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Life cycle assessment for food production and manufacturing: recent trends, global applications and future prospects

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Abstract

The food production and manufacturing industry involves an extensive amount of raw materials, energy and water consumption, and releases a significant amount of wastes to the environment. In order to enhance the environmental performance of this sector, the measurement or assessment of current performance and identification of hotspots are imperative. In this regard, life cycle assessment (LCA) is a comprehensive and commonly known tool, which is also applicable to various food products, processes, etc. Recently, LCA has been frequently used in different studies around the globe as an environmental impact assessment method in food production and manufacturing sectors. These studies were based on different and varied food items, assessment boundaries, aiding tools, indicators, impact categories, etc. Therefore, there is a need for a recent review study to provide an updated status and future research prospects of LCA for food production and manufacturing industries. The primary objective of this article is to review and analyze the recent (published from 2010 to 2018) LCA studies in order to depict the status quo of LCA applications and describe future research directions. The results showed that recent studies were more focused on cradle-to-grave and cradle-to-factory out gate assessment boundaries while covering multiple life cycle phases. Currently, product level assessment was more common than sector or process level evaluation. Most of the reviewed studies did not rely only on one type of data, but the collected data were based on primary as well as secondary sources. Mass allocation of resources and burdens was comparatively more common than other allocation methods. Additionally, most of the reviewed LCA studies were limited to the mid-point impact category only, whereas end-point impacts were overlooked. Based on the challenges in the application of LCA, future research avenues were also presented. In the future, using LCA in a more consistent way and focusing further on process level assessments in food manufacturing industries may provide more detailed and comparable results.

Keywords: Life cycle assessment; Food production and manufacturing; Sustainability assessment; Sustainable manufacturing; Food industry

1. Introduction

Global food production and manufacturing is increasing due to the rapid growth in world population and changing lifestyles, which result in the consumption of global resources at a faster pace [1]. Although it is an important value-adding sector of both local economies and the global economy [2], the food industry as the world's largest industrial sector consumes a large amount of energy [3, 4] and other resources. It resultantly causes major impacts on the environment. The food sector contributes more than 25% of greenhouse gas (GHG) emissions [5, 6] and is responsible for a large share of

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water withdrawal and contamination [7, 8]. Moreover, food production and manufacturing also produces a significant amount of solid wastes, air emissions and wastewater [9, 10]. If this trend of adding environmental burdens continues, our society will no longer be sustainable and future generations will not be able to meet their own needs.

The food manufacturing sector is also heavily responsible for food security [11], and could be operated in a more environmentally friendly way [12]. It must operate more efficiently, consume less energy, produce less waste, and provide food with extended shelf life [13]. The various facets of food concerns (security, quality, safety, sustainability, etc.) call for urgent and resolute attention by policy makers, businesses and civil society globally [14]. In order to improve the green perception and environmental performance of this sector, assessment is an essential process [15, 16, 10, 17, 18]. The environmental impacts of food items are associated with different life cycle phases of the products, such as raw materials' production, agriculture, manufacturing (processing and packaging), distribution, usage, end-of-life, etc., [19, 20]. In this regard, Life Cycle Assessment (LCA) is a well-known and widely used tool to evaluate the environmental loads of a product, process, or service throughout its entire life cycle [3, 21, 22]. LCA has also been a suitable tool to analyze the environmental performance of a food industry or product [23, 24].

As LCA is applicable to a number of food products or production systems [25, 26], there is a need to review and analyze the available studies in order to evaluate the recent trends, current global level of applications and future requirements. The release of LCA reports for studies which are performed by many food companies, is limited due to confidentiality constraints [25]. Additionally, there is a serious lack of studies on the evaluation of environmental impacts of different food industries [27]. Therefore, it is beneficial to provide a review of various LCA studies and their analysis which may resultantly improve the practical usage and effectiveness of LCA. There were several studies that provided reviews of LCA for food products [28, 3, 29, 30]. However, these reviews were based on studies which were mostly conducted before 2010. Another review by Xu and Flapper [31] was based on energy consumption and CO_2 emissions from the dairy processing sector only. A more recent and relevant review by Cerutti et al. [32] was focused on fruit production which included agriculture and farm-based processing of fruits only.

The above discussion reveals the need for a recent and comprehensive review of LCA studies in the overall food production and manufacturing sector while considering various dynamics of an LCA study, such as assessment boundaries, assessment levels, sources of data, databases, types of inventory indicators, software tools, impact categories, etc. Additionally, as the use of LCA in the food industry is still evolving, this paper highlights its challenges and provides future research directions accordingly. Hence, this article is aimed to provide a comprehensive review and analysis of recent LCA studies for the overall food industry which is not only limited to some specific life cycle phases or food products and the review is based on recent studies (published from 2010 to 2018). In this way, this paper answers two research questions of what is the status quo of LCA and what are its challenges and future research prospects in the food production and manufacturing industry. The results are expected to be useful for a wide range of stakeholders, including LCA practitioners, researchers in the field of food manufacturing and production, policy makers and food manufacturers and producers. The rest of the article is arranged as follows. Section 2 briefly presents the background and some general concepts, and the methodology is described in section 3. The review of the LCA studies is presented in section 4. Sections 5 and 6 discuss the results and future research directions, respectively. Section 7 outlines the implications, and the important conclusions are provided in section 8.

2. Background and general concepts

A typical LCA study provides important insights about the impacts of environmental indicators, such as raw materials, energy, carbon, water footprint, etc., due to its inclusive boundary [33]. Generally an LCA study consists of goal and scope definition, life cycle inventory, impact assessment and interpretation. A goal is clearly stated in order to simplify scoping and study boundaries, and make the data collection more effective and accurate. Along with goal setting, the selection of 'functional unit,' a distinct attribute of LCA which makes it unique from other environmental assessment methods. A functional unit is a quantified description of the performance of the product system [34]. Cautious selection of functional unit will improve the accuracy of the LCA study and the usefulness of results [35]. A life cycle inventory is, basically a process of maping and quantifying inputs and outputs the process or system. During impact assessment, the impacts of input and output streams on human health, plants, and animals, or the future availability of natural resources are defined and assessed. In the end, at interpretation stage, the results are analyzed, conclusions are formed, limitations are explained, and recommendations are provided based on the findings of the study. As LCA is an ISO [36] standardized approach, more information on the method can be found in literature.

From classification viewpoint, two types of LCA are distinguished: attributional and consequential LCA (although sometimes different authors have used different names). An attributional LCA aims at describing the environmental properties of a life cycle and its subsystems, whereas a consequential LCA aims at describing the effects of changes within the life cycle [37, 38]. Moreover, the literature has also reported various models of LCA, such as process-based LCA, economic input-output LCA, hybrid LCA, etc., [12], which are selected depending on the level of the study, such as process, product, sector, etc. Generally, production processes can be divided into upstream processes (from cradle-to-factory in gate), core manufacturing processes (from factory gate-to-gate), and downstream processes (from factory out gate-to-grave). However, LCA studies are also based on other various assessment boundaries, depending on the life cycle phases they include [39]. These boundaries and levels of LCA studies, actually define the difficulty level of analysis, utility of results, etc.

LCA studies are conducted using primary data (plant records, laboratory testing, site visits, etc.) [40], whereas when primary data are not available, secondary data (databases, literature survey, assumptions, etc.) [41, 22] are also used. There are also various databases (Ecoinvent, etc.) and modeling software tools (SimaPro, GaBi, etc.) which are used to perform an LCA study. In this regard, some studies are based on data from one database. For example, Vázquez-Rowe et al. [42] and Finnegan et al. [24] used only Ecoinvent. However, others also employed multiple databases depending on the requirements of the analysis. For example, Calderón et al. [37] used five different databases (Ecoinvent, LCA Food DK, BUWAL250, ETH-ESU 96, IDEMAT 2001) for different life cycle phases or materials used.

Moreover, an LCA study employs different types of allocation methods (economic, mass, etc.) in order to allocate the inputs and impacts to various products. Normally, a plant produces more than one product (co-products) and data are available at the plant or work cell level [43]. In such situation, there must be an allocation of impacts, energy and other materials between the products [44, 43]. The allocation is about assigning the burdens to each functional input or output of a multiple-function system [45]. With respect to impact assessment, the CML 2 baseline 2000 V2.04/World 1990 method belongs to the tools of environmental impacts or midpoint impacts (ozone depletion, acidification, toxicity, etc.). The Eco-indicator 99 (H) V2.05/Europe EI 99 H/A method belongs to damage oriented impact assessment or endpoint methodologies (damage caused directly to human health, ecosystem and resources) [37], whereas the ReCiPe is a method used for both mid-point and end-point impacts' assessments [43].

3. Research methodology

As mentioned earlier, the purpose of this study is to review the recently conducted LCA studies in the food production and manufacturing sector. A comprehensive literature survey was undertaken and a variety of databases and library catalogues were explored to find the relevant scientific journals, books, conference proceedings, doctoral dissertations, standards and relevant reports. The important online databases that were inspected included Emerald, IEEE Xplore, Science Direct, Springer, Sage, Taylor and Francis, Wiley, Scopus, Web of Science, etc. Articles were searched while employing five keywords in two stages. The first stage keywords were "sustainable food production", and "sustainability assessment" which were used to search for papers on an overall level of sustainability. These overall level keywords were used because sometimes, LCA studies were published in papers having life cycle costing (LCC) and/or social life cycle assessment (SLCA) along with LCA. To identify articles which were based on environmental performance measurement, the second set of keywords ("life cycle assessment of food products", "green food manufacturing", and "environmental performance measurement") was used.

The LCA tool has been applied to various food-related products, processes, etc. A variety of papers and documents were found on the topic which included many conference and journal papers, etc. For instance, initially more than 200 documents were collected from the above mentioned sources. However, in order to make the analysis more reliable, maintain the appropriate length of this paper, and include only good quality studies, only the Web of Science indexed papers were selected for review and analysis purposes. From the data extraction viewpoint, information about the LCA studies in terms of categories of inventory indicators, descriptions, countries of origin, assessment boundaries, assessment levels, sources of data, databases, modeling software tools, allocation methods, impact categories, etc., was extracted from the reviewed studies. Based on the extracted data, these studies were analyzed and the results were discussed.

4. Review of LCA studies in the food manufacturing industry

As mentioned earlier, for review purposes, only the Web of Science indexed papers were included. Based on this criterion, 18 such papers were analyzed. These studies were listed and described in Table 1 in ascending order of date of publication. Table 1 briefly reported the studies in terms of their countries of origin, objectives and inventory indicators. Additionally, the results and shortcomings of each study were also mentioned in Table 1. Different LCA boundaries mentioned in Tables 1 and 2 are cradle-to-grave (includes all life cycle phases), cradle-to-farm out gate (based on production of ingredients, agriculture, and initial processing at farm), farm out gate-to-customer (includes transportation from farm to factory, processing and packaging, and transportation to customer), gate-to-gate (based on processing and packaging at factory/facility), cradle-to-factory out gate (includes all upstream phases and core manufacturing processes), cradle-to-customer (includes production of ingredients, agriculture, processing and packaging, and transportation to customer), and farm out gate-to-factory out gate (includes transportation from farm to factory, and core manufacturing processes at factory). More information and a clearer illustration of these boundaries are given in Ahmad and Wong [39].

Table 1 showed that for LCA in food production and manufacturing sectors, comparatively more reviewed studies were based on raw materials, water used, and energy consumption related input indicators, whereas among the output indicators, the major focus remained on air emissions related indicators. In contrast, wastewater and solid waste based indicators were less commonly used.

Table 1. Review of LCA studies in the food production and manufacturing industry

No.	Reference	Description	Results and shortcomings
01	[37]	The LCA study reported the environmental performance of canned food (ready meal that included cooked pulses and pork meat), in a food industry in Spain with a cradle-to-grave perspective. The inventory was based on indicators related to materials used, energy consumption, water used, air emissions and solid waste.	Main affected categories were land use, fossil fuel combustion and water eco-toxicity. In contrast with glass jar based packaging, biopolymer packaging reduced the environmental impacts. Both, mid-point and end-point impacts were evaluated. It was a comprehensive study with special focus on core manufacturing.
02	[46]	LCA of Australian sugarcane products was undertaken while focusing on industrial processing phase. The objective was to evaluate the effects of different allocation approaches on the results under different processing models. Indicators were based on materials used, energy consumption, air emissions and wastewater.	The results were affected by the type of cane processing system, sugarcane growing process, and allocation method. The data for sugarcane growing process were taken from another study for discussion purposes. Except industrial processing the remaining life cycle phases were overlooked.
03	[47]	Plant based processing of various food products (edible bean, dairy products, and corn masa) was evaluated in terms of environmental performance. From the inventory viewpoint, water used, energy consumption, and wastewater were analyzed.	The zero discharge process was possible by decreasing water and energy consumption. With the water reuse system, 70% amount of energy was saved. The study did not consider the air emissions aspects.
04	[48]	Product level cradle-to-grave LCA was undertaken on Canadian wine production while comparing multiple scenarios and improvement options. Analysis was based on indicators related to materials used, energy consumption and air emissions.	Results revealed that viticulture and transportation to customers were the greatest environmental hotspots. Solid waste and wastewater categories were not analyzed. Moreover, the end-point impacts were not calculated.
05	[42]	Efficiency of different grape producers was evaluated through LCA in a sector level approach. Moreover, the reductions in the consumption of input materials were also studied in terms of environmental gains. Inventory indicators were based on materials used, water used, energy consumption, air emissions and solid waste.	The results revealed that an average material reduction of 30% could result in 28% to 39% environmental gains. The study was limited to gate-to-gate (vineyards) and the remaining life cycle phases of wine production were not included. End-point impacts were also not evaluated.
06	[49]	The study assessed the environmental impact of wheat gluten powder production including all life cycle phases including agriculture, industrial processing, end-of-life, etc., in a European context. Inventory indicators were based on materials used, water used, energy consumption and solid waste.	The wheat cultivation and gluten drying stages were the main hotspots in most of the impact categories. The favorable scenario was wheat gluten film manufacturing by extrusion and it was incinerated to recover embodied energy. However, the end-point impacts were not included.
07	[40]	Environmental performance of traditional fruit (apple) production was investigated in Northern Italy, with a cradle-to-farm out gate boundary, based on various functional units. From the inventory viewpoint, water used, materials used, energy used, and air emissions were studied.	The results ranked the fruit production systems grounded on their environmental impacts. Different functional units gave different results. The wastewater and solid waste aspects were not considered. Moreover, the transportation, industrial processing, and usage phases, etc., were also ignored.
08	[50]	Life cycle impacts of carbonated soft drinks were estimated at the sectoral level in the UK, while employing a cradle-to-grave approach and different packaging options. With respect to inventory, the materials used, energy consumed, water used and air emissions were analyzed.	Packaging was the main burden for the majority of the environmental impacts, contributing between 59 and 77 %. The sector produced over 1.5 million tons of CO_2 equivalent emissions per year. The solid waste and wastewater categories were not analyzed.
09	[43]	The study was based on a farm out gate-to-customer assessment of the US cheese manufacturing industry. The focus was to quantify the emissions to air, water and soil based on the materials used, energy consumption, chemical used and water used.	The major contributors to climate change were electricity usage (28.3%), transportation (22.5%), natural gas usage (17.3%), etc. Freshwater depletion was dominated by the processing stage (90.8%). This study ignored the agricultural, consumption and end-of-life phases.
10	[12]	LCA of the US food manufacturing sectors was undertaken while considering a supply chain perspective. Datasets were based on water used, energy used and air emissions in terms of carbon footprints and land footprints.	19 out of 33 food sectors were found to be inefficient due to their environmental impacts. Forest land was found to be the most sensitive indicator from the food manufacturing sector viewpoint. The wastewater and solid waste categories were not included.
11	[51]	LCA with a scope of cradle-to-customer for bread was performed from the viewpoint of several food supply networks in a European context. The water used, energy consumption, materials used, air emissions, wastewater and solid waste categories were analyzed.	The study revealed a high variability of environmental impacts between alternative food supply or distribution networks The usage and end-of-life phases were not analyzed in the study.
12	[41]	The study aimed to analyze the environmental burdens of canned sardines by considering fishing, processing, and packaging stages in Portugal. The objective was to find the hotspots and potential improvements. Inventory was based on energy consumption, water used, materials used, air emissions and wastewater.	The environmental impacts of canned sardines were about seven times higher than edible products. The GHG emissions decreased by half when plastic packaging was used. The usage and end-of-life phases, etc., were ignored in the study.
13	[22]	The environmental performances of two different varieties of rice were evaluated in Brazil through a cradle-to-factory out gate approach while including agriculture, grain drying, and processing and packaging at factories.	The results showed that the cultivation stage was a main hotspot for environmental impacts. The study was based on global warming potential impacts only and other impact categories were not included.

		The materials used, energy consumption, water used and air emissions based indicators were analyzed.	
14	[33]	33 US food sectors were studied for seven environmental impact categories while considering the impacts of uncertainty on eco-efficiency assessment. Indicators were based on water used, energy consumption and air emissions.	Most (31 out of 33) of the food sectors were found to be inefficient because of their environmental impacts. The transportation, usage and end-of-life phases were not included in the study.
15	[52]	The environmental performance of cheesecake manufacturing, based on its different packaging solutions was evaluated in an Italian context. The inventory indicators were based on materials used, water used and energy consumption in a cradle-to-customer (also include retail activities) perspective.	Results revealed the new packaging solution was suitable for extending the shelf life and reducing the food losses and environmental impacts of cheesecake. It was a fine comprehensive study, however the usage of cheesecake and end-of-life phase of packaging (waste from consumers) were not included.
16	[24]	The study was aimed to assess the environmental impacts of milk powder and butter manufacturing in Republic of Ireland with a scope of farm out gate-to-factory out gate. The inventory indicators were related to materials used, water usage, energy consumption, chemical used, wastewater and solid waste.	Evaporation and drying processes have the most significant environmental impacts on milk powder manufacturing. Thirty nine percent of the electricity was used in refrigeration alone for butter manufacturing. Except transportation from farm to factory and core manufacturing, all other upstream or downstream phases were overlooked.
17	[45]	A cradle-to-grave approach was used to assess the environmental profile of high quality gluten-free biscuits. From the inventory viewpoint, the water used, materials used, chemical used, wastewater and solid waste aspects were studied.	Ingredient production was the main hotspot in almost all the impact categories. It was a useful study that focused on solid waste and wastewater, however air emissions were not discussed categorically.
18	[8]	The study was aimed to evaluate the environmental impacts of an Italian dark chocolate from a cradle-to-grave perspective. Inventory indicators were related to materials used, chemical used, water used, energy consumption, solid waste, air emissions and wastewater.	Significant variability of environmental impacts was observed due to the agriculture phase. It was a comprehensive study which covered all life cycle phases of the product and sufficient aspects of environmental performance.

Moreover, the recent studies, such as [24], [45], [8], etc., were more comprehensive in terms of using the inventory indicators. Whereas, the older studies, such as [48], [40], [50], etc., were comparatively less thorough when analyzing the aspects of environmental performance. This finding revealed that LCA applications were getting more mature in terms of comprehensive analysis of various aspects of environmental performance.

5. Results and analysis

Based on the reviewed LCA studies, an analysis of results is presented in Table 2. These studies are analyzed based on various characteristics or dynamics of LCA. Firstly, their countries of origin are categorized into two categories: developed countries, such as USA, Europe, etc., and developing countries, such as China, Brazil, Pakistan, India, Malaysia, etc. Table 2 shows that the majority of the reviewed LCA studies are reported from developed countries. Out of 18 studies, only one [22] is based on a developing country's context which was conducted in Brazil.

With respect to assessment boundaries, more studies are performed with cradle-to-grave (all life cycle phases, starting from production of ingredients to disposal) and cradle-to-factory out gate (production of ingredients, agriculture, transportation from farm to factory, till completion of industrial manufacturing) boundaries. The other five assessment boundaries (cradle-to-farm out gate, farm out gate-to-customer, gate-to-gate, cradle-to-customer, and farm out gate-to-factory out gate) are comparatively less common in LCA studies in food production and manufacturing sectors. However, when this situation is compared with the older status of LCA (studies published before 2010) in food sectors, Roy et al. [3] found that most of the life cycle studies were carried out involving either the agriculture or industrial refining phase.

The analysis also shows that the reviewed LCA studies are mainly based on three assessment levels: process, product and sector. Among these categories, the major focus remains on product level assessment which is followed by sector and process level analyses. This shows that detailed analyses of industrial manufacturing (processing and packaging) are overlooked by these studies. Product level assessment may miss the detailed analysis at each process [39]. Moreover, from the data sources viewpoint, except few studies, almost all are based on primary as well as secondary data. This shows that one kind of data may not be sufficient for an accurate LCA in food production and manufacturing sectors. In addition, Ecoinvent and SimaPro are found to be the more commonly used database and software tool respectively, in LCA studies.

Similarly, the mass allocation method is comparatively more commonly used in LCA studies. The reason to prefer mass allocation over economic allocation may be the difficulties to accurately estimate the prices and other economic information of products [49]. Moreover, the ISO 14040/44 series suggest to use economic allocation only as a last resort compared to others [53]. However, some studies also use different allocation methods at different life cycle phases in the same assessment. For example, Kulak et al. [51] used economic allocation at livestock farming, whereas mass allocation was used for the transportation stage. In comparison with older LCA based reviews, this paper is more comprehensive because it does not screen out studies based on the allocation methods. For example, de Vries and de Boer [29] analyzed only those studies that applied economic allocation. Moreover, de Vries and de Boer [29] found that economic allocation was more common at that time.

Table 2. Analysis and main characteristics of LCA studies

No.	Food types	Countries' categories		Assessment boundaries							Assessment levels			Data sources		Databases					Software tools				Allocation methods			Impact categories		References
		Developed	Developing	Cradle-to-grave	Cradle-to-farm out gate	Farm out gate-to-customer	Gate-to-gate	Cradle-to-factory out gate	Cradle-to-customer	Farm out gate-to-factory out gate	Process	Product	Sector	Primary	Secondary	Ecoinvent	LCA Food DK, BUWAL250	IDEMAT 2001, ETH-ESU 96	Gabi	Global Footprint Network	SimaPro	SuperPro	GaBi	CCaLC	Mass fraction	Energy fraction	Revenue/economic	Mid-point	End-point	
01	Canned ready meal	√		√							√			√	√	√	√	√			√				√			√	√	[37]
02	Sugar cane products	√					√					√		√	√	√				√	√				√		√	√		[46]
03	Various items	√					√				√			√								√								[47]
04	Wine	√		√								√		√	√						√							√		[48]
05	Grape	√					√						√	√	√	√					√							√		[42]
06	Wheat gluten	√		√								√			√	√					√				√			√		[49]
07	Fruit	√			√							√		√											√		√	√		[40]
08	Soft drinks	√		√									√		√	√			√				√	√				√		[50]
09	Cheese	√				√					√			√	√	√					√					√	√			[43]
10	Food sectors	√						√					√		√					√								√		[12]
11	Bread	√							√			√		√	√	√									√		√	√		[51]
12	Canned sardine	√						√				√		√	√	√					√				√			√		[41]
13	Rice		√					√				√		√	√	√					√				√			√		[22]
14	Food sectors	√						√					√		√													√		[33]
15	Cheesecake	√							√			√		√		√					√							√	√	[52]
16	Milk powder and butter	√								√		√		√	√	√									√	√		√		[24]
17	Biscuit	√		√								√		√	√	√					√				√			√		[45]
18	Chocolate	√		√								√		√	√	√					√				√	√		√		[8]
	Frequency count	17	1	6	1	1	3	4	2	1	3	11	4	14	15	13	1	1	1	2	11	1	1	1	10	3	4	16	2	

However, now, because of problems with economic allocation (as mentioned above), mass allocation is preferred.
Additionally, there are only two studies [37, 52] which have evaluated both the mid-point and end-point impacts. Most of the reviewed LCA studies are limited to only mid-point impacts. This shows that damage oriented impact assessment is still not common in LCA studies for food industries. However, for a better understanding of the results, knowledge of the measured impacts is also important.

6. Future research

This study found that the majority of the reviewed LCA studies were focused on product level assessments. However, the industrial manufacturing phase also has considerable environment related burdens, such as packaging related hotspots [54], on-site emissions from factories and energy requirements [55], etc. As mentioned earlier, product level studies might miss the detailed analysis at each process [39]. In this respect, future LCA based studies may put more effort on process level assessments in food manufacturing industries. Moreover, as can be seen in Tables 1 and 2, it was difficult to compare the results of various LCA studies because there was no consistency in using inventory indicators, assessment boundaries, assessment levels, etc. Future research may seek to conduct more consistent and standard LCA studies so that results may be compared at a process, product, sector or country level, etc.

Additionally, the majority of the reviewed studies were reported from developed countries rather than developing ones. The reason for this was generally due to the unavailability of proper databases in developing countries [39]. However, Nunes et al. [22] used the Ecoinvent database while adjusting the source of electricity to the Brazilian grid in order to conduct an LCA of rice production. This showed that LCA could be performed in developing countries by using even the available databases for developed countries. Based on this finding, future research would be expected to use LCA in developing countries for evaluating the environmental performance of food production and manufacturing sectors. Moreover, as the reviewed studies were normally limited to just mid-point impacts, future LCA studies could also include the end-point impact category in order to depict a clearer and bigger picture of environmental performance.

7. Implications

This study has various implications. Firstly, with respect to practical utility, this paper is expected to increase the utilization of LCA in food industries. The older reviews on LCA application in food sectors, such as Roy et al. [3], de Vries and de Boer [29], etc., were more focused on finding and/or comparing hotspots of different food products and highlighting possible measures. In contrast to such reviews, this paper may guide practitioners on how to conduct an LCA study and which software tools, databases, data types, allocation methods, etc., are normally preferred and commonly used. Specifically, practitioners from developing countries are suggested to use databases of developed countries, while adjusting electricity and other parameters according to their respective countries.

Moreover, this study also has significant implications for researchers. For example, they can work further to make LCA databases available in developing countries and more research effort can be directed on process level assessments to analyze food manufacturing activities in more detail. In addition, this paper has compared the LCA studies undertaken in developed and developing countries. Policy makers can use this observation to facilitate researchers and practitioners to conduct more LCA studies in developing countries. Last but not least, the findings revealed the inconsistent usage of indicators, assessment levels, etc. Thus, researchers may work to ensure the standard and consistent usage of LCA in food industries.

8. Conclusions

As mentioned earlier, because of various environmental burdens and other reasons, the food industry is required to improve its environmental efficiency. In this respect, the usage of LCA is applicable to food sectors, but there is no recent comprehensive review and analysis of LCA studies which covers different food production and manufacturing sectors. Hence, this article was aimed to provide a comprehensive analysis and recent picture of LCA trends and global applications in food production and manufacturing sectors. In order to achieve this objective, recent LCA studies (published from 2010 to 2018) for various food manufacturing industries were reviewed. This article has highlighted the challenges of LCA and its future research prospects in these sectors.
The results showed that the majority of the reviewed LCA studies were reported from developed countries and only one paper was found from developing countries. More reviewed studies were based on cradle-to-grave and cradle-to-factory out gate assessment boundaries. However, previously (reported in an older review), most of such studies were based on the agriculture or industrial refining phase only. With respect to assessment levels, the major focus of the reviewed studies remained on product level assessment which was followed by sector and process level analyses. In addition, for data collection purposes, except few studies, almost all were based on primary as well as secondary data sources. The mass allocation method was comparatively more common than other allocation methods in the reviewed LCA studies. Nevertheless, the older reviews found economic allocation as a more common method. Likewise, from the viewpoint of impact categories, most of the reviewed LCA studies were limited to only mid-point impacts, whereas the end-point impact category was overlooked.

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