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EDITED BY
Rakesh Bhardwaj,
Indian Council of Agricultural Research (ICAR), India

REVIEWED BY
Natasha R. Marak,
Central Agricultural University, India
Shalini Gaur Rudra,
Indian Agricultural Research Institute, India

*CORRESPONDENCE
Martina Cassarino
✉ martina.cassarino@unicatt.it

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nLCA in bakery food products: state of the art and urgent needs

Martina Cassarino[1]*, Gianluca Giuberti[1], Lorenzo Morelli[1], Marco Trezzi[2], Andrea Pelattieri[2], Loris Manicardi[3] and Pietro Scaglia[3]

[1]Department of Sustainable Food Process – DiSTAS, Università Cattolica del Sacro Cuore, Piacenza, Italy, [2]Research and Development Department, Bauli S.p.A., Verona, Italy, [3]Deloitte & Touche S.p.A., Milan, Italy

This study analyzes the nutritional life cycle assessment (LCA) of bakery products and the current state of the art. The analysis focuses on (1) the importance of applying a methodology, such as LCA, in a general way and the division into different stages considering the UNI EN ISO; (2) the development of nutritional LCA; (3) the difference between functional units in LCA and nutritional LCA; and (4) the different nutritional LCA approaches. The study emphasizes the lack of nutritional LCA studies regarding the bakery category, underlining the urgent need for this type of investigation concerning this specific food sector.

KEYWORDS

life cycle assessment, nutritional life cycle assessment, bakery, cereals, sustainability

1 Introduction

The food system contributes approximately one-third of the total anthropogenic greenhouse gas (GHG) emissions (Tubiello et al., 2021). The term "carbon" refers to greenhouse gases because carbon dioxide is the main greenhouse gas released by different human activities. The activity that is used for this measurement is referred to as "carbon footprinting." Product carbon footprinting also includes emissions over the entire life cycle of a product or service, from raw material extractions through production to use and reuse (Bouchery et al., 2017). This aspect, combined with the fact that the world population is expected to increase by 2050 (Ansari et al., 2011), will lead to more intensive agriculture to meet the growing demand for food and, consequently, the overuse of natural resources (Tilman et al., 2011). In parallel, consumers' interest in safe, high-quality products produced with the least environmental impact has progressively increased (De Boer, 2003).

The increased importance of environmental protection and the possible impacts associated with products have increased interest in developing methods to better understand and address these impacts (UNI EN ISO 14040, 2006). One of the techniques being developed for this purpose is life cycle assessment (LCA). Today, LCA is the most widely used approach to model and calculate the environmental impacts of certain products and processes. In addition, the LCA methodology is at the core of sustainability assessment and is used to evaluate the environmental impact associated with alternative agricultural and food technologies, food supply chains, ingredients, foods, meals, and whole diets (McLaren et al., 2021). The international normative reference for the execution of LCA studies is the 14040 series of ISO standards, particularly the UNI EN ISO 14040 (i.e., environmental management, life cycle assessment, principles, and framework) and the UNI EN ISO 14044 (i.e., life cycle assessment, requirements, and guidelines). LCA comprises four iterative phases: the goal and scope definition phase, the inventory analysis phase, the impact assessment phase, and the interpretation phase (Figure 1).

2 General view on the principles of the life cycle assessment

The scope of LCA, including the system boundary and level of detail, depends on the subject and intended use of the study (UNI EN ISO 14040, 2006). Establishing the intended application, such as product improvement, strategic planning, and policy-making for sustainability, is important. In addition, the functional unit (FU) is a critical aspect of the scope and quantitatively describes the function (Cucurachi et al., 2019). ISO 14040 and 14044 state that the specific FU should be chosen according to the objective and purpose of the study, and Schau and Fet (2008) stated that it is the unit to which the results of the LCA are reported. The FUs most commonly used in food LCAs have, until now, been based on mass or volume (McAuliffe et al., 2020).

The life cycle inventory analysis (LCIA) phase is the second phase of LCA. It involves collecting data, identifying relationships, and quantifying the inputs and outputs of the system (UNI EN ISO 14040, 2006). It is important at this stage to define the unitary processes that make up the system. In this way, the "elementary flows," are recorded, i.e., all natural resources extracted from the environment, and the "economic flows." The boundaries of the system are defined to help understand what to evaluate and what to omit, which should cover the entire life cycle from upstream to downstream of the system. Depending on the product in question, the boundaries of the system will change. However, processes rarely produce a single economic output, that is, when a product or system consists of multiple parts or processes (Cucurachi et al., 2019). In this situation, it is crucial to consider the allocation rules, i.e., rules that attribute the environmental impact of a product or system to its parts or activities. Another aspect to include is that the data are divided into those relating to inputs and those corresponding to output flows. The collected data can be divided into primary and secondary; the difference is that the primary data are those coming from direct surveys; the latter, on the other hand, are drawn from the literature. At the end of this phase, an inventory table will be constructed between the system being assessed and the natural environment (Cucurachi et al., 2019).

The life cycle impact assessment (LCIA) phase is the third phase of the LCA. The purpose is to use predefined methods in the LCA software to group and aggregate a system's LCI results to better understand their environmental significance (UNI EN ISO 14040, 2006). The results of the inventory analysis are multiplied by the respective global warming potentials (GWPs), and the greenhouse gas emissions (CO_2 and CH_4) are expressed in kg of CO_2 equivalent (Cucurachi et al., 2019). The impact assessment phase is divided into several elements: classification, characterization, and standardization. The classification consists of aggregating inventory data based on the type of environmental impact; characterization deals with calculating the relative contributions of emissions and resource consumption to each environmental impact; and in normalization, the results are dimensionless so that they can be compared with a reference value. Each LCA must include classification and characterization.

Life cycle interpretation is the final phase of the LCA procedure, in which the results of an LCI, LCIA, or both are summarized and discussed for conclusions, recommendations, and decision-making in accordance with the definition of the goal and scope (UNI EN ISO 14040, 2006). This phase highlights potential areas for improvement related to hotspots in the lifecycle.

There has been increased interest among nutrition and environmental scientists regarding nutritional quality and health impacts (Bianchi et al., 2020). Accordingly, Broekema and Blonk (2020) argued that, for a product to be future-proof, it is important that a good balance exists between nutrition and environmental impact. Consequently, when evaluating agri-food products, researchers have considered incorporating nutritional science into environmental LCA studies. This analysis has become known as

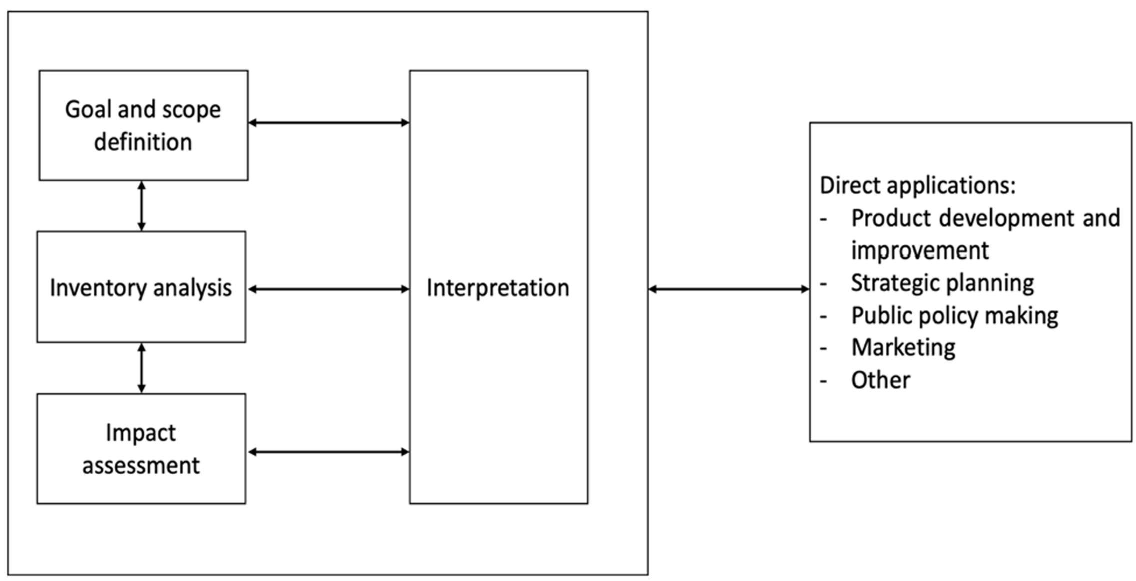

FIGURE 1
Different stages of LCA (UNI EN ISO 14040, 2006).

nutritional LCA (nLCA) (McAuliffe et al., 2020; McLaren et al., 2021). In short, the nLCA addresses the food–nutrition–environment nexus. The nLCA considers the nutritional impact of the product by assessing its nutritional quality, processing methods, and its nutritional value. In the FAO document, McLaren et al. (2021) used this term to refer to an LCA in which nutrient supply is considered the main functional unit (FU). Moreover, nLCA studies can help identify the healthiest and most environmentally friendly options for consumers. In this context, McAuliffe et al. (2023) pointed out that the use of simplified nutritional FUs (nFUs) is one of the main problems in LCA. Currently, nFUs are used to provide a common unit of analysis to standardize the comparative LCA of alternative food products.

In addition, it is important to distinguish the role that nutrition can play in the functional unit and in the calculation of impacts (Weidema and Stylianou, 2019). Knowing that the nutrient content in nLCA is considered critical, one cannot exclude some nutrients rather than others. According to Weidema and Stylianou (2019), the degree of satiety of food should also be considered, as it indicates the time that passes until the next meal is requested. For a given food product, the inclusion of the nutrient content along with the satiety in the nLCA can therefore be used as a functional unit. However, it is important to consider the other side of the coin: Could nutrition also have an impact on human health? It is necessary to consider a framework that, in terms of nLCA, combines foods and diets with harms and benefits for human health. In particular, Weidema and Stylianou (2019) have proposed an index, the Daly Nutrition Index (DANI), which provides continuous single-score quantification, expressed in disability-adjusted life years (DALYs) per functional unit of food, of associated marginal (small, additional) health burden from all-cause premature mortality and disease morbidity and uses Global Burden of Disease (GBD) epidemiological evidence to classify and evaluate foods and diets. This index can be used as a nutritional health assessment method aligned with LCA, and it can be combined with the nutrient balance indicator to improve differentiation at the level of individual nutrients. However, although DANI places a focus on food groups and dietary patterns, it may not give correct indications of the level of diets.

3 Application of life cycle assessment methodology

LCA methodology has been widely applied to industrial products and processes, with special emphasis on the food system and related products. In particular, the environmental impacts of conventional and alternative production systems are described by this methodology, which identifies opportunities to develop sustainable production systems with minimal environmental impact (Green et al., 2006). Concerning the bakery product food sector, Roy et al. (2009) combined the organic production of wheat, industrial milling, and a large bread factory, considering it the most advantageous method for bread production. Noya et al. (2018)evaluated the environmental impact linked to the production of gluten-free biscuits in the UK following an LCA perspective and reported that ingredient production and transport activities are the main environmental hotspots in the examined impact category. Andersson and Ohlsson (1999) conducted an LCA case study of common white bread, aiming to compare different scales of production and potential environmental effects. In particular, the system included agricultural production, milling, baking, packaging, transport, consumption, and waste management. In addition, the authors considered different scales: a home bakery, a local bakery, and two small industrial bakeries with different distribution areas. In this case study, the four phases of the LCA ranged from the definition of the objective and scope, followed by the analysis of inventory analysis and impact assessment, whereas the final stage was the interpretation of the results. The authors concluded that the differences between home baking, the local bakery, and the small industrial bakery were not significant.

In the LCA, the FU is used as a reference unit and as the basis for any product comparison. McLaren et al. (2021) in the FAO report on the integration of environment and nutrition in food LCA, which contains recommendations on how to conduct a nutritional LCA, focus on the nUF that should be chosen. In this case, the nFU must be chosen based on the simultaneous consideration of environmental impact and nutritional/health aspects (McLaren et al., 2021). However, there is no established method for defining an nFU. As a result, different nFUs are used depending on the study. A protein nFU is used to include nutritional functionality in the LCA and is one of the most widely used FUs (Oonincx and de Boer, 2012; Saarinen et al., 2017). In addition, the studies in the literature are based on diet-level comparisons and consequently fail to guide farmers on how best to produce food (McAuliffe et al., 2020). Furthermore, nLCA can consider changes in diet within different populations (Sonesson et al., 2017, 2019). Batlle-Bayer et al. (2020) evaluated the environmental impacts of current average regional diets in Spain. They considered an FU based on both nutritional and socioeconomic dimensions. The authors noted that environmental benefits result from adopting a diet based on the National Dietary Guidelines (NDGs). In particular, NDGs are public documents that provide recommendations and advice on healthy diets and lifestyles. In addition, NDGs give guidance on individual foods that should be consumed to improve health and can provide quantitative recommendations by food groups or more general qualitative advice on overall diets. In the literature, the meal is considered an FU, representing the sum of the environmental impacts of each individual ingredient. In fact, Mazac et al. (2023) compared the environmental impacts of meals including novel/future foods with those of vegan and omnivore meals. The authors aimed to show that the use of nLCA has the advantage of considering nutrition as a FU in assessing food sustainability.

As mentioned above, nutrients should be considered in the development of an nLCA, and the most widely used method to supplement them is based on the use of nutritional indices, which, however, can include nutrients to be encouraged and limited. These indices, therefore, must be combined, even if their combination can produce negative values. For this reason, Saarinen et al. (2017) and McLaren et al. (2021) proposed to use an index based on the nutrients to be encouraged as FU and to assess the impact of the nutrients to be restricted. Should the index be used for all foodstuffs, or should a product-group-specific approach be taken? McLaren et al. (2021) and Scarborough et al. (2010) proposed to use a product-group-specific nutrition index in the UF, and Saarinen et al. (2017) introduced an index such as nFU, the Finnish Nutrient Index (FNIprot), for protein-rich foods. However, using different indices according to different product categories leads to different results for the study of LCA.

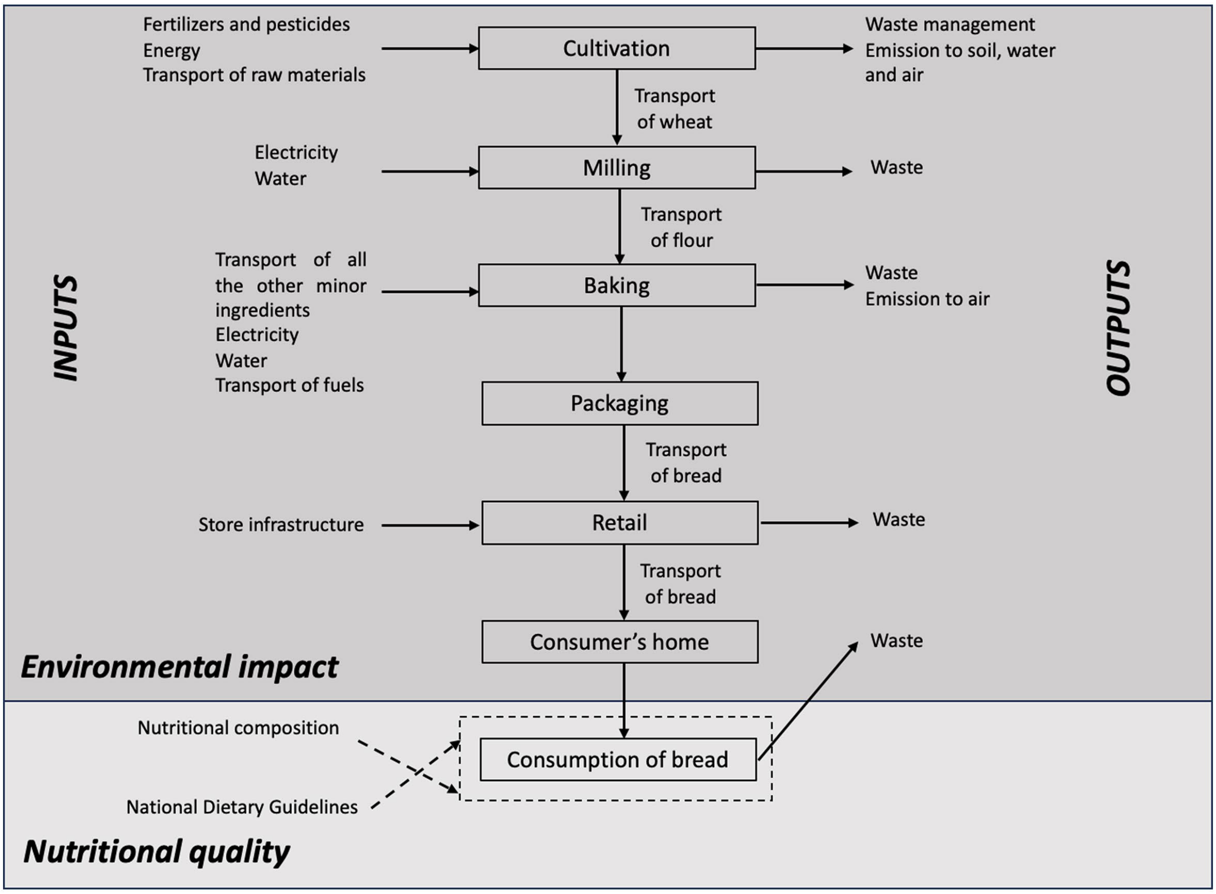

FIGURE 2
Illustrative flowchart considering the environmental impact combined with the nutritional quality of common white bread to provide possible guidance for conducting a nutritional LCA in this food system.

4 Urgent needs for cereal-based food products

Concerning food products, wheat flour, pasta, bread, and bakery products are widely consumed due to their convenience and affordability (Dinelli et al., 2009; Cappelli et al., 2018). For example, Green et al. (2006) underlined that bread is consumed in the UK by 96% of the population, whereas Nadi et al. (2022) stated that bread is featured in the diet of three-quarters of the world's population due to its nutritional and economic value. Accordingly, cereal-based food products are globally considered to be essential for human nutrition because they are an important source of macronutrients (i.e., mainly starch and protein), micronutrients, dietary fiber, and energy (Cappelli and Cini, 2021). In addition, bakery products may contain various bioactive compounds that can provide a series of different health-related benefits (Dinelli et al., 2009). However, as far as we know, no published studies have considered the nLCA of different cereal-based bakery food products. This may be concerning, as integrating nutritional aspects with environmental indicators is particularly important in the context of bakery food systems. Therefore, the goal is to develop a more comprehensive and integrative approach to suggest sustainability strategies for shaping future dietary patterns. In this context, referring to common industrial bread, and after the definition of the FU, one of the possible strategies to conduct an integrated approach should be a system in which the production of inputs to the cultivation of wheat, milling, all types of transportation, energy used, different baking processes, packaging, consumption, and waste management are considered. Of course, similar considerations should be applied not only for major ingredients entering a bread recipe but also for all the minor components, including, but not limited to, water, salt, and yeast. Obviously, all the components can change according to each specific cereal-based food product. Then, accounting for the fact that food serves a nutritional function as well as having direct environmental impacts, the obtained data from the LCA evaluation should be aggregated with the nutritional composition of bread and with the NDGs specific to this type of food product in an effort to provide an all-inclusive approach for current and future food systems (Figure 2).

To date, only a few studies have considered nLCA, but from a general point of view. There are studies in the literature that use nLCA to assess the impact of diet on the environment without considering individual food categories. For example, Batlle-Bayer et al. (2020) defined the FU of a diet as the annual basket of representative food items, divided into eight categories (vegetable base, meat, fish, eggs, dairy, ready meals, desserts, and beverages), consumed by a Spanish citizen that provides the required energy and nutrient intake. They

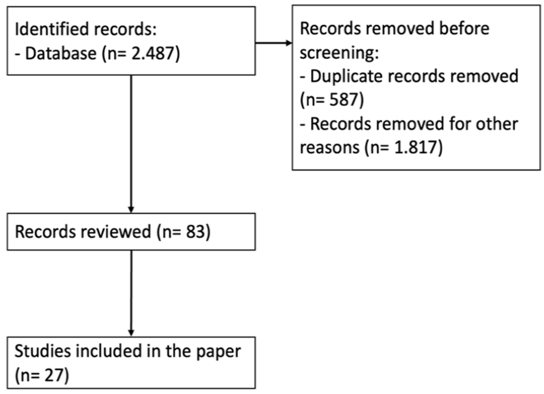

FIGURE 3
Bibliographic research flowchart.

assessed the environmental impacts associated with average regional diets in Spain and those of a diet based on the NDGs. The results showed that the NDG diet could reduce the environmental impact by between 15 and 60% by using this type of FU.

Other studies took protein as the FU of nLCA, considering it only a macronutrient. McAuliffe et al. (2023) stated that, although protein is considered an FU in the nLCA, it does not represent the nutritional value of a protein-rich food because it does not take into account the assessment of the macro- and micronutrients that compose it.

The bibliographic research was carried out on different datasets, and Figure 3 shows the method used to carry it out. It is important to know whether we consider the FU of the nLCA; the category of bakery products is further behind other categories, such as the milk category, in which different functional units have not yet been established and defined. Guerci et al. (2013) were the first to consider 1 kg of fat- and protein-corrected milk (FPCM) as a FU, which is based on fat content (4%) and protein (3.3% of true protein).

5 Future perspective and conclusion

This mini-review took a closer look at how the world of sustainability is gaining momentum. Consideration must be given to the environmental impact that a product and/or product category has on the environment, as the population is expected to increase by 2050. One of the methods used in the food world is LCA, which, based on UNI EN ISO 14040 and UNI EN ISO 14044, gives a general overview of how to approach this type of analysis, which differs from product to product. At the end of the entire process, LCA assesses the environmental footprint of the product and/or product category that has been analyzed. Recent research suggests considering both environmental and nutritional impacts, referring to the nLCA. Especially in the bakery world, this type of analysis is still in its infancy. Therefore, this is an important gap, mainly due to the lack of studies that take into account both the environmental and nutritional footprint. In this context, it is important to look to the future by expanding nLCA studies on bakery products.

Author contributions

MC: Writing – original draft. GG: Writing – review & editing. LMo: Writing – review & editing. MT: Writing – review & editing. AP: Writing – review & editing. LMa: Writing – review & editing. PS: Writing – review & editing.

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Conflict of interest

MT and AP were employed by Bauli S.p.A. LM and PS were employed by Deloitte & Touche S.p.A.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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