



# Beyond nutrients: advancing nutritional Life Cycle Assessment towards food context and health effects

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## 1 Introduction

Over the past century, nutrition science has undergone a significant transformation (Moughan 2020; Mozaffarian et al. 2018). Initially focused on identifying essential nutrients and preventing deficiencies, the field gradually expanded to consider whole foods, meals and, more recently, dietary patterns. As chronic diseases have emerged as the leading public health challenge, their complex and multifactorial etiology underscores the limitations of a reductionist, nutrient-centric approach. This evolution reflects a growing recognition that health outcomes are shaped not only by the amount of nutrients consumed but also by their source, the food matrix in which they are embedded, and the broader dietary context.

In parallel, Life Cycle Assessment (LCA) has emerged as a key methodology for evaluating the environmental impacts of foods (Clark et al. 2022; Gephart et al. 2021; Poore et al. 2018), diets (Aleksandrowicz et al. 2016; Fresan et al. 2019) and food systems (Crippa et al. 2021, 2022; Cucurachi et al. 2019). The integration of nutritional dimensions into LCA—known as nutritional LCA (nLCA)—represents an important step toward assessing the sustainability of foods and diets (Bianchi et al. 2020; Hallström et al. 2018; McLaren et al. 2021). However, many nLCA models continue to rely on nutrient profiling systems that fail to capture the complexity of food-health relationships (McAuliffe et al. 2020; Reguant-Closa et al. 2024). This commentary

argues that nLCA must evolve beyond nutrients to incorporate health effects, aligning more closely with contemporary nutrition science and public health priorities.

## 2 Integrating nutrition science into LCA

Over time, LCA studies of food products and diets have evolved from relying mainly on mass- or volume-based functional units (FUs) to adopting nutrition-based FUs that incorporate metrics such as protein or caloric content (McLaren et al. 2021). More recent work has expanded this approach by considering multiple nutrients simultaneously, recognizing that the nutritional contribution of foods cannot be adequately captured by single-nutrient indicators alone (Katz-Rosene et al. 2023; McLaren et al. 2021). Aggregated nutrient-based scores, traditionally used in nutrition science to classify foods by their nutritional composition, have been proposed as useful metrics for nutrient-based FUs on nLCAs (Hallström et al. 2018; McLaren et al. 2021; Reguant-Closa et al. 2024). Such metrics have been tailored to specific food groups (Kårlund et al. 2024; Kyttä et al. 2023), cross-category assessments (Bianchi et al. 2020; Katz-Rosene et al. 2023), and adapted for specific populations and regional contexts (Bianchi et al. 2020; Torán-Pereg et al. 2025). To improve the reliability of nutrient-based assessments, some researchers have proposed also accounting for nutrients quality and bioavailability (Beal et al. 2025; Berardy et al. 2019; Kyttä et al. 2023; McAuliffe et al. 2023; Sonesson et al. 2017; Stubbendorff et al. 2025; Tukiainen et al. 2025), bioactive components such as antioxidants (McLaren et al. 2021), and dietary context (Sonesson et al. 2019).

Nutritional data are widely available in official food composition databases, and nutrient profile characterization is therefore feasible for researchers and food producers seeking to apply nLCA to food products (Strid, Johansson, et al. 2021b). However, their practical application remains limited due to difficulties in interpreting and communicating

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aggregated nutritional scores as FUs in nLCAs (McLaren et al. 2021; Reguant-Closa et al. 2024; Strid, Hallström, et al. 2021a). Furthermore, a recent review of nutrient intake recommendations—often used in aggregated scores to compare nutrient provision against requirements—highlight the need for additional research to enhance their accuracy (Bajaj et al. 2025). Beyond this, the usefulness of aggregated nutrient-based scores as FUs in nLCA is fundamentally constrained: they fail to account for food matrix effects or capture interactions among foods within dietary patterns—factors that ultimately shape health outcomes (Guo et al. 2022; Strid, Hallström, et al. 2021a; Weidema et al. 2020). Notably, superior nutritional composition does not necessarily equate greater healthiness (Cardinaals et al. 2024).

Building on the limitations of nutrient-based approaches as FUs, some researchers have moved toward explicitly incorporating the healthfulness of foods and diets into nLCAs like an impact category. Two main approaches have emerged (Guo et al. 2022). One complements environmental data with estimated health risks and benefits derived from primary observational cohort studies (Fresán et al. 2019, 2020a, b; Peruvemba et al. 2025), while the other relies on meta-analyses of epidemiological evidence to model disease burden (Rockström et al. 2025; Springmann et al. 2020). Leveraging population-level data on food healthiness could indeed facilitate broader implementation of health-oriented nLCAs (Scherer et al. 2024; Stylianou et al. 2021). Nevertheless, this emerging framework has faced considerable criticism. Key weaknesses include (Guo et al. 2022; Jolliet 2022; Ortenzi et al. 2023; Scherer et al. 2024): (i) the exclusion of certain foods (e.g., beverages, discretionary items) from analyses, which implicitly assumes these foods have neutral health effects; (ii) a tendency to draw strong conclusions about the health impacts of aggregated food categories (e.g., nuts) without addressing variation between specific products (e.g., walnuts vs. hazelnuts); and (iii) a general lack of discussion regarding the quality and uncertainty of underlying data and analyses.

Despite this important and necessary progress toward focusing on the health impact of foods and diets, the shortcomings identified have not consistently driven methodological improvements. Instead, critiques have reinforced the persistence of a narrow approach: most nLCAs still assess healthiness primarily through selected nutrient metrics as FUs. Moreover, even when health impact is assessed, many applications evaluate the health effects of foods and nutrients simultaneously, with little or no attention to mediation effects and food sources of such nutrients (Reguant-Closa et al. 2025; Stylianou et al. 2021; Walker et al. 2019).

### 3 Gaps in nutrient-based nLCAs

A key limitation of nutrient-based approaches is the implicit assumption that nutrients are equivalent across food sources, an assumption that neglects the contextual health effects of foods and diets. The food matrix—the physical and chemical structure in which nutrients are embedded—plays a central role in shaping metabolic responses and nutrient bioavailability (Weaver et al. 2025). Yet even when bioavailability of nutrients is considered, it is insufficient to capture the healthiness of foods. Several examples illustrate these complexities.

Evidence indicates that identical dietary components can have distinct health effects depending on their food sources. For instance, the increased prostate cancer risk associated with calcium appears to be linked primarily to dairy products, whereas calcium from plant sources has not shown the same association (Aune et al. 2015; Xiong et al. 2025). Bioactive compounds further illustrate the limitations of such a reductionist approach. Naturally occurring nitrates in vegetables may support cardiovascular health by promoting nitric oxide production, thereby improving vascular function and lowering blood pressure (Lidder et al. 2013). In contrast, nitrates and nitrites added to processed meats to increase food safety and shelf-life can lead to the formation of carcinogenic N-nitroso compounds, such as nitrosamines, particularly in the presence of heme iron, which catalyzes their formation (Xie et al. 2023).

Sugars offer a clear illustration of the influence of the food matrix. Intrinsic sugars in whole fruits are not associated with adverse health effects; on the contrary, fruits are associated with notorious health benefits (Hay et al. 2025). However, when fruits are juiced, cooked, or otherwise processed, the matrix is disrupted and intrinsic sugars become free sugars. This structural change, combined with reduced satiety due to lower chewing requirements and the frequent removal of fibre, may contribute to the lack of health benefits observed for processed fruit (Della Corte et al. 2025; Mavadiya et al. 2025).

The effect of the food matrix is also evident in the energy provision of nuts. Although nuts are often classified as highly caloric based on gross energy content and are frequently excluded from diets due to concerns about weight gain, epidemiological evidence does not support this assumption. On the contrary, regular nut consumption is associated with healthier body weight profiles (Jackson et al. 2014; Nishi et al. 2021). This discrepancy arises because, due to their complex matrix and incomplete digestibility, the metabolizable energy absorbed from nuts is substantially lower than predicted, challenging simplistic interpretations based solely on caloric values (Tan et al. 2014). Furthermore, their high satiety effect helps regulate subsequent energy intake,

thereby contributing to overall energy balance throughout the day (Tan et al. 2014).

Dietary iron occurs in two forms: heme and non-heme, with the former generally exhibiting higher bioavailability. This differentiation has to some extent been accounted for in nLCAs studies (Katz-Rosene et al. 2023; Kytä et al. 2023). However, greater bioavailability does not necessarily translate into health benefits. Heme iron is more readily absorbed but possesses pro-oxidant properties that may increase oxidative stress and elevate chronic disease risk. In contrast, non-heme iron lacks this pro-oxidative capacity and is not associated with increased risk (Aglago et al. 2023; Chang et al. 2019; Sil et al. 2025; Ward et al. 2019). Moreover, non-heme iron absorption, while generally considered lower, is strongly influenced by both dietary and physiological factors. For example, non-heme iron absorption is inhibited by phytates but enhanced when consumed with vitamin C-rich foods (Heffernan et al. 2017), and is up- or down-regulated according to the body's iron stores (Aglago et al. 2023; Chang et al. 2019; Ward et al. 2019). Therefore, using theoretical bioavailability proportion of non-heme iron may not necessarily reflect its actual absorption.

The need to consider meals and overall dietary patterns—rather than isolated foods—is also evident in the case of protein quality. While protein quality metrics have traditionally been applied as FUs to individual food products (McAuliffe et al. 2023), it has been suggested that incorporating them into multi-nutrient indices offers little or no additional benefit (Tukiainen et al. 2025). Moreover, amino acid complementarity within meals, and even across the day, largely mitigates the suboptimal protein quality of individual foods (Young et al. 1994). Importantly, replacing high-quality animal protein sources with plant-based alternatives—often individually characterized by incomplete amino acid profiles—can yield health benefits (Fernández-Figares Jiménez et al. 2025; Neuenschwander et al. 2023).

These examples highlight that the health effects of nutrients depend not only on their content or bioavailability, but also on their source, the food matrix in which they are embedded, and their interactions within foods and across dietary patterns.

#### 4 Advancing LCA methods to capture health impact

To address these limitations, nLCA must evolve toward a framework that integrates food source differentiation, dietary pattern contextualization, and health impact integration. Food source differentiation requires recognizing that nutrients from different foods can have distinct health effects. Considering the food matrix implies accounting for

the structural and compositional characteristics of foods that influence nutrient bioavailability and metabolic responses. Dietary pattern contextualization entails evaluating foods within realistic consumption patterns rather than in isolation, acknowledging that health effects arise from interactions among multiple foods and nutrients over time within a broader dietary context. This step moves beyond nutrient profiling FU toward assessing the actual health impact of foods and diets, offering a meaningful basis for sustainability and public health decision-making.

Importantly, this does not imply that nutrient-based FUs has no role in nLCA; rather, methods capturing health impact and nutritional quality can complement one another and serve different purposes (Cardinaals et al. 2024; Fresán et al. 2020a, b). Nutrient-based FUs could be used when comparing the same product produced under different production techniques (Montgomery et al. 2022). Additionally, it is especially useful in contexts where nutrient deficiencies are prevalent or where specific nutritional targets are relevant (Beal et al. 2025; Katz-Rosene et al. 2023; Torán-Pereg et al. 2025). Examples include fortification programs, specialized diets for vulnerable populations, or product reformulation to meet public health goals. In these cases, nutrient composition can provide valuable insights into the potential of foods to support nutrition objectives, provided it is interpreted within an appropriate food and dietary context.

Transitioning from a nutrient-centric to a health-focused nLCA framework presents several methodological and practical challenges. One central issue is data availability and quality. While nutrient-composition databases are widely accessible, comprehensive datasets linking specific foods to health outcomes remain scarce and difficult to interpret (Hay et al. 2025; Ortenzi et al. 2023). This gap is especially pronounced for processed and composite foods, where evidence on the health effects of additives, degree and intensity of processing, and food matrix degradation is still emerging (Mendoza et al. 2025). Moreover, health outcomes can vary among individuals and populations due to differences in nutritional status, health conditions, and genetic factors, and they are further influenced by the amount of food consumed according to established dose–response relationships (Guo et al. 2022). Another challenge lies in the substitutive nature of dietary choices: adding one food typically displaces another. As a result, the health impact of a food cannot be assessed in isolation but must be interpreted relative to what it replaces (Chiu et al. 2025; López-Moreno et al. 2025; Sonesson et al. 2019). Moreover, the combined effects of foods are often multiplicative rather than additive, a consideration that is essential when applying nLCA to whole diets (Hay et al. 2025). These dynamics further complicates the integration of health impacts of individual foods into LCA methodologies and reinforces the need for dietary

pattern-based modeling. It should be noticed, however, that methodological challenges are not unique to dietary health impacts but reflect a broader issue across many LCA impact categories: balancing simple, practical models against more complex and contextually relevant approaches that are harder to implement.

Addressing these challenges requires interdisciplinary collaboration among nutrition scientists, epidemiologists, and LCA practitioners, alongside the development of robust databases linking food items to health impacts across diverse population groups. It also calls for methodological innovation to integrate epidemiological data, account for confounding variables, and translate relative risks into meaningful health impact indicators that can be compared across foods, dietary patterns, and populations.

Despite the difficulties, the potential for advancing nLCA is considerable. As the urgency to address climate change, environmental degradation, resource overuse, and diet-related diseases intensifies (Rockström et al. 2025), nLCA could become a cornerstone methodology for driving systemic transformation. Developing approaches that deliver reliable and practical assessments of both nutritional value and health impacts represent not only a scientific breakthrough but also a strategic opportunity to align human and planetary health objectives. A more nuanced, health-informed perspective can enhance the relevance of LCA for public health and sustainability policy. By integrating nutrient-based FU and health-impacts, nLCA can inform educational tools—such as dietary guidelines and food labeling—that are environmentally sustainable, nutritionally sound, and health-promoting, while guiding holistic food policies toward comprehensive food system transformation.

## 5 Conclusion

The evolution of nutrition science from nutrients to foods and dietary patterns has profound implications for nLCA. To remain relevant and scientifically robust, nLCA must move beyond a reductionist nutrient-centric approach and embrace the complexity of food context and health effects. This shift will enable more accurate, meaningful, and actionable assessments that support the dual goals of human and planetary health. By integrating epidemiological evidence, food matrix effects, and realistic dietary patterns, nLCA can become a more powerful tool for guiding sustainable and health-promoting food system transformations.

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## Declarations

**Competing interests** The authors declare they have no financial or non-financial interests to declare.

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