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The evolution of life cycle assessment in the food and beverage industry: A review

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Abstract

Life cycle assessment (LCA) has been progressively used as an tool to quantify and compare environmental impacts in the food and beverage industry. This paper reviews LCAs on single-use food and beverage plastic products from January 2000 to June 2022. Studies are also analysed in the context of marine plastic pollution which is a global concern. A total of 91 studies were reviewed with 44% conducted for the European region. Findings suggest that most studies follow the traditional approach and structure of LCA with some studies focusing on global warming potential and others incorporating aspects such as life cycle costs and mass-based indicators. A total of 62% of reviewed studies had a cradle-to-grave scope. LCA studies can be influenced by public discourse, for example, the rising concern surrounding plastic marine pollution. From 2019, additional environmental indicators have been included in LCAs wherein the product is a major contributor to pollution. To date, six studies have proposed marine litter indicators. In future years, we can expect further development of life cycle impact assessment methods to reflect concerns in the public discourse. This includes methodologies for assessing circularity or plastic pollution. Furthermore, product foci will continue to follow popular trends.

Impact statement

This paper reviews life cycle assessments (LCAs) in the food and beverage industry. The environmental impacts of single-use plastic products have become of particular concern due to the rising concern surrounding marine pollution. This makes LCA a much-needed tool as we make decisions on the different material choices for products. Further, it can be used as a decision-making tool in policy development. The review shows that the product focus of studies follows popular trends with respect to which products are currently in public discourse. Further, it demonstrates the subjectivity of LCA studies as comparisons of similar studies may yield very different results. It also shows LCA methodologies to be ever-evolving according to different environment concerns. For example, recent studies wherein some sort of marine litter indicator has been included.

Introduction

Life cycle assessment (LCA) is a popular environmental assessment tool that evaluates the environmental impacts of a product or process from raw materials extraction to disposal (cradle-to-grave). Since its inception, LCA has continued to develop methodologically including the broadening of impact categories and an increase in the complexity of the underlying methods (Finnveden et al., 2009; Roy et al., 2009; Guinée, 2015). Furthermore, the concept has been expanded to include social (Social-LCA) and economic (life cycle costing) aspects culminating in a more sustainable development-oriented tool, the life cycle sustainability assessment.

The food and beverage industry has been a focus area for LCA for many decades. For example, one of the first comprehensive LCA studies was commissioned by the Coca-Cola Company in 1969 on its beverage packaging options (Sonneveld, 2000). It is commonly used as a decision-support tool in packaging design. Its ubiquity in this sector is exemplified by the development of an LCA tool in order to 'streamline' LCA: Packaging Impact Quick Evaluation Tool (PIQET) (Verghese et al., 2010).

Plastic packaging has been a major concern with regards to its contribution to plastic marine pollution. In 2015, an estimated 42% of non-fibre primary plastic went into producing plastic packaging globally (Geyer et al., 2017). Single-use food and beverage packaging has been found to be prone to leakage into the marine environment (Barnes et al., 2009; Hanke, 2016; Chitaka and von Blottnitz, 2019; Fauziah et al., 2021). This has led to many regions putting in place interventions and/or policy measures to reduce the use of single-use plastics. For example, India banned 19 single-use plastic items including straws and cutlery as of 1 July 2022 (India Bans 19 Single-Use Plastic Items to Combat Pollution, 2022). With these sweeping changes coming into force, LCA has become more important to inform whether alternatives such as bio-based plastic products and packaging will be more or less harmful to the environment. This has influenced the continued development of LCA with a concerted focus on the inclusion of marine plastic pollution as an impact assessment category.

With single-use plastics associated with food and beverages in the spotlight, it would be remiss to only consider their pollution potential when planning interventions. However, it must be acknowledged that LCA is not well equipped to address the impacts of plastic pollution despite the fact that it is a popular environmental assessment tool. Although progress has been made to investigate plastic litter impact pathways, research on the fate and consequences of marine litter is still limited. This review tracks the progression of single-use plastic food and beverage LCAs conducted from the year 2000 to June 2022. Studies are also analysed from plastic pollution perspective wherein the focus of studies is related to the rising concern in plastic pollution and highlighting of high contributors. Further, it reviews the progression of LCA methodology in addressing marine plastic pollution.

LCA methodology

LCA methodology consists of four stages: goal and scope definition, inventory analysis, life cycle impact assessment and interpretation. The framework is based on ISO 14040 standards for LCA which were released in 1997 and updated in 2006. The goal and scope definition focuses on the reasons for carrying out the study, the intended audience, and application (ISO, 2006). The scoping part of the initial stage also included the description of the system boundaries of a study. The functional unit, which is a quantitative measure of the function provided by the product or service, is also defined. For the inventory analysis, a list of the inputs and outputs from a product in relation to the functional unit is compiled. The third stage aims at translating the calculated flows into environmental impacts via emission factors. In the interpretation stage, the results are evaluated against the goal and scope to derive conclusions and recommendations (ISO, 2006).

The unique feature of a LCA is its holistic perspective on a product's life cycle. This comprehensive scope avoids burden-shifting from one stage of the life cycle to another or from one environmental concern to another. LCA has been increasingly used for decision-making and learning as well as for the promotion of life cycle thinking on a policy level (Finnveden et al., 2009). LCA methodology has matured and changed in line with these new developments namely in the creation of new databases and harmonisation of methods.

Methodology

The review only considers LCA studies including plastic single-use products associated with food and beverages. This included packaging such as bottles as well as straws, tableware and cutlery. Carrier bags were also included as they are then used to transport food and beverages and are considered as single-use products. Only studies that included an assessment of at least one conventional/fossil fuel-based single-use plastic were considered. The dates reviewed were January 2000–30 June 2022.

Only peer-reviewed journal articles were included in the review as the focus of the review was on studies that have undergone independent peer review Books and book chapters were excluded as there was no way to determine whether they had been subject to the same level of peer review. However, this presents a limitation to the review in that relevant LCA studies may have been overlooked. Reviews and methodology papers were excluded as the focus was the LCA studies. Review papers whilst they provide a critical analysis of LCAs they do not provide any new information in terms of LCA results; further, there is the risk of duplication whereby a paper may be reviewed by the authors and then reviewed again in a review paper. Methodology papers were excluded unless the proposed methodology is applied to an LCA in the same paper.

A literature search was conducted using Web of Knowledge, Scopus and Google Scholar. The search included the following keywords in combination with the word 'plastic': LCA, life cycle analysis and carbon footprint. From the literature search, 8,161 potential papers were retrieved. Following screening, based on the subject matter, 244 studies remained. Further refining according to the publication text, eliminated 40 studies. Duplicates were then removed, leaving a total of 91 studies to be reviewed.

Results and discussion

The earliest studies that were found within the review's parameters were published in 2003 (Sevitz et al., 2003; Zabaniotou and Kassidi, 2003). An analysis of the studies published over the review period shows that the number of LCA studies reviewed did not follow a consistent trend with studies increasing and decreasing (Figure 1). Since 2017, there has been a steady increase in LCA studies being published with 2022 promising to follow that trend.

Types of LCA studies

The inner ring of the figure below shows the distribution of studies per LCA type (Figure 2). The results show that the number of carbon footprints conducted within the review period is 10 (Supplementary Table S1), traditional LCAs is 57 (Supplementary Table S2), and six studies that combined the traditional structure of an LCA with an additional environmental indicator estimating the impact of plastic pollution (Supplementary Table S3). The balance of the studies (defined as 'other' studies in the chart) consisted of assessments which included aspects that differed from the traditional scope of an LCA (Supplementary Table S4). Examples of these are studies that compared various end-of-life scenarios and waste management options (Hou et al. 2018; Martin et al., 2021).

One study incorporated life cycle costing into the analysis (Foolmaun and Ramjeeawon, 2012a) while another study used a hybrid approach to evaluate the environmental benefits of a re-designed plastic milk bottle (Pomponi et al., 2022). An additional example of a study that used LCA as part of a two-step process is Cottafava et al. (2021) where an environmental break-even point was established by comparing several end-of-life and use phase strategies for single-use versus reusable cups.

Only one study considered circularity by taking a material circularity indicator into account (Lonca et al., 2020). Additionally, two studies used a combination of material flow analysis (MFA) and LCA to link mass-based indicators to indicators of environmental damage (Kang et al., 2017; Lonca et al., 2020). MFA and LCA are complementary tools enabling further analysis of complex systems (Laner and Rechberger, 2016).

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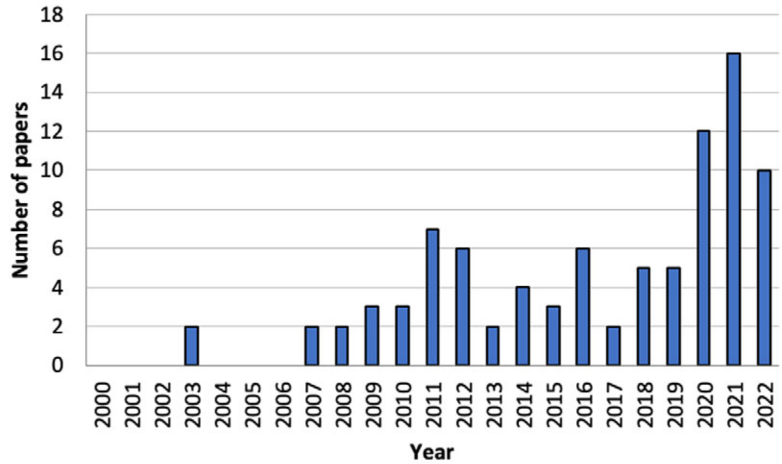

Figure 1. Number of product-specific, food and beverage LCAs conducted from 2000 to 30 June 2022.

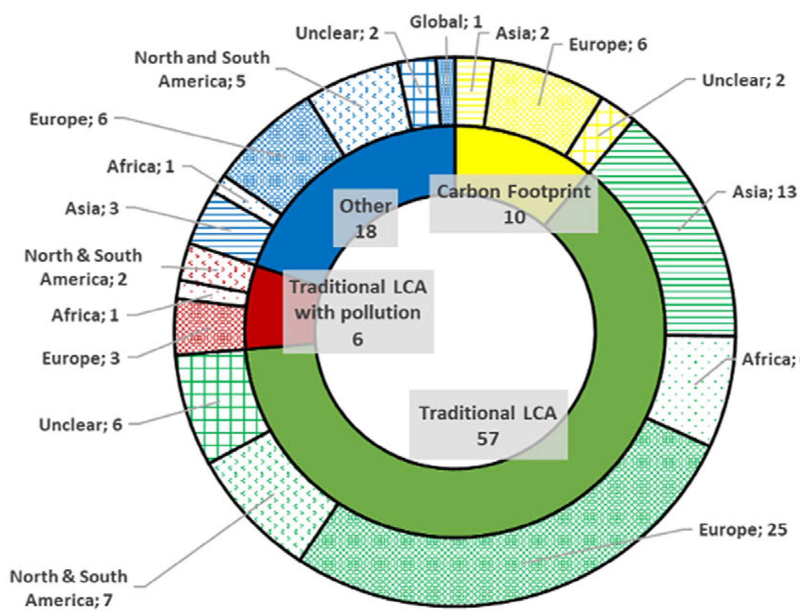

Figure 2. Distribution of life cycle-based studies per type and location.

Carbon footprint and water footprint are also considered special types of LCAs (Finkbeiner, 2016). The analysis indicated that studies that considered the estimation of GHG emissions (namely a carbon footprint) also include a calculation of energy consumption/cumulative energy demand within the scope of the assessment (Pasqualino et al., 2011; Nikolic et al., 2015). Furthermore, Fetner and Miller (2021) examined water consumption as an additional indicator to determine environmental payback periods. The overall number of studies found also indicated that although increasing attention has been paid to global warming and climate change, the majority of studies included multiple environmental indicators.

In recent years, the concern surrounding marine plastic pollution has become reflected in LCA studies. The Medellin declaration on marine litter in LCA (Sonnemann and Valdivia, 2017) acknowledged that impacts related to marine debris including plastics are not suitably addressed in the current LCA methodology. Life cycle studies to date are yet to characterise the impacts of leakage of plastic fractions to the surrounding environment. Thus, no major life cycle database has included these emission flows into their datasets nor developed specific characterisation factors that convert leakage flows into indicators of environmental impact. It is noted that there are ongoing projects such as marine impacts in LCA (MarILCA) aimed at integrating marine litter impacts in LCA (Marine Impacts in LCA n.d.). This may provide useful information regarding impact assessment methods and indicators to quantitatively address potential impacts arising from plastic leakage in the marine environment.

Although plastic litter impact models are the subject of recent research, its application to case studies illustrating the use of these models is limited. Some studies have investigated the development of effect factors and characterisation of plastic pollution impacts. In 2019, Woods et al. developed a preliminary effect factor for the impacts associated with entanglement. However, the authors acknowledged that the lack of data on the effects on populations for species as well as the associated impacts of litter densities along the water column (Woods et al., 2019). Saling et al. (2020)

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developed a characterisation model for the impacts of microplastics on species which took into consideration fragmentation and degradation rates. More recently, in 2022, Corella-Puertas et al. (2022) proposed simplified fate and characterisation factors for microplastics resulting from expanded polystyrene and tyre wear. The work took into consideration different degradation, fate and sedimentation rates. However, the development of robust models is still hampered by the poor understanding of the impacts of plastic on species as a population and ecosystems at large (Woods et al. 2016, 2019).

In the absence of these marine litter impact assessment methods, rudimentary indicators have been applied in lieu of it. The proposed marine litter indicators are based on a number of factors including weight (Civancik-Uslu et al., 2019; Herberz et al., 2020; Stefanini et al., 2021), leakage rates (Chitaka et al., 2020; Zanghelini et al., 2020; Gao and Wan, 2022) and degradation (Civancik-Uslu et al., 2019; Chitaka et al., 2020; Stefanini et al., 2021; Gao and Wan, 2022). For the six studies that were located, three were conducted for European countries with the remainder of research conducted for South Africa, Brazil, and the United States of America respectively.

Geographical spread

The outer ring of the doughnut chart (Figure 2) describes the location of studies where the geographical context is divided per continental region. Across the various types of studies and in total, 44% of the studies have been conducted for European countries. Just over 35% of the total studies were conducted for countries within the European Union (EU). This includes studies conducted for the region. Within Europe, the predominant countries where studies occurred are Italy and Spain with eight studies apiece. Of the eight studies conducted for the African continent, half of the assessments were for Mauritius while the remainder were carried out in the southern parts of Africa namely South Africa and Zimbabwe. For Asia, the countries that featured the highest number of studies were Thailand and China with four and five studies respectively. The United States of America had the greatest number of studies within North and South America.

In some cases, the study covers a region rather than a specific country (Brock and Williams, 2020) while, for other assessments, studies were located across multiple countries (Muthu et al., 2011; Schmidt et al., 2020).

For several studies, the location of the research was unspecified which potentially hinders the value of the publication; it limits the interpretation of the results and its potential comparability. From the online search conducted, there were no studies reviewed that were conducted for Australasia. This is not due to an absence of LCA studies but a reflection of our eligibility criteria.

Scope of studies

The scope of the LCA is dependent on the system boundaries selected by the researcher/practitioner. Traditionally an LCA should be conducted from cradle-to-grave, however, one may choose to focus on one section of the production process (eg, gate-to-gate) (Figure 3). With the rising popularity of circularity and recovery and recycling of waste products, one may also conduct an LCA from cradle-to-cradle (Figure 3) as previously discussed.

The majority (62%) of studies had a scope of cradle-to-grave. However, there was a growing focus on end-of-life impacts, including in some cases where a cradle-to-grave assessment was conducted

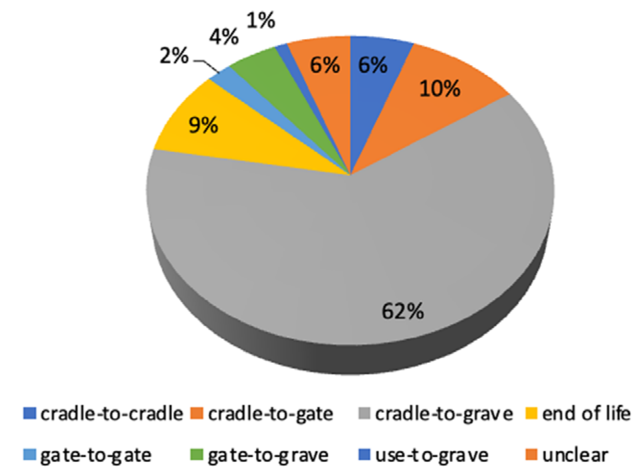

Figure 3. Scopes of reviewed LCA studies.

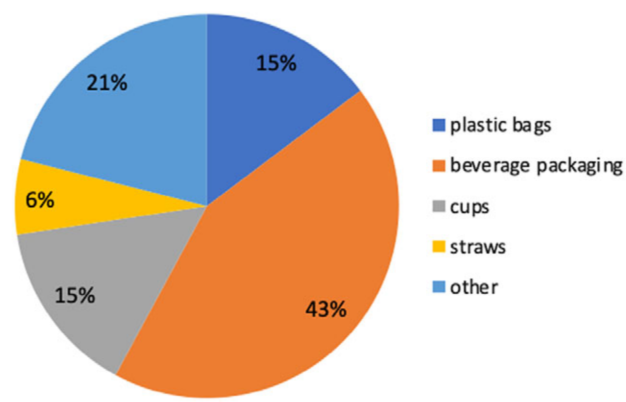

Figure 4. Product composition of reviewed LCAs.

(Romero-Hernández et al., 2009; Foolmaun and Ramjeeawon, 2012a; Simon et al., 2016). For example, for beverage bottles, there was a notable interest in the potential benefits of product waste recycling (Romero-Hernández et al., 2009; Foolmaun and Ramjeeawon, 2012a, 2012b; Simon et al., 2016; Martin et al., 2021). One study integrated two different scopes, that is, cradle-to-gate and cradle-to-grave (Muthu et al., 2011).

Product foci

The largest product groups of focus were aligned with items identified as major contributors to plastic pollution. Beverage packaging has been a focus area of LCA for many years, representing the largest category of LCA studies reviewed (Figure 4). They started rising in popularity in 2011 with 5 publications in 2012, 6 in 2016 and 10 in 2021. The majority of beverages under investigation were milk (Bertolini et al., 2016; Stefanini et al., 2021; Cappiello et al., 2022; Pomponi et al., 2022), and mineral water (Gironi and Piemonte, 2011; Garfí et al., 2016; Ferrara et al., 2021; Grisales et al., 2022). However, not all LCA studies specified the beverage type.

A total of 70% of the beverage packaging LCAs included PET bottles. They started gaining popularity from 2011 with 1–4 studies published yearly, excluding 2019, culminating in seven studies being published in 2021. PET bottles are either studied in isolation or compared to glass bottles or aluminium cans. Generally, PET was

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found to outperform both glass and aluminium however, this was subject to a number of factors including the number of glass reuses and the respective disposal scenarios (Amienyo et al., 2013; Saleh, 2016; Boutros et al., 2021; Ferrara et al., 2021).

Plastic bags and disposable cups each contributed 15% of the LCAs reviewed respectively. Plastic bags have seen periods of high interest with nine studies conducted from 2009 to 2012, none from 2013 to 2016 and a renewed interest from 2017. This may be linked with public concern surrounding pollution associated with plastic bags. The 'other' category consisted of a variety of products including jars, cutlery, meat trays and clamshell containers.

Product focus can be influenced by public discourse. This is clearly represented in the case of straw LCA studies. In recent years, straws have been in the spotlight as a major contributor to marine plastic pollution. This may have contributed to the products being studied, with straw LCA studies only first being published in 2020. Results varied, being impacted by factors such as the location and the number of reuses for reusable straws. Most of the studies incorporated a marine litter indicator further linking the studies to marine plastic pollution (Chitaka et al., 2020; Herberz et al., 2020; Zanghelini et al., 2020; Gao and Wan, 2022). This further supports the notion that LCA product foci is influenced by the global concern surrounding plastic pollution.

The future of LCA

Based on the reviewed studies one can postulate a trajectory for the future of studies in the food and beverage industry. We can expect more product LCAs from Europe, especially as policy decisions are made by the European Union with regards to problematic plastic plastics. However, we may see an increased proportion in the studies from other regions as human capacity and economic development increases.

Product popularity seems to have an influence on what is studied. Thus, product foci will continue to trend towards what is popular. LCA may continue to aid as a decision-support tool to inform public discourse and policy development.

Lastly, we can expect more methodological advances in life cycle impact assessment with particular focus on addressing rising concerns surrounding circularity and plastic pollution. Although initial research has been conducted to integrate marine plastic impacts into LCA methodology, work is still needed to define detailed fate factors and further investigate degradation and fragmentation models.

Conclusion

The analysis revealed that the earliest studies located within the study's parameters were published in 2003. The numbers since then fluctuated with a steady increase from 2017. The majority of studies (63%) conducted within the review period can be classified as traditional LCAs with the balance focusing on a certain environment indicator (eg, the release of GHG emissions) or integrating other sustainability aspects. Overall, a relatively large percentage of studies (44%) were published by European countries with contributions from various other countries in Asia, Africa and the Americas.

Although beverage packaging has been the focus over the years, accounting for 43% of studies, it has been shown that product focus can change due to the influence of global conversations as in the case of increasing concern surrounding marine plastic pollution. Thus, we shall continue to see changes in product foci according to changing global concerns.

Increasing attention on plastic pollution is reflected in LCA, with six studies proposing marine pollution indicators of varying complexities. The nature of LCA studies has also been influenced by the popularity of circularity. In particular, there has been a change to LCA scopes from the traditional cradle-to-grave to a more circular cradle-to-cradle scope, with specific focus on product 'waste' treatment.

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Competing interest. The authors declare none.

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