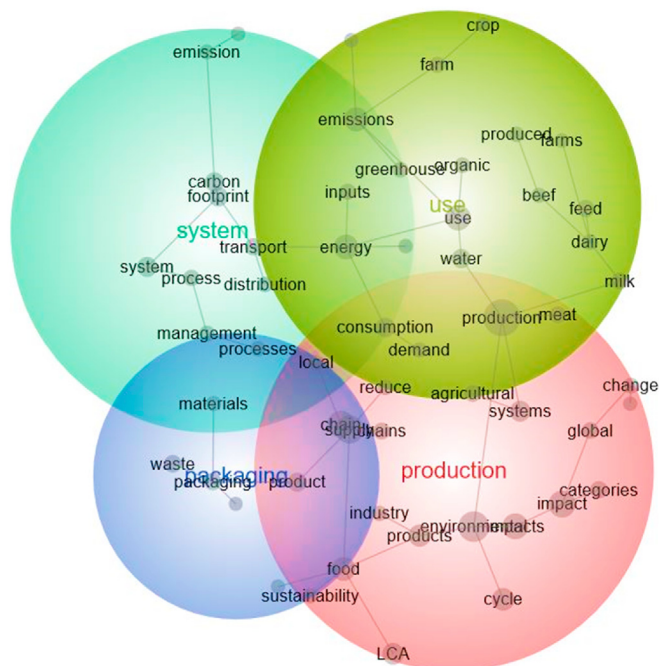

Fig. 4. The conceptual map obtained utilising the Leximancer software reveals four high-level themes, namely production, use, system, and packaging.

the theme *use*, concepts such as 'water', 'energy', and 'organic' are related to the resource used. The strong correlation between the concepts of 'transport', 'energy', and carbon footprint' is highlighted in the theme *system*. It is also discussed in the studies of Neto et al. (2013); Pelletier (2017); Rivera et al. (2014), and Pattara et al. (2012). Many authors also carried out carbon footprint calculations (e.g. Pattara et al., 2012, Stoessel et al., 2018; Farmery et al., 2015, Perez-Neira et al., 2018), showing a strong connection to the theme. The concept of 'management' is of great interest. In fact, it suggests that environmental performance is strongly depended on system management. The fourth central theme is *packaging*, in which 'waste', 'product', 'materials' are closely related. When carrying out an LCA, authors such as Biswas and Naude (2016), López-Andrés et al. (2018), and Palmieri et al. (2017) mentioned the importance of packaging and its burden to the environment.

A more in-depth analysis focused on the nodes connecting concepts (the grey bars linking dots), which represents a measure, a relative strength indicator of a concept's occurrence frequency. As indicated, 42% of the texts containing the concept 'production' also contains the concept 'beef', 'agricultural' (relevance at 39%), 'systems' (relevance at 38%) and 'feed' (relevance at 37%). We can explain this by knowing that food production usually starts at the agricultural level and is related to the systems that manufacturers have established to produce food. As mentioned, most of the studies considered the impacts of producing the feed for the animals. Accordingly, the production of food is strongly connected with the concept of 'feed'. There are also intersections among themes, identifying concepts, which have high relevance for respective themes. For example, 'energy' or 'emissions' are relevant in both *systems* and *use*.

Particular attention was given to the 'LCA' concept (Fig. 5) and its relevance and likelihood of other concepts. As indicated, 18% of the texts containing the concept 'LCA' also incorporate the concept 'food', as expected from the selection of the "keywords". Then, 'agricultural' (relevance at 14%) and 'sustainability' (relevance at 12%) are following. The concept 'agricultural' appears as there is a strong correlation between food supply chains and the agricultural sector. The relation with 'sustainability' concept is supported by the fact that LCA assists in identifying opportunities to improve the supply chain environmental performance.

4. Discussion

Literature review results on LCA and food supply chain give an in-depth overview of the LCA methodology employed and its compliance with the ISO standards. Besides, it illustrates that research on LCA and supply chain reveals numerous interrelated concepts and themes, defining research trends and coverage as well as further opportunities towards sustainability.

4.1. LCA methodology

Most studies defined a functional unit, determined by a product's weight or volume and were insufficiently specified and related to product performance. The results are in line with the outcomes of Holden et al. (2017), claiming that one of the issues associated with the LCA of food supply chains is being able to define the product function correctly. In the studies reviewed, we have not perceived a three-step procedure regarding the functional unit, as suggested by Weidema (2017) nor the suggestions by the Product Environmental Footprint (PEF) Guide requirements (European Commission 2013, 2016).

The LCA study should comprehend the whole life cycle, as suggested by the ISO 14040 and 14044 (ISO 2006a; 2006b), but it
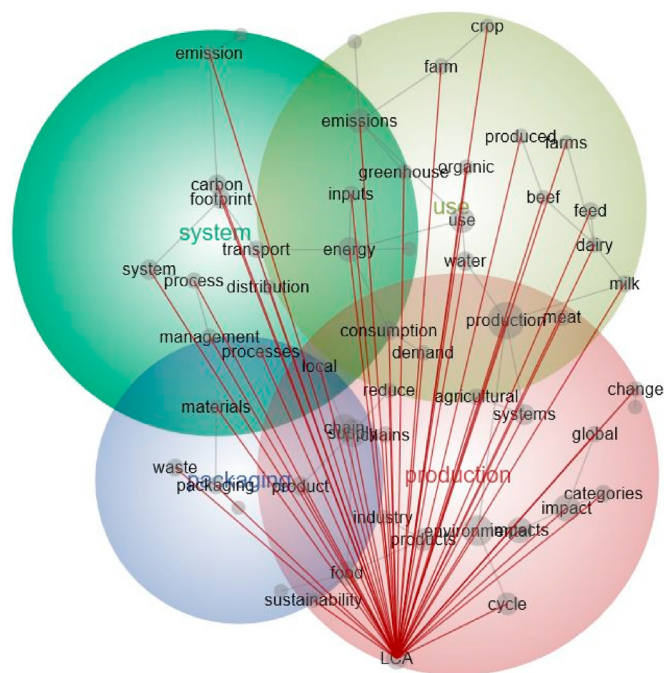

Fig. 5. A network-based visual representation of concepts that are connected with LCA.

was considered only in only 26% of examined studies. 74% of studies emphasised cradle to gate, generally excluding use and end-of-life stages, especially those related to diaries (consumption habits) and waste. Furthermore, to account for shipping distances, the average value was always used. However, this might reduce the reliability of results. No explanations of cut-off criteria or system boundaries were perceived in the forty-nine papers. This aspect represents a critical weakness that affects LCA results and that increase the complexity of comparing outcomes significantly. As explained by Li et al. (2013), results must be interpreted considering the boundaries of the analysed system.

Scope and goal definition presented fewer difficulties, as all studies suggested evaluating the environmental performance of the observed systems. Most studies addressed target audiences (e.g. companies, stakeholders, governments or other decision-makers). Studies were also used to improve the decision-making process, which is one of the goals to achieve more environmentally friendly processes. However, when adapting limited LCAs, decision-making processes can be vague (Holden et al., 2018).

The inventory procedure is very complex for the food supply chain, and it sometimes requires collaboration between several stakeholders along the food supply chain (Holden et al., 2018). In the reviewed papers, authors focused more on production stage rather than end-of-life, due to greater availability of the inventory data for the production. Collecting data for the inventory phase was problematic in several papers. Some authors obtained their data only from the literature or data sets, and data quality and reliability for the observed system become a concern. Consistency and quality, as well as data quality assurance (i.e. review), are essential requirements that support valid studies JRC-IES (2010). However, it should be noted that using the same existing database for the observed systems may increase the comparability of the results, as the same data can be used in more studies.

Another cause of differences among LCA studies of food supply chains is the impact category selection. It was observed that only a few studies included all the impact categories within the selected

LCIA methodology, and the selection process of impact categories was rarely adequately augmented. The authors mostly focused on global warming potential (GWP). However, to obtain a comprehensive impact overview, especially in a food supply chain, the consideration of other impact categories related to land use and water pollution is of utmost importance, and neglecting them might be misleading. It is necessary to point out that in 37% of studies, we observed an "energy-related impact category" such as, CED, non-renewable energy demand, etc., which is arbitrary. Only 16% of reviewed studies included normalisation and weighting steps, as these steps are denoted as optional in ISO standards. Only a few authors included uncertainty and sensitivity analyses.

In order to assure LCA studies' comprehensiveness in the food supply chains, improvement options are possible: standardised databases and identifying real function, considering cradle-to-grave, including circular economy and sustainability principles, providing procedures for the inventory data as well as LCIA and impact categories, which were introduced in the PEF Guide. Our results also identified that studies published in high impact journals are more likely following the required methodological approaches.

4.2. Content analysis

Content analysis showed that existing LCA studies on food supply chain are very comprehensive from the perspective of concepts, covering four main themes: *production*, *use*, *system*, and *packaging*.

The prevailing theme is *production*, indicating a primary focus of the supply chain LCAs. An interesting theme is *system*, although a whole life-cycle approach was rarely perceived. This suggests that 'system' is related to the observed system within the boundaries of the LCA studies. As the *use* theme emerged, it covers mostly the usage of resources (water, energy) in the production stage, and not in the consumption stage. The results are in line with the LCA outcomes as most studies focused on the resource usage in the production, without considering the use and end-of-life environmental impacts, where a research gap exists. Often the concept analyses confirm the gaps discussed in section 4.1. For example, the lack of specific impact categories, such as land use, human and ecosystem toxicities. 'Water' and 'energy' terms emerged as the most frequent and crucial concepts when performing the food supply chain. The results are contradictory as studies mostly consider the impact category of global warming potential and disregard the impact categories related to water, toxicity, land use, etc. *Packaging* as the fourth central theme is related to 'product', 'waste', and 'materials'. The 'packaging' theme emerged as it was considered to be add-on processes within the food supply chain in the reviewed studies. It appeared despite specific food packaging studies. Particular attention was given to the 'LCA', closely relating to concepts 'food', 'agricultural' and 'sustainability', suggesting that food supply chain LCAs mostly focus on agricultural food production and its sustainability. The core identified concepts were 'production', 'environment', and 'energy', suggesting existing research trends within the LCA food supply chains.

5. Conclusions

A non-ambiguous supply chain evaluation is clearly needed, taking into consideration holistic and system perspectives to achieve sustainable food production and consumption. Such studies further determine a reliable decision-making process. The reviewed studies show a vital attempt to evaluate and improve the environmental supply chains' performance. These studies and represent valuable data sources, especially those, comprehending

primary data sources and *in-situ* measurements in micro-environmental locations, which can be further used to develop food supply chain databases for performing LCA. Studies examined were generally following the ISO standards. Still, only a few of them provide the additional information necessary to obtain high-quality, comprehensive LCA results, valuable also in the decision-making process. In the studies, insufficiencies (*e.g.* considering only one impact category), often missing uncertainly of results and inadequacies (*e.g.* secondary data for inventory analyses) were detected, in comparison with an entirely ISO compliant methodology. However, good examples were in the majority perceived in the journals with high impact factors. Room for improvement exists in the field of standardised databases, identifying suitable functional units, considering cradle-to-grave, including the circular economy, providing procedures for the inventory data as well as impact categories selection. Carrying out an LCA should give insight into how to improve, change, or optimise the production and consumption processes, and circulate valuable resources. Thus, it requires critical thinking and critical examination of results, high-quality primary data, clear, transparent and repeatable methodologies, and data validation.

A content analysis, represented via concept maps, identified by the software represents an in-depth understanding of the aspects of authors preparing LCA food supply chain studies and their primary focus. The results revealed the main research areas, which were production, use, system and packaging. Specific themes also indicated the application of LCA within the food supply chains. However, this is limited from the perspective of the concepts. Thus we have identified gaps. Additional research contents are needed to improve the sustainability of food supply chains, mainly focusing on the whole life-cycle, including use and end-of-life as well as circular economy principles, and stakeholders' roles. For example, a circular economy or stakeholders' roles were not even perceived as a concept or topic. However, the circular economy was widely emphasised since 2015, while food production and consumption is directly linked to various stakeholder groups. Focusing only on the environmental inputs, economic and social dimensions of sustainability were neglected. However, these aspects should be further evaluated, as the food sector plays a crucial role in economies and involve numerous workers.

Uncompleted or unreliable studies from methodological or data perspectives can negatively affect the decision-making process. Therefore, the research was carried out to examine the current state-of-the-art of the published LCA studies in the food supply chain field, their coherency with the existing standards, and to promote the research in the area. This study provides significant insights into the LCA in food supply chains from a methodological perspective. Such a critical evaluation gives guidance and an opportunity to LCA practitioners and experts to rethink and improve their studies, and to ascertain a need for holistic and systemic evaluations, approaching real-world models, using appropriate scientific methodological approaches. Furthermore, with the recognition of the importance of high-quality and detailed data from primary data sources, they will bring and added value by enriching existing databases. Compliance with the scientific methodologies and data reliability of the studies will lead to better, unambiguous and transparent decision making towards sustainability.

However, we should address some limitations of our study. A first limitation relates to the database Web of Science, which we have considered as it is the world's leading citation database. Scopus could give even more results, but not all the papers have science citation indexes. The second limitation was the nature of the studies, as we have considered only original scientific papers and review papers, excluding monographs, conference papers,

proceedings, etc. The third limitation relates to the topic "life cycle assessment" and "food supply chains". Thus, our study cannot be generalised to all the existing LCA studies. To overcome the limitations, further research on the methodological compliance and standardisations of the LCA studies will accomplish our survey. Further examination of LCA studies in other fields (transport, production processes, products, specific products, etc.), could reveal patterns and methodological developments as well as particular connections from the topics perspectives (e.g. main impacts considered).

CRediT authorship contribution statement

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.

Acknowledgements

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125506.

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