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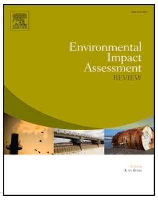

Can we estimate the impact of small targeted dietary changes on human health and environmental sustainability?

Flaminia Ortenzi [a], Graham A. McAuliffe [b,*], Frédéric Leroy [c], Stella Nordhagen [a], Stephan van Vliet [d], Agustin del Prado [e,f], Ty Beal [g,*]

[a] Global Alliance for Improved Nutrition (GAIN), Rue de Varembé 7, 1202 Geneva, Switzerland
[b] Net Zero and Resilient Farming, Rothamsted Research, North Wyke, Okehampton, Devon EX20 2SB, UK
[c] Industrial Microbiology and Food Biotechnology (IMDO), Faculty of Sciences and Bioengineering Sciences, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium
[d] Center for Human Nutrition Studies, Utah State University, Logan, UT 84322, USA
[e] BC3 Basque Centre for Climate Change, Scientific Campus of the University of the Basque Country, 48940 Leioa, Spain
[f] Ikerbasque — Basque Foundation of Science, E-48007 Bilbao, Spain
[g] Global Alliance for Improved Nutrition (GAIN), Washington, DC 20036, USA

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ABSTRACT

A recent analysis by Stylianou et al. (2021) estimated the impact of small dietary changes in the consumption of individual foods on human health and the environment, expressed as minutes of healthy life lost or gained daily combined with dietary carbon footprints. While an appealing concept given its simplistic interpretation, we aim to draw the attention of nLCA practitioners and developers to the significant limitations and uncertainties of this analysis, based on existing evidence. Stylianou's approach produces results that fail to recognize the importance of essential nutrient density and the risks associated with ultra-processed foods, added sugar, and refined starches. The novel impact assessment undoubtedly brings a new perspective to the growing field of nutritional Life Cycle Assessment. However, the authors neglect numerous methodological limitations, fail to direct the readers' attention to (mis)interpretation risks, and draw highly definitive recommendations aiming to directly influence consumer choices and policymaking. Due to extensive data limitations and associated uncertainties in extant databases (both environmental and nutritional), we recommend caution in the use of this (or any other) food classification system to inform consumer behavior, front-of-package labelling, policies, and programs.

1. Introduction

There is consensus among sustainability-orientated scientists that unhealthy diets and environmental degradation are two of the greatest global challenges of our time (Rockström et al., 2021; Willett et al., 2019). A common scientific focus has thus been on developing diets that simultaneously improve human health and the wider sustainability of food systems, at all scales: local, national, or global. Most of the relevant literature, often highly simplified through modelling 'reductionism' (Leroy et al., 2022), recommends substantially limiting intake of animal-source foods in favor of plant-source foods (Willett et al., 2019). Given the over-consumption of nutrient-poor and energy-dense ultra-processed foods and low intakes of minimally processed plant-source foods, such as fruits, vegetables, legumes, whole grains, nuts, and seeds, in many diets across the world, increased consumption of the latter certainly holds potential to improve population health. However, issues of nutrient adequacy, affordability, and cultural acceptability have not yet been fully integrated into these recommendations (Beal, 2021; Beal et al., 2023a; Hirvonen et al., 2020).

Nutritional Life Cycle Assessment (nLCA), a rapidly growing subfield of LCA, is gaining popularity as demonstrated by the number of publications being released each year over the last decade (McAuliffe et al., 2020). In brief, nLCA aims to appropriately address the food- *or* nutrition-environment nexus by integrating the nutritional and health sciences into the LCA framework (e.g., McLaren et al., 2021, who carried out the first comprehensive assessment of state-of-the-art nLCA and identified common weaknesses which are relevant to the current discussion, i.e., data gaps and uncertainties). There are, *broadly* speaking,

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* Corresponding authors.
E-mail addresses: graham.mcauliffe@rothamsted.ac.uk (G.A. McAuliffe), tbeal@gainhealth.org (T. Beal).

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three tiers to carrying out an nLCA (McAuliffe et al., 2020): (Tier 1) using one or more single nutrients as a functional unit, with (total) protein being the most commonly used denominator; (Tier 2) the inclusion of composite nutritional indicators, often known as nutrient density scores, to assess, for example, how much of each food is required to meet a specified proportion of recommended nutrient intakes for a range of nutrients (often subjectively defined) for a certain population; and (Tier 3) developing novel Life Cycle Impact Assessments (LCIA) to complement existing ones, usually at the end-point level (e.g., accounting for a product or service's impact on human health), and then carrying out a trade-off analysis to determine optimal food commodities across a range of impacts. As is common with many stepwise changes in complexity, i.e., moving from Tier 1 to Tier 3 in this case, the uncertainties of results become exponentially higher and more challenging to capture. A simple example of this in environmental LCA is when a researcher calculates nitrate and phosphate losses to water arising from a system under investigation at the mid-point level (e.g., water-based acidification and eutrophication potentials) and then attempts to interpret the damage caused to aquatic biodiversity at the end-point level. This analogy can also be applied to the impact of foods on human health.

A recent analysis by Stylianou et al. (2021), which we suggest falls under nLCA Tier 3 as defined by McAuliffe et al. (2020), estimated the impact of small dietary changes related to the consumption of individual foods on human health and the environment, expressed as minutes of healthy life gained or lost daily combined with dietary carbon footprints. In other words, the authors conducted a trade-off analysis using a subjective weighting system to rank each food by its healthfulness and environmental impact. While an appealing concept for its simplistic interpretation, we aim to draw the attention of nLCA practitioners and developers to the significant limitations and uncertainties of this analysis, based on existing evidence. For instance, we argue that the results produced by the authors fail to recognize the importance of essential nutrient density and disregard risks associated with ultra-processed foods, added sugar, and refined starches. The novel impact assessment undoubtedly brings a new perspective to the growing field of nLCA, and the use of 'ready-made' environmental impact values arising from food items (i.e., those coming from peer-reviewed databases or literature) is common practice within nLCA due to direct supply-chain data restrictions. However, in this case the authors draw highly definitive recommendations, a practice rarely, if ever, carried out by nLCA practitioners, and which could have strong implications for consumer choices and policymaking.

For clarity, we contacted Stylianou et al. (2021) in the hope of discussing our concerns with their approach, but they did not reply to our correspondence. We believe these concerns are worth discussing, and hope our contribution will foster further scientific debate within the nutritional and environmental communities which are working closer together at an ever-increasing rate. At present, we recommend the (n) LCA community to exercise caution in using Stylianou et al.'s (2021) food classification system (or any other) to inform consumer choices, front-of-package labelling, or policymaking. We lay out the foundations for our concern below with a specific focus on nutritional weaknesses (including data uncertainties and reductionist approaches) which LCA experts may not be aware of as they move into the realm of nLCA. We conclude our discussion with six recommendations to assist LCA practitioners with *interpreting* a health-based (or 'Tier 3′ as outlined above and illustrated schematically in McAuliffe et al., 2023a) nLCA study appropriately, that is, by minimizing risks associated with uncertainties and misinformation.

2. Concerns about the health benefits and risks analysis

Stylianou et al. (2021)'s approach focused on making small dietary changes in the consumption of single foods rather than overall diets. The authors developed the Health Nutritional Index to quantify the minutes of healthy life gained (+) or lost (−) per serving of individual foods (or mixed dishes). Health Nutritional Index scores were calculated by combining the marginal health burden associated with 15 dietary risk factors from the 2016 Global Burden of Disease study (Vos et al., 2017). This approach is founded on the assumption that it is possible to reasonably estimate the quantitative health burden of individual dietary components. However, the relationship between food and health is incredibly complex. Foods are consumed as part of the broader diet consisting of meals with nutritional complementarities, which is only one of the many individual-level determinants of health, together with other lifestyle (e.g., exercise, tobacco use, alcohol consumption, stress, sleep quality) and biological (e.g., genetics, age, sex) factors. In turn, these elements interact with numerous socio-economic, environmental, and commercial determinants (e.g., education, income, access to healthcare, and localized pollution) over the course of a lifetime (WHO, 2022). Given the intricateness of the relationship between food and health, quantifying the minutes of healthy life gained or lost per serving of individual foods consumed is problematic. A related issue pertains to using estimates from the Global Burden of Disease study, which has several important limitations (Beal et al., 2019). Indeed, concerns have been raised about the transparency, methodological robustness, and credibility of the dietary implications of the Global Burden of Disease study, which assumes causal relationships between single dietary components and health outcomes and may have led to a false sense of confidence in uncertain estimates (Beal et al., 2019; Lescinsky et al., 2022; Stanton et al., 2022). Stylianou et al. (2021) added an additional layer of uncertainty by applying population-level health burden estimates to the individual level, disregarding factors contributing to individual variability and local context, which are important to capture in health impact assessments (Leuenberger et al., 2019).

Importantly, Health Nutritional Index scores assume that dietary components not included in the Global Burden of Disease study have neutral health effects (Stylianou et al., 2021). Yet, several food components and attributes associated with health benefits or risks are not covered by the Global Burden of Disease study (Beal et al., 2019). For example, calcium is the only micronutrient included among beneficial dietary risk factors, while all other essential vitamins and minerals are not considered, even though deficiencies in other micronutrients such as iron, zinc, folate, vitamin B_{12}, vitamin A, and vitamin D are common worldwide, causing substantial public health burdens (Stevens et al., 2022). Protein and essential amino acids are also omitted, even though it has been estimated that 1 billion people worldwide do not consume enough protein (Wu et al., 2014), and inadequate consumption of certain essential amino acids (e.g., lysine and methionine) has been implicated in poor child growth and development in many low- and middle-income countries worldwide (Parikh et al., 2022).

Further, milk is listed as a beneficial dietary risk factor, whereas other nutrient-dense animal-source foods such as yogurt and eggs are not. Among harmful dietary risk factors, sugar and refined starches are not considered (Beal et al., 2019), yet they are associated with the noncommunicable disease epidemic (Cordain et al., 2005). Sugar-sweetened beverages are the only ultra-processed food included, despite the substantial evidence linking ultra-processing per se with negative health outcomes (Hall et al., 2019; Lane et al., 2021). On the contrary, although the evidence suggests that, when minimally processed and consumed in moderation as part of a balanced diet, red meat does not significantly increase risk for noncommunicable diseases (Beal et al., 2023b), it is listed as a harmful dietary risk factor regardless of its level of processing, with no consideration for its density in high-quality protein and bioavailable micronutrients commonly lacking in diets globally, including iron, zinc, and vitamin B_{12} (Beal and Ortenzi, 2022).

The little-to-no consideration for the type of processing and its health implications, and the assessment of foods' nutritional performance based on a limited number of dietary risk factors, illustrates a common issue in nutritional science, namely that of reductionism (Fardet and Rock, 2020). For instance, vegetables, legumes, and whole grains are only considered in terms of fiber content, disregarding the added value of the food matrix, which goes beyond single nutrients. Further, no distinction is made between naturally occurring or fortified nutrients, even though fortification is unlikely to fully replicate the potential benefits of the food matrix (Jacobs and Tapsell, 2007). Indeed, foods are more than the mere sum of their nutrients. The food matrix can be seen as the physical domain in which a set of complex physical and chemical interactions between over 70,900 food compounds (comprising both nutrients and non-nutrients) take place (FooDB, 2022). This matrix provides foods with specific characteristics, functionalities, and behaviors which are different than those of their individual components taken in isolation (Aguilera, 2019) and which synergistically impact metabolism, including nutrient absorption, and may have beneficial effects on satiety and the immune system (Aguilera, 2019; Barabási et al., 2020). The quality of the food matrix is greatly affected by the type and level of processing; it is thus crucial to consider processing when assessing the nutrition and health impacts of foods (Fardet and Rock, 2020).

In our view, these limitations result in numerous unjustified Health Nutritional Index scores (Fig. 1). For example, peanut butter and jelly sandwiches—the vast majority of which are made with bread from refined grains and jelly with added sugars—are the food category with the highest median score (+33 min), only remotely comparable to nuts and seeds (+25 min). Non-starchy vegetables (+3 min) receive a similar score to ready-to-eat cereals (+4 min) and snack/meal bars (+3 min); whereas candy (0 min), sugar (0 min), and sweet bakery products (0 min) all are apparently neutral and score higher than poultry (−2 min), eggs (−3 min), and red meat (−6 min).

3. Issues related to nutritional life cycle assessment

3.1. *Risks related to dietary advice based on novel modelling methodologies*

Stylianou et al. (2021) combined Health Nutritional Index scores with pre-calculated environmental LCAs (e.g., sourced from *ecoinvent* and *World Food LCA Database*) to classify foods based on their combined health and environmental impacts. While the idea of providing consumers and other stakeholders with simple guidance on the health and environmental effects of individual foods is appealing, our issue is with the limitations of the methodology and conclusively interpreted results reported by the authors.

One of our main concerns is the authors' attempt to directly influence both health and environmental policy based on the results of a study that is mostly focused on methodological advancement rather than applied science, which is unclear from the authors' conclusions and assessment of limitations. There are inherent uncertainties in (n)LCA models, which become borderline random (i.e., involving large degrees of uncertainty) when moving towards end-point modelling, such as assessing impacts on human health (e.g., individuals have different health and socio-economic status and dietary habits, which cannot be standardized). Stylianou et al. (2021) add an extra layer of uncertainty by pairing nutritional and environmental datasets which are not derived directly from the same supply chain (a common practice in nLCA due to 'direct' data availability restrictions). This additional uncertainty is difficult to account for because of heterogeneity at both the landscape level (McAuliffe et al., 2022) and the supply-chain level (McAuliffe et al., 2018). However, as briefly alluded to above, avoiding this issue is not always possible, and developing tailored, primary-data-driven Life Cycle Inventories (LCIs), which would be ideal in nLCAs, is enormously time-consuming, despite work on-going in this area by industry and scientists.

Therefore, while LCA models can be useful and informative, attempting to influence consumer choices and policymaking directly contravenes the uncertain nature of these models, particularly in the growing field of nLCA, which has yet to have official standard practices in place (McAuliffe et al., 2020; McLaren et al., 2021). Nevertheless, Stylianou et al. (2021) conclude that their findings enable '*decision-makers to quantitatively evaluate the performance of recommended diets and identify the best individual foods meeting these recommendations that will maximize health benefits while minimizing environmental impacts*', and provide '*evidence-based guidance to inform agricultural policy and health-promoting revisions of current food assistance programmes, accounting for both health and environmental considerations, and identifying which foods to incentivize, disincentivize or restrict.*' This reference to incentivizing (or disincentivizing) is treading dangerous territory, as unintended consequences of decreasing intake of nutrient-dense foods (such as animal-source foods) need to be examined, both from a nutritional and environmental perspective (including indirect land use change via displaced food production). In addition, economic modelling would need to supplement this work to assess the implications on rural economies, a knock-on factor the authors appear to have overlooked.

3.2. *Consideration of agricultural heterogeneity when assessing environmental impacts*

We commend Stylianou et al. (2021) for their extensive attention to environmental concerns, both at the mid-point and end-point level of LCA (for example, see Supplementary Table 7 provided by Stylianou et al., 2021), which is uncommon in agri-food LCAs. However, a major limitation of Stylianou et al. (2021)'s analysis, and many (n)LCAs more broadly, is an oft-applied simplistic approach, which typically uses nationally or regionally averaged environmental impact values that do not reflect the complexities inherent in agriculture (Adewale et al., 2018; Leroy et al., 2022). Indeed, agri-food systems are, by nature,

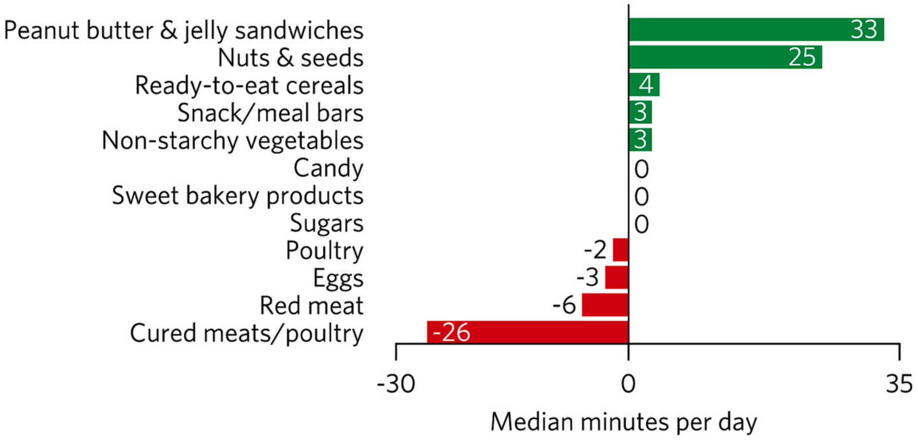

Fig. 1. Illustrative examples of select Health Nutritional Index scores. These data were extracted from Supplementary Table 5 in Stylianou et al. (2021).

heterogeneous. For example, farmers use differing amounts of fertilizers depending on soil type and quality, pesticides, and, in the case of animal-based farming, apply different stocking densities and achieve various feed conversion ratios. These management decisions affect yield and overall efficiency, whether the end products are animal- or plant-source foods. As a result, the environmental impacts of both plant- and animal-source foods vary substantially depending on production methods, as well as agroclimatic and ecological characteristics (Kremen and Miles, 2012; Lark et al., 2020). Yet, in Stylianou et al. (2021)'s food classification most plant-source foods are included in the 'green zone' (to increase), while most animal-source foods fall within the 'amber' (tolerable) or 'red zone' (to decrease) based on national- or regional-level data lacking sufficient consideration of worldwide agricultural heterogeneity.

Additionally, the definition of these color zones is problematic, generating important trade-offs between nutritional and environmental sustainability. For instance, the 'red zone' includes foods assumed to be *either* highly nutritionally detrimental *or* highly environmentally detrimental. Given that foods with high nutritional value do not always produce low environmental impacts, they risk being labelled as 'to decrease'. On the contrary, lean red meat sourced from wildlife (e.g., venison steak) has both high nutritional value, as well as low environmental impacts compared to domesticated livestock (Fiala et al., 2020), but also risks being labelled as 'to decrease' under Stylianou et al.'s (2021) approach because of red meat being intrinsically considered as a harmful dietary risk factor (independently from its level of processing, fat profile, and mitigation of potential harms by healthy background diets).

3.3. *Sensitivity analysis coverage and allocation issues*

Another issue we have identified within the authors' methodology is that, while their Taylor expansion analysis might capture *many* (but not all) environmental system-level propagation errors, their choice of sensitivity analysis requires further justification. For example, the authors carry out a robust sensitivity assessment of the environmental impacts associated with greenhouse cultivation; however, there appears to be little attention paid to animal-based produce except for the authors' uncertainty analysis. As discussed in detail in Section 3.2, domesticated livestock production systems are highly heterogeneous at local, national, regional, and global levels, and consequently are worthy of exploring in more detail as compared to foods which typically have lower environmental footprints (i.e., greenhouse-cultivated produce). Although Stylianou et al. (2021)'s supplementary material generally provides granular details of modelling assumptions, we contend that the authors' justification for focussing on greenhouse-cultivated produce is insufficient: '*As a sensitivity analysis, seven complementary ingredient-LCI pairs were considered to represent heated greenhouse cultivation. This addition aimed to illustrate the variability of environmental impacts for the same food as a function of differences in the ingredient production methods*' (Stylianou et al., 2021; Supplementary Material Report). This is particularly puzzling as the authors openly acknowledge that animal-source foods (particularly ruminant-based systems) present large variability regarding impacts to nature and human health which would inevitably affect the numerator (i.e., pollution potentials) of animal-based produce, and therefore their overall environmental impact scores, due to the effect of changes in individual LCI parameters (e.g., enteric methane, manure management ammonia, and nitrous oxide emission factors applied to various nitrogen-based fertilizer rates for feed production; Takahashi et al., 2019).

Finally, despite the authors' admirable attention to system-wide uncertainties, they do not appear to have addressed other complexities such as those associated with their choice of allocation (i.e., economic) between co-products and reference flows, which does not adhere to LCA best practice involving subjective decisions (ISO 14040, 2006). Allocation procedures of co-products have been demonstrated to drastically affect the interpretation of LCAs (Rice et al., 2017) and should therefore receive much more attention than covered in Stylianou et al. (2021).

4. Recommendations surrounding nutrition-environment trade-offs

Based on the above concerns related to Stylianou et al. (2021)'s analysis, we suggest six simple interim steps to reduce subjectivity-related bias in 'Tier 3' nLCAs (as defined by McAuliffe et al., 2020, and visualised by McAuliffe et al., 2023a), including Stylianou's, until formal protocols are developed (where still missing), and to minimize potential risks to human (and environmental) health via misinterpretation of modelling studies, particularly those that involve comparing foods that play different roles within diets (e.g., comparing protein-rich foods with carbohydrate staples). Here are our six recommendations for conducting a Tier 3 (or health-based) nLCA:

1. When conducting nLCAs, determine if the chosen nutritional functional unit or impact assessment fairly represents the nutritional profile and quality of *all* food items being compared (McAuliffe et al., 2023b); if not, consider breaking the analysis down into directly comparable products which play similar roles within diets (e.g., protein sources vs. protein sources and carbohydrate staples vs. carbohydrate staples, etc.).
2. As far as feasibly possible, source modelling data (both environmental and nutritional) from the same geographic region under investigation and try to minimize mixing data sources for baseline analyses to reduce the risk of incompatible system boundaries in the case of LCIs and different nutritional content and/or quality in the context of food composition.
3. Identify the most sensitive parameters determining an nLCA's results and test these assumptions using best- and worst-case scenarios as well as distributions (in the case of uncertainty analyses), both of which should be transparently reported; other data sources can, and perhaps should, be adopted in this step, but the geographic boundary should remain the same unless relevant to the research question (e.g., in the case of imported foods which may have different nutritional profiles to domestically produced foods, thus affecting both health and environmental impact assessments, where applicable).
4. Given the notable uncertainties associated with modelling, especially when moving towards the end-point level of (n)LCA, practitioners should *never* make conclusive recommendations to consumers based solely on nLCA results, particularly given extant concerns surrounding data sources and quality thereof (McLaren et al., 2021) required to reach such conclusions. Interpretation of models with such high degrees of uncertainty should be objective and not used to advise dietary choices, particularly when said advice is based on novel methodologies not widely applied nor robustly validated through replication and deeper interpretation (e.g., carrying out sensitivity analyses on multiple products which provide various dietary functions).
5. To aid policymakers with potentially useful outputs and associated decision-making, always include a limitations section that outlines all subjective decisions (e.g., data sources' fallibility, allocation approach(es), nutrients included and why) which would affect the model's interpretation. Ideally these limitations should be quantitatively addressed and reported using appropriate statistical approaches.
6. Out-scaling of results to broad(er) geographic regions, regardless of similar supply-chain production practices, should be avoided unless considered carefully. This is largely because the nutritional requirements of some populations and sub-populations may differ from others due to, for example, energy requirements for highly active or sedentary people, protein needs of the elderly or diseased, prevalence of nutrient deficiencies, as well as climatic conditions such as high temperatures which may increase perspiration thereby likely

requiring higher levels of sodium intake to replace increased losses compared to those living in more temperate areas.

5. Conclusion

To conclude, Stylianou et al. (2021) attempted to translate complex nutritional and environmental information into simple scores to inform decision-making by consumers and other stakeholders. While their classification of foods into color zones, and their recommendations for targeted dietary changes, might be relatively easy to understand and act upon, many of the obtained scores are unjustified, overly simplified, and overlook many trade-offs for human nutrition (and thereby health) and the environment (as outlined in Sections 3.1 and 3.2). The proposed method is undoubtedly of theoretical interest to the novel field of nLCA. However, if used to directly inform decision-making, whether top down (e.g., policy, front-of-package labelling) or ground up (e.g., food baskets), the resulting food classification may have negative implications for nutrient adequacy and reinforce the consumption of nutrient-poor yet energy-dense, ultra-processed foods, added sugars, and refined starches. Furthermore, the authors overlooked other important sustainability issues affected by their scoring mechanism, such as unintended effects on the environment (e.g., indirect land use change), the economy (changes in supply and demand), and broader societal issues such as workforce wellbeing (and, where applicable, animal welfare). We urge scientists producing nLCAs to take a more cautious approach regarding interpretation of results, given the high uncertainties and potential for unintended negative consequences.

Author contributions

FO, GAM, and TB wrote the manuscript. All authors critically reviewed, revised, and approved the final manuscript.

CRediT authorship contribution statement

Flaminia Ortenzi: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Graham A. McAuliffe:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Frédéric Leroy:** Writing – review & editing. **Stella Nordhagen:** Writing – review & editing. **Stephan van Vliet:** Writing – review & editing. **Agustin del Prado:** Writing – review & editing. **Ty Beal:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

FO, GAM, SN, and TB declare no competing interests. SvV reports travel reimbursements for academic talks but does not accept speaking fees from food industry groups/companies. FL is a non-remunerated board member of various academic non-profit organizations including the Belgian Association for Meat Science and Technology (president), the Belgian Society for Food Microbiology (secretary), and the Belgian Nutrition Society. On a non-remunerated basis, he also has a seat in the Scientific Board of the World Farmers' Organization. The views he expresses in this commentary are his alone and not necessarily those of the aforementioned organizations. AdP in his role as researcher within BC3 reports having received funds from CAPSA Food, The Global Dairy Platform and Friends of the Earth Spain.

Data availability

No data was used for the research described in the article.

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