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Editorial: Pushing the Frontiers of nutritional Life Cycle Assessment (nLCA) to identify globally equitable and sustainable agri-food systems

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Editorial on the Research Topic
Pushing the Frontiers of nutritional Life Cycle Assessment (nLCA) to identify globally equitable and sustainable agri-food systems

Introduction

Life Cycle Assessment (LCA) has been applied to food supply chains for decades to identify environmental "hotspots" where action needs to be taken to reduce pollutants of interest or optimize land/resource use as defined under a study's goal and scope definition. The framework is also highly informative for decision making discussions when, e.g., comparing two or more systems performing the same function. Hypothetically speaking, such models may elucidate sustainability-related ramifications of changing ingredients in a food item across relevant environmental indicators (known as "impact categories"), often resulting in trade-offs whereby one system may generate more greenhouse gas (GHG) emissions, whilst another system may generate the same GHG emissions but demonstrate less water pollution. As alluded to, such comparative-based studies are assessed using the same "functional units" (scaling factors intended to represent the *function* of a product or service). In agri-food LCAs, functional units are commonly reported in the form of mass, volume or area at a system boundary's point of exit, often at the point of leaving the farm (cradle-to-gate). As environmental awareness is rapidly increasing globally, sustainability-related scientific research questions are targeting the consumer-facing side of food systems (cradle-to-plate). As a result, decisions made at the point of sale cannot be reliably informed using mass, volume or area alone; hence, nutritional LCA (nLCA; McLaren et al., 2021) has emerged as a sub-framework of LCA exploring the environment-nutrition nexus. Broadly speaking, nLCA can be broken down into three tiers pending a study's goal (McAuliffe et al., 2020): (1) single or multiple *individual* nutrients as functional units (McAuliffe et al., 2023; Saarinen et al., 2017); (2) adopting *composite* nutritional metrics (Katz-Rosene et al., 2023); (3) augmenting one or both of the first two tiers with the *direct* effect of a system's impact to human, or indeed planetary health (e.g., potential rises or falls in non-communicable diseases or species abundance, respectively). This additional layer of complexity is often assessed through the development of novel end-point impact assessments (LCIAs) and *multi-level* trade-off analyses, naturally making interpretation of such studies challenging (Ortenzi et al., 2023; Stylianou et al., 2016, 2021).

Building upon the brief introduction to nLCA hitherto, the sub-framework's evolution is reliant on multidisciplinary collaborations which, for simplicity, are described in the present editorial under four broad yet overlapping topics: functional units; nutritional complexities; data availability; and future directions. This editorial introduces 12 articles which, collectively, demonstrate how nLCA is evolving into a multi-faceted sustainability assessment framework that is highly informative for *consumers*, relative to, e.g., *producers*, the former of whom are arguably the most important food-system stakeholders under cradle-to-plate system boundaries. As will become clear in the subsequent sections, certain articles in this novel compendium on nLCA are applied case studies showcasing the method's capabilities, whilst others propose methodological advancements or considerations. The "data availability" and "future directions" sections draw the reader's attention to another branch of articles which raise awareness of beneficial issues to the progression of nLCA, or further, provide novel data and/or information to do so.

Nutritional LCA functional units

"Nutritional functional units" have been adopted for well over a decade by reporting LCIAs based on, e.g., energy (kcal/mass unit) or protein (g/mass unit) content in agri-food commodities, thus preceding the *formal* development and subsequent rise of nLCA. Given the importance of functional units when answering specific research questions (i.e., goal and scope definitions), they have perhaps received the most methodological attention in literature surrounding "pushing the frontiers of nLCA," both *within* the current Research Topic *and* beyond. Apart from utilizing individual nutrients (quite commonly total protein as demonstrated by Poore and Nemecek, 2018b, a nutrient with limitations of its own discussed elsewhere; McAuliffe et al., 2023) the most common way of transforming functional units into a nutritional lens is via utilization of composite nutritional scores such as the Nutrient Rich Food (NRF) index as proposed by Fulgoni et al. (2009). At the simplest level, using NRF or similar nutritional metrics as a functional unit standardizes the nutritional content of a food against the recommended intake levels in a target population (thus offering the benefit of being able to consider differences in nutritional requirements between different population groups) for a range of nutrients, including nutrients to promote and nutrients to limit, when assessing a food's environmental footprint (Majumdar et al.). Countless authors have developed bespoke variations of the NRF-style approach (see McAuliffe et al., 2020), but one novel and interesting approach stands out within the current Research Topic by Majumdar et al.. The authors applied composite-based nutritional functional units to a "toppings on toast" case study, to evaluate the effect of NRF choice (9 vs. 28 nutrients to encourage) when assessing climate change impact of different toast topping options. This novel adoption of nLCA is interesting not only to developers/practitioners, but also consumers worldwide given the global applicability of using toppings on food (e.g., condiments), not just toast.

McNicol et al. build upon and evolve earlier, simpler work conducted alongside the development of the UK Nutritional Index (UKNI; McAuliffe et al., 2018) by focussing on long-chain polyunsaturated fatty acids (specifically omega-3 fatty acids) as individual nutritional functional units. The study represented sheep production systems in the UK, with inventory analyses conducted using a combination of primary, farm-level data and a commercial process-based model for calculating GHG emissions. Also important to note, both McNicol et al. and Wingett and Alders add to sustainability literature of ovine production systems, with the latter focussing upon nutrient losses from Australian supply chains, strengthening the overall contribution to (n)LCA literature contained within the present Research Topic.

Whilst Cardinaals et al. present an interesting discussion on the strengths and weaknesses of various approaches to nLCA, including complexities surrounding functional units, their study is more nutritionally complex than other (n)LCAs and thus covered in more detail in the next section. The compendium of articles introduced here also includes a useful bibliographic resource in the form of a "mini review" on bakery products, whereby Cassarino et al. also consider methodological considerations of waste in nLCA, an understudied yet emerging topic of interest.

Nutritional complexities and associated uncertainties

Foods contain thousands of compounds, most of which scientists have limited understanding of, especially with respect to how they interact and form complex matrices (Barabási et al., 2020). Diverse genetic characteristics, as well as variability in nutritional, developmental and health status across individuals further complicate our ability to understand how specific foods and nutrients impact human health (Stover and Caudill, 2008). Limitations relating to availability of reliable food composition data and nutritional intake estimation also hinder the implementation of scientific best practices in nLCA, as demonstrated in this editorial and associated articles. These factors collectively explain the significant challenges in quantifying the nutritional *quality* of foods for use in nLCA.

Articles in this Research Topic highlight several key aspects of nutritional complexity in nLCA. Cardinaals et al. demonstrate that nutrient density and the estimated disease burden associated with a food complement each other as measures of nutritional quality, emphasizing the need for comprehensive approaches that consider both nutrient content and health impacts in line with global expert recommendations (Scherer et al., 2024). Cassarino et al. underscore the importance of incorporating factors like satiety and the need to consider both beneficial and harmful aspects of foods, suggesting integrated indices as a means to provide a more complete picture of a food's nutritional impact. Majumdar et al. identify significant variability and uncertainty in nutritional impacts due to factors such as production practices, food varieties, and population-specific contexts, advocating for flexible, context-sensitive approaches in nLCA. These findings collectively point to the multifaceted nature of nutritional assessment(s) in LCA and stress the importance of considering a wide range of factors to accurately capture food's nutritional value.

The key research gaps highlighted by these studies center on the need for more comprehensive approaches to capture the full complexity of nutritional impacts in LCA. This includes improving our understanding of nutrient bioavailability and interactions within food matrices, long-term health impacts of dietary patterns, and population-specific nutritional effects. There is also a need for better methods to quantify and integrate both beneficial *and* potentially harmful aspects of foods, as well as physiological responses like satiety and social impacts associated with purchasing (e.g., rural/community-based "localness") and improvements to mental health via "family mealtime," for instance. Additionally, researchers face challenges in scaling up assessments from individual foods to capture broader diets (or indeed dietary changes and associated yet unintended consequences) and food system levels while *maintaining* the accuracy and relevance expected from environmental LCAs under international standards such as ISO 14044. Addressing these gaps, perhaps via formal standard development, could improve the ability of nLCA to provide more complete pictures of cross-pillar agri-food sustainability assessments considering nutritional dimensions.

Data availability and geographical representation

Whilst this Research Topic of publications cannot in any degree be considered representative of nLCA literature overall, a brief scan of scientific repositories will largely concur with the reality that, until recently, most contributions to cutting-edge sustainability assessments occur in, and/or focus on, high income countries, an observation bolstered by Poore and Nemecek (2018a). This is by no means a novel observation, e.g., see table 1 in Roy et al. (2009), but it indicates an element of data-based stagnation manifesting as a barrier restricting *rapid* expansion of nLCA to low- and middle-income countries where: (a) it is potentially more societally impactful as more is already known about the environment-nutrition nexus in high-income countries, and (b) there are anecdotally-indicative demands for novel, sustainability-focussed research projects evidenced by recent efforts to achieve this (Kamudoni et al., 2024; Ndung'u et al., 2022). The present Research Topic goes some way to breaching geographical representation barriers by offering crucial data to directly inform nLCAs, or, at the very least, develop locally specific, detailed goal and scope definitions. For instance, Duvivier et al. use social science methods (a mix of quantitative surveys and qualitative interviews) to identify localized issues such as gender inequalities and associated health statuses between male and female farmers in Haiti. This approach provides (n)LCA scientists with the foundations to follow up with a cross-pillar (i.e., environment-economic-nutrition/health) system-scale analysis, not dissimilar in data-driven impact potentials offered by Sarma et al. in Bangladesh.

Granados-Echegoyen et al. provide more direct nutritional data on a highly topical subject: edible insects. The authors not only provide broad nutritional values of native insects in multiple nations across Latin America and the Caribbean, they also provide detailed amino acid and fatty acid profiles, as well as antinutrient factors, all of which combined lay a pathway to fulfilling previous recommendations surrounding fatty acid and amino acid complexities (McAuliffe et al., 2018, 2023) by developing or enhancing sophisticated nutritional metrics, with the Nutritional Value Score (NVS; Beal and Ortenzi, 2023) being one such holistic example.

Future directions for nLCA

Although not all articles presented as part of this Research Topic ("Pushing the Frontiers of Nutritional Life Cycle Assessment") are nLCAs themselves, each one contributes to the scope *and* capability of nLCA, either geographically speaking or via methodological innovations; thus, this Research Topic improves the efficacy of decision-making based on such studies. Due to available space, each article was not discussed in detail herein; nevertheless, as presented in this brief introduction to the Research Topic, aforementioned enhancements to scope and efficacy arise from three broad topics: (1) novel functional units or discussions thereof; (2) nutritional complexities which require attention by LCA scientists through collaboration with expert colleagues in the nutrition, health, and social sciences; and (3) data restrictions and routes to overcome them, each of which is addressed by this novel compendium. Further, it is important to acknowledge that each of the topics are interlinked. For instance, data restrictions may be summarized from both an environmental perspective and a nutritional perspective as follows: (i) environmentally speaking, poor geographical coverage of low- and middle-income countries' inventory compilation data, as well as understandings of local/regional agricultural, cultural, and cooking uniqueness all need to be improved in terms of data transformations and model interpretations; (ii) Improving nLCA through a nutritional science lens is more challenging, as the issues are known (e.g., differences in product quality arising from digestibility and bioavailability of individual nutrients), but are incredibly difficult to measure. However, as our understanding improves from what experimental data *already* exists, metrics such as the NVS (Beal and Ortenzi, 2023) are, in time, going to produce more insightful messages via nLCA. With the above issues in mind, the guest editorial team hopes you see the value of each of the studies included herein and enjoy reading them. More importantly, the team hopes the Research Topic inspires future nLCAs, regardless of whether methodologically-focussed or the development of new research questions, which would not only fill gaps in the current evidence base, but also aid consumers in making more environmentally friendly and simultaneously nutritionally beneficial decisions at the point of sale.

Author contributions

GM: Conceptualization, Project administration, Validation, Writing – original draft, Writing – review & editing. TB: Project administration, Validation, Writing – original draft, Writing – review & editing. ML: Project administration, Validation, Writing – review & editing. JP: Project administration, Validation, Writing – review & editing.

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Conflict of interest

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