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Review: The need for holistic, sector-tailored sustainability assessments for milk and plant-based beverages

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Highlights

- Milk and plant-based beverages require review on their sustainability in the food system.
- Sustainability includes economics, nutrient supply, and environmental footprint.
- Nutrient indexes need to be demographically stratified and food-group specific.
- Qualitative measures can be included into environmental and economic assessments.
- Single-metric indexes hinder transparency of results from sustainability analyses.

Abstract

Sustainable food systems encompass nutrition, the environment and socioeconomics, each aspect requiring unique assessment and consideration. This is especially important in the dairy industry, since livestock contributes 14.5% of global greenhouse emissions while also contributing 49% to global calcium supply and 12% to global protein supply. This necessitates strict measurement to ensure science-based decision-making while producing sustainably, ensuring adequate nutrient supply. This review aimed to identify and evaluate existing measures of sustainability with the goal to generate recommendations for future sustainability measurements. From a nutritional perspective, it identified existing measures such as nutritional life-cycle analysis (**nLCA**), hybrid nutrient rich food index (**NRF-h**), NRF adjusted for adequate intake and nutrient deficiencies (**NRF-ai**), as well as the priority micronutrient density score, as methods which consider broader nutrient profiles and utilise more recent research, and therefore serve as a basis for future models. Major limitations exist in the incorporation of bioavailability or the food matrix effect in such measures, as well as food-group specific indices. The Prospective Urban Rural Epidemiology (**PURE**) healthy diet score also provides promise in serving as an updated version of current dietary guidelines. Environmentally, the life cycle analysis (**LCA**) approach forms a detailed basis for environmental footprint assessment, although the practical application thereof in modern agriculture may be cumbersome and may warrant the use of simpler metrics. However, the complexity of sustainability assessments due to differing production methods and system boundaries make comparisons difficult, which justifies either standardised or contextualised indices. Lastly, socioeconomics which are often measured only via retail price with a focus on economics, also deserve consideration of affordability at consumer and producer level by evaluating the effect of the production system on the local and global economy, producer affordability and the potential to improve livelihoods. In conclusion, a localised and holistic measure of sustainability is warranted which is both sector and context specific and reported in sufficient detail to prevent the masking of poor results due to single metric expressions.

Keywords: Dairy, alternatives, nutrient density, sustainability, footprint

Implications

This review provides insights into sustainability assessments, addressing the shortfalls of and making recommendations on existing measures. It can be used by aspiring scientists, the agricultural industry, and policymakers as a basis to improve current measures. There are no direct economic, environmental, or social implications, but rather an awareness and broader understanding of the subject-matter. This may indirectly influence decision-making in each of the domains mentioned, with specific focus on the environment, socioeconomics, and nutrition.

Introduction

Engaging in sustainable practices and ensuring transparent, replicable and continuous reporting are critical imperatives for industries across the board (O'Dwyer et al., 2005; Eccles et al., 2012). In light of sustainable production, given its intricate nature and heightened importance amidst global climate challenges, growing population estimates, and the increasing demand for reliable nutritional supply, Drewnowski (2018) encapsulates the multifaceted complexity within sustainable food systems, covering health, economics, society and the environment (United Nations, 2015; Drewnowski, 2018). In this context, crucial questions emerge about how single metric sustainability assessments, like environmental life-cycle analyses (**LCAs**), and the resulting decisions, resonate across these diverse domains. These inquiries gain particular significance within the agricultural industry and the broader food system, and in this case dairy within dairy production (Drewnowski, 2018).

The agricultural industry, particularly the livestock sector, faces mounting pressure to curtail its environmental impact, propelled by findings from environmental studies and LCAs. In one way of LCA measuring, FAO estimated that 14.5% of anthropogenic greenhouse gas (**GHG**) emissions are derived from livestock (FAO, 2018), while other approaches yielded both lower and higher numbers depending on methodology deployed. In the dairy sector, comparative studies reveal that dairy milk yields 1.586 CO_2eq/kg of product, while beverages such as soy beverage yield 0.48 CO_2eq/kg (Sing-Povel et al., 2022). In addition, the Green Deal's conservation efforts, which include reducing land-use, restoring natural habitats and reducing greenhouse gas emissions, further pressure the agricultural industry to reduce their inputs which can lead to productivity losses in the livestock sector (European Commission, 2024). These efforts and measures have prompted a shift towards plant-based products and the development of novel protein and milk alternatives such as cell-based meats or precision fermentation products, as these are perceived to have a lower environmental footprint and reduced land use (Wood et al., 2023; Rombach et al., 2023). However, relying solely on single-metric-based results and ensuing consumer shifts neglects the potential repercussions on health, economics and society (Ramsing et al., 2023). For instance, dairy milk plays a pivotal global role in calcium and protein supply and provides job security and income for local communities, whereas alternative proteins may provide investment opportunity and diversified consumer choices (FAO, 2016; Smith et al., 2022a; White & Gleason, 2023; Wood et al., 2023).

Thus, it becomes evident that oversimplified comparisons may lead to misguided decisions. Since sustainability demands robust and consistent units of measure for accurate comparisons which are both replicable and representative of the substances in question, effectively measuring and comparing the sustainability of products, such as milk or plant-based beverages, is crucial. Utilizing a multi-dimensional metric can offer a more holistic perspective, guiding comprehensive decision-making on farms and among consumers. Due to the contribution of dairy to the global food system and the potential consequences to be faced should the sector reduce production (Smith et al., 2022a), this narrative review will focus on the sustainability of milk and plant-based beverages, emphasising nutrition, environment and social aspects. Through the use of these topics as keywords in a broad literature overview, the examination of current metrics, and critical review, it aims to identify practical indicators and offer informed recommendations for holistic sustainability assessments.

Milk and plant-based beverages in human nutrition

Nutrition and health are crucial in discussions surrounding sustainability, especially considering the current status of the global nutrient supply (Drewnowski, 2020; Smith et al., 2021). While global supply of energy is reportedly sufficient to meet global energy demands, logistic and accessibility hurdles still lead to hunger and undernourishment, particularly in areas of social instability or wars. More so, large scale global incidences of malnutrition characterised by specific nutrient deficiencies such as zinc, protein, vitamin B12, vitamin A, and calcium are widely spread (Sivaprasad, 2019; Smith et al., 2021; Han et al., 2022; Dave et al., 2023). In light of this, it is crucial to identify products that combat these deficiencies and contribute to global nutrient supply in an adequate manner, while still managing contributions to the economy and the environment.

Upon comparing the range of nutrient profiles of dairy milk, oat beverage, almond beverage and soy beverage, such as summarised in Table 1, it is evident that each milk type offers distinct nutritional characteristics. Dairy milk naturally stands as a primary source for essential nutrients such as calcium (49% of global nutrient availability), vitamin B2 (24%), lysine (18%), and dietary fat (15%), in addition to contributing over 10% of global nutrient availability for various other crucial components such as five indispensable amino acids, protein (12%), vitamins A, B5, and B12, as well as phosphorus and potassium (Dave et al., 2023; Smith et al., 2022a). Based on this, a potential deduction is that the avoidance of milk in diets may aggravate existing nutrient deficiencies if not adequately replaced or supplemented.

Meanwhile, plant-based beverages, including soy, almond and oat beverage, have gained popularity globally, of which the nutrient contributions have not been reported yet. While these beverages may not naturally replicate the nutritional profiles of dairy milk, fortification processes have addressed gaps in essential micronutrients, providing a range of nutrients similar to that of dairy milk, as seen in the diversity in nutrient profiles depicted in Table 1 (Magkos et al., 2020; Grasso et al., 2023). Fortification is a crucial component for these beverages, especially for calcium and vitamin B12, which are primarily found in animal-sourced foods. Yet, it is important to note that these beverages may provide additional nutrients such as vitamin E which is not readily found in animal-based products (Abeyrathne et al., 2022; Leroy et al., 2020 White & Gleason, 2023)

The most evident, however, is that comparing different milk products solely based on nutritional profiles is challenging due to variations in production processes, fortification and ingredient composition (Reinecke & Casey, 2017; Winans et al., 2020; Walther et al., 2022). Bioavailability discrepancies between plant-based and animal-based products, coupled with differing nutrient compositions, further complicate direct comparisons (Beal & Ortenzi, 2023; Dave et al., 2023). For instance, fat-soluble vitamins are more efficiently absorbed in high-lipid products, while iron bioavailability decreases in the presence of high fibre content (Adams et al., 2018; Dave et al., 2023). Specific substances such as lactose can enhance nutrient uptake, particularly calcium (Kwak et al., 2012).

Another example is the complexity of protein profiles. The protein profile of milk is among the most complete, with all essential amino acids present and being characterised by high-quality proteins such as whey protein and casein (Ramsing et al., 2023). These proteins are associated with anticarcinogenic effects and have different absorption rates, allowing for both quick and slow release to provide short- and long-term supply of protein and amino acids (Davoodi et el., 2016). Considering the continuous catabolism and anabolism of amino acids in the body and consequent steady supply of amino acids required, this is an advantage (Kadowaki & Kanazawa, 2003). In some cases, the bioavailability of protein in milk exceeds 100, as determined by digestible indispensable amino acid (**DIAAS**) scoring, making it a valuable addition to a diet otherwise poor in protein content, since it can supplement amino acids in other foods to increase collective uptake of protein (Dave et al., 2023). While the protein content and bioavailability of oats and almonds are reportedly low, soy beverage exhibits almost similar bioavailability DIAAS scores and also contain all essential amino acids (Reynaud et al., 2021; Dave et al., 2023). This emphasises the additional consideration factors when comparing nutrient profiles in an attempt to assess nutrient adequacy or make healthy consumer choices.

Dietary recommendations, however, provide guidance in focusing on whole food groups rather than single nutrients, although discrepancies exist even in that. Previously, low fat dairy has been recommended with avoidance of animal-based fats for the safety of heart health (Reedy et al., 2018; USDA, 2020). Recently, however, full fat dairy such as milk, cheese or yogurt form part of the healthy diet as released by PURE, where daily intake is recommended up to 113 grams (Poli, 2020; Mente et al., 2023). Contrary to standard public dietary recommendations and previous assumptions on dairy and cardiovascular health, multiple studies have found dairy to have a neutral and even a protective effect on cardiovascular health (Mozaffarian, 2021 Mente et al., 2023; Ramsing et al., 2023). Plant-based beverages, on the other hand, have no associated dietary recommendations with the exception of fortified soy beverage, which has recently been added to the dietary guidelines for Americans (USDA, 2020).

Thus, despite the evident disparity in the intrinsic nutritional profiles of milk and plant-based-beverages, each of these products can play a role in a sustainable food system, whether naturally, such as with dairy milk, or through fortification, such as with plant-based beverages. However, it is clear that examining single nutrient deficiencies and their remediation is just one facet of assessing nutritional adequacy. Factors such as overall health impact, the influence of the food matrix, and nutrient bioavailability all contribute to a more comprehensive understanding (Shkembi & Huppertz, 2022). Additionally, it is essential to consider the context of specific individuals or populations (Ridoutt, 2021). Evaluating nutrient density by assessing content per kilojoule can further illuminate the picture, especially given that milk ranks among the most nutrient-dense foods (Drewnowski, 2018). In this context, it is clear that viewing the sustainability of a product from a nutritional adequacy perspective will depend on the desired outcome, as well as the way in which it is measured and expressed. Hence, it is necessary to investigate the existing methods of measure and how they are expressed before considering these parameters within sustainability assessments.

Existing measures of nutritional profiles

A multitude of nutrient profiling or indexing methods exists, in addition to the conventional assessment of nutrient profiles which examines individual nutrient content per 100 ml, 100 g, or per serving. These methods, of which the majority are captured in Table 2, mostly reward food items based on specific ingredients or nutrients perceived as healthy, and penalises foods for '"unhealthy" nutrients or nutrients and food groups to limit, such as saturated fat. Exceptions are in specific outcome-related measures such as the Dietary Approaches to Stop Hypertension (**DASH**) diet, which focuses on hypertension prevention, or the priority micronutrient density score which rather focuses on combating malnutrition in low-to-medium-income groups. Regardless, the common trend is to move past nutrient content and gravitate towards a more holistic view of a product's nutritional profiles, especially focusing on nutrient density and on health outcomes. There are, however, still limitations to some of these measures, which recognises the urgency of accurate research in health outcomes of dietary choices and nutrients, such as discussed below.

Shortcomings and recommendations

In all of the above measures, a risk of bias or the use of outdated dietary guidelines exists pertaining to the definition of beneficial or harmful attributes, in addition to failing to consider food matrix effects or bioavailability, of which the priority micronutrient density score is an exception (Dehghan et al., 2017; Aguilera, 2019). In general, the existing measures have played a valuable role over the years in conveying nutrient information, aiding consumers in healthier dietary choices, in addition to assisting policy-makers with decisions. Yet, these methods may not offer a comprehensive view of the product's overall healthfulness, especially when education about individual nutrients or whole product benefits are lacking (De Temmerman et al., 2021; Ortenzi et al., 2023).

Adaptations to future nutrient profiling systems require continuous revision based on updated research and dietary recommendations, along with components that capture the whole food benefits or consider nutrients within the context of the product, food group and even targeted consumer. Recent studies and innovations like the Prospective Urban Rural Epidemiology (**PURE**) Healthy Diet Eating Pattern, priority micronutrient density score, and NRF-ai could assist in this as these address issues such as nutrient deficiencies, specific population requirements, and a comprehensive assessment of dietary and health outcomes within whole food groups, rather than fixating on isolated nutrients (Ridoutt, 2021; Mente at al., 2023; Beal et al., 2023).

Furthermore, while adaptations to the nutrient rich food (**NRF**) Index related to carbohydrates exist, there is an absence of food-group-specific nutrient indexes, such as an NRFi tailored specifically to dairy foods or proteins (Drewnowski et al., 2022). This absence can lead to unintended favourable or unfavourable results when comparing foods from entirely different food groups (Adams et al., 2018). Moreover, these indexes fail to account for the global supply of specific foods or their contributions to global nutrient adequacy; dairy as an example, which substantially contributes to the global protein and calcium supply (White & Gleason, 2023). When considering substitutions, it becomes essential to evaluate whether plant-based beverages can sufficiently supplement these nutrients to the same extent, on a bioavailability basis. Moreover, plant-based beverages may excel in delivering important antioxidants or nutrients not naturally present in dairy (Craig et al., 2023). This leaves room for more nuanced evaluations and potential nutrient weightings based on their contributions or the inclusion of both whole-food health outcomes, particularly when comparing specific foods within the same food group (Ridoutt et al., 2021). Such an approach enables a more comprehensive assessment of a food’s sustainability within the broader context.

Thus, for future nutrient assessments to be more accurate and comprehensive, it is recommended to include localised and population-specific nutrient requirements, in addition to considering factors such as bioavailability and uptake, where data availability allows. Existing models would further benefit from revision based on more up-to-date research on the benefits and risks associated with specific nutrients, which may include the addition of food matrix effects as opposed to focusing on single nutrients. Finally, for comparison, it is recommended to tailor nutrient indexes to food groups or types.

However, nutrient profiles cannot be viewed in isolation, but should be considered in conjunction with environmental and economic assessments, guiding more sustainable consumer choices from both a human and a planetary health perspective (McLaren & Chaudhary, 2021; Hatjiathanassiadou et al., 2023). An example of such is a nutritional life-cycle analysis (**nLCA**), offering a more detailed approach to environmental aspects (Weidema & Stylianou, 2020). However, if similar approaches are to be adopted in future sustainability assessments, a deeper understanding of the environmental footprint of products and the methodologies employed in their measurement becomes imperative. The environmental components of milk and plant-based beverages are therefore explored in the following section.

The environmental footprint of milk and plant-based beverages

The environmental footprint of a product encompasses a range of indicators such as carbon emissions, land use, water use and biodiversity loss, among others (Hoekstra et al., 2011). However, it is most typically characterised by the carbon footprint or emissions associated with product production, expressed as carbon dioxide equivalents (Dong et al., 2021). When examining the environmental footprint of milk and plant-based beverages, distinct differences become evident, as highlighted in the comparison in Table 3. These emissions result from existing LCA's which were used to investigate factors such as fuel used during cultivation or transportation, fertiliser and pesticide application on farms, energy consumption, total water usage, direct greenhouse gas emissions, and more.

Based on Table 3, plant-based beverages exhibit comparable carbon footprints, while dairy milk requires nearly twice the emissions for its production. Yet, considering that within the same product category, emissions can vary by up to 1 kgCO_2eq/kg of the product, the comparability of results is once again questioned, being emphasised by some cases of soy beverage and oat beverage production requiring higher emissions compared to specific instances of dairy production. Raw material production further yields markedly different outcomes. In most cases, on-farm dairy production demonstrates lower emissions than plant-based production, except for oat beverage, which, in this particular case, was produced through regenerative agriculture and consistently yielded lower emissions (Blignaut et al., 2019). The primary contrast between on-farm carbon emissions and final product carbon emissions stems from the quantity of raw material present in the final product. In the case of dairy milk, all the raw material is processed into milk, whereas plant-based beverages primarily consist of water, 2–11% plant-based raw material, along with flavourings and additional vitamins or minerals (Pointke et al., 2022). A similar pattern emerges when examining water footprints (Hoekstra et al., 2011; Ercin et al., 2012; Owusu-Sekyere et al., 2016; Tozzini et al., 2021). The observed differences and variances within and among different products, both in terms of raw materials and final products, can be attributed to differences in production systems and system boundaries included in the life-cycle analysis, meriting the review of an LCA as a method of measure for environmental footprint (Volpe et al., 2015).

Existing measures of environmental footprint

The LCA methodology, the most widely-used method in environmental sustainability assessments, provides a comprehensive evaluation of total emissions and sustainability indicators from cradle-to-grave to measure the overall carbon and water footprints of production – the most commonly used indicators (Kayo et al., 2014, Marvinney & Kendall, 2021). The carbon footprint refers to direct and indirect greenhouse gas emissions, including those resulting from energy usage and other inputs (Kayo et al., 2014; Winans et al., 2020). Emissions such as carbon dioxide, methane and nitrous oxide are converted into carbon dioxide equivalents (Jungbluth & Meili, 2019; Winans et al., 2020). The water footprint includes categories such as blue water, green water and grey water, which reflect direct and indirect water usage (Hoekstra et al., 2011).

Results may vary depending on the chosen system boundaries. The cradle-to-gate assessment is applicable to on-farm production for plant-based beverages, measuring inputs over the crop's lifespan to calculate emissions per kilogram (Winans et al., 2020; Marvinney & Kendall, 2021). Dairy production assessments consider both pasture cultivation and animal inputs. Recycling products into farming systems, like using manure for fertiliser, is deducted from emission calculations (Chobtang et al., 2016; Reinecke & Casey, 2017). However, co-products sold (e.g. meat or soybean hulls for livestock feed) and their emissions may or may not be included. An overview and example of inputs considered in dairy production and plant-based beverage production can be seen in Figure 1 and Figure 2.

In plant-based beverage production, the final processing steps involve milling raw ingredients, creating a slurry, enzymatic hydrolysis, filtration and flavour modification (Winans et al., 2020). Dairy milk focuses on homogenisation, pasteurisation and cooling. Processing time and temperature contribute to the carbon footprint, with additional factors like ingredients, co-products, additives and energy sources impacting it (Chobtang et al., 2016). The efficiency of direct and indirect heating methods in ultra-pasteurisation also affects emissions (McClements et al., 2019). In gate-to-gate or cradle-to-grave assessments, transportation is included with factors such as transport mode, distance and material weight influencing emissions, in addition to considering logistical inputs, marketing and other factors to maintain the product (Kayo et al., 2014; Jungbluth & Meili, 2019; Winans et al., 2020; Marvinney & Kendall, 2021).

On farm level, dairy farming exhibits similarities pertaining to cultivation processes required for feed production. However, key differences exist in herd-management, manure management, as well as the extent of processing at factory level, which is less extensive than that of plant-based beverage production (Chobtang et al., 2016; Reinecke & Casey, 2017). Hence, as previously observed, assessments can vary widely between farms and factories due to differences in input variables, values and system boundaries, requiring careful scrutiny when comparing the results of one LCA with one another.

Despite variations, an LCA remains the most common tool for determining environmental footprints in production, owing to its integration in nutritional LCAs (nLCA) to calculate the carbon emission "cost" of achieving a sufficient nutrient profile (Weidema & Stylianou, 2020; McLaren & Chaudhary, 2021). While the incorporation of LCAs into metrics like nLCA is accepted, the unit of expression has sparked debate, emphasising the need to consider other subcomponents alongside LCA outcomes for a comprehensive sustainability perspective, such as a different unit of expression or the inclusion of ecological indicators in combined metrics (Weidema & Stylianou, 2020; Manzano et al., 2023).

The conventional measure of environmental footprint is global warming potential (**GWP**), which is converted to carbon equivalents to standardise the measurement across all greenhouse gasses. However, a key argument revolves around the atmospheric lifetime of different gasses, for example, methane is more potent in the short-term but decays quicker in the long-term (Manzano et al., 2023). Thus, depending on the timeframe in which an LCA is conducted, and whether it serves as a predictive or current analysis, methane or nitrous oxide is argued not to be treated as equivalent to carbon dioxide. However, **GWP*,** a variation of GWP, takes into account the lifespans of different gases in the atmosphere. (Blignaut et al., 2022; Manzano et al., 2023).

Yet, additional arguments caution against using any form of GWP due to the complexities described above and GWP not accurately representing the heat-capturing capacity of greenhouse gasses, particularly over extended periods, among other reasons (Meinshausen & Nicholls, 2022). An alternative approach, radiative forcing (**RF**), is considered more reliable in the short term, as it focuses on the immediate impact of gasses on the earth's radiative balance (Jungbluth & Meili, 2019). Unlike GWP, which relies on long-term predictions of gas interactions and atmospheric conditions, RF provides a more dependable measure for shorter timeframes (Vallero, 2019; Jungbluth & Meili, 2019).

Additional measures to carbon emissions, regardless of unit of expression, are ecological indicators such as those outlined by the **TRACI** system (Tool for the Reduction and Assessment of Chemical and other environmental Impacts) or planetary boundaries framework (Bare et al., 2003; Rockström et al., 2009). These include biodiversity loss, acidity, eutrophication potential, atmospheric toxicity, land use, and other indicators. Although not typically included in emission factors on front of pack (FOP) labelling which aim to integrate environmental profiles, studies have experimented with consumer behaviour when including measures like the environmental footprint single score (**EF single score**) on labels, which accounts for a host of ecological indicators, with positive results in terms of more environmentally friendly consumer choices (Arrazat et al., 2023).

Shortcomings and recommendations

The environmental assessment of milk and plant-based beverage sustainability faces challenges and opportunities in achieving greater transparency, simplicity and holistic evaluations. While detailed methodologies like LCAs offer depth, reliance on their quantitative measures alone can oversimplify sustainability's complexity (Weidema & Stylianou, 2020; Ridoutt et al., 2021). On the contrary, extreme LCA detail may hinder effective comparisons due to varied system boundaries and input parameters (Waas et al., 2014; Heusala et al., 2020). Adapting assessments with qualitative measures, simpler day-to-day producer-recorded metrics, and diversified, localised approaches may address these limitations. This includes adapting assessments to the geopolitical circumstances in which the production systems operate, from ecological conditions to support structures such as governance, and cultural or social preferences. In addition, exploring alternative units of expression, like RF, and considering sub-units relevant to ecological impact, productivity and farmland conditions before and after production may further enrich assessments, especially when tailored to the geographical environment.

As with nutritional front-of-pack (**FOP**) labelling, a limitation in current FOP expression of environmental impact is transparency and consumer education on the label, along with contextualisation of the results. However, more sustainable consumer choices still warrant the inclusion thereof on packaging (Arrazat et al., 2023). In the same breath, recognising that a single metric cannot encapsulate the full context of sustainability, particularly when it comes to FOP labelling for consumers, can prompt the development of a framework that addresses socioeconomics in addition to nutrition and the environment, as reviewed below.

A socioeconomic view on milk and plant-based beverages

The affordability of a product is an inevitable driver of sales and a simple metric to assess the economic sustainability of a product (Mendoza-Velázquez et al., 2023). However, in a space where global trade has opened access to products across continents and contributed to more diverse and inclusive diets, the production and sale of products, their source and cost, each affect local and global economics and deserves consideration (Jiaqi et al., 2021; Silvestrini et al., 2023). The parameters to be considered in an economic evaluation is further dependent on the perspective from which it is assessed, such as the consumer perspective, producer perspective and the global or national perspective (Fleurbaey & Blanchet, 2013; Dynan & Sheiner, 2018).

From a consumer perspective, affordability is one of the main measurement tools to assess socioeconomic sustainability. Globally, where 9% of the population is undernourished, and 13% of the population is obese, both of which are prevalent in the low-to-middle-income group, it can be deduced that although caloric needs can be met in the same income group where deficiencies exist, a diverse and healthy diet cannot be afforded, highlighting affordability as a main indicator. This is emphasised by Figure 3, as visualised by Ederer et al. (2023), where the difference between the percentage able to afford a healthy diet in low-income groups compared to high-income groups varies by more than 70%.

In that context, solely on a cost-comparison, plant-based beverages are 2–4 times more expensive than dairy milk, as seen in Table 4 which compares retail prices in America and South Africa, both highlighting the extreme diversity within the same product and the concern for nutrient supply when considering costs (Johnston & Pretorius, 2020; Skorbianksy, 2022). In that regard, the NRFi has been adapted by its original author to include price and affordability indexes, i.e. the Nutrient Rich Food Price Index (**NRFPI**). This serves as a method of considering costs in relation to nutrient supply and can be valuable in comparing the different dairy and plant-based beverages on this basis (Mendoza-Velázquez et al., 2023). However, still in this regard clear definitions and standards need to exist to avoid extreme differences in outcomes. For example, in Figure 4 Drewnoski et al (2018) showed the differences in results when comparing the cost of a product in relation to energy density vs cost in relation to NRF. In this case vegetables excelled in the first instance and scored the worst of all food groups in the second instance, with dairy being fairly constant in both cases.

From a more qualitative measure, measured either by means of surveys or quantitatively defined by consumption figures and trends, social acceptability is used as an indicator of economic sustainability which indicates the rising demand for plant-based beverages across the globe (Tennakoon & Janadari, 2022), whereas bovine milk has varying trends where consumption increases in some countries and decreases in other countries as milk substitute consumption rises (OECD, 2019; McCarthy, 2019).

On the other hand, socioeconomic indicators relevant to producers encompass factors directly impacting the producer and the community they serve (Strezov et al., 2016). Profitability, measured by return on investment (ROI), remains a central focus for producers, guiding decisions related to growth and improvement, and predicting future trends (Abdallah, 2017). Beyond this, considerations extend to the workforce employed by the producer and the consequential effects on both local and global economies. Factors such as wealth improvement or number of employees are common indicators used to determine the economic contribution of a producer. However, a more in-depth analysis extends to assessment of education levels of family members of employees, job satisfaction, health-plan, number of financial dependents and even succession planning within the family, amongst others (Akarsu, 2023; Drakou & Symeonidis, 2023; Reich et al., 2023). The quantification of such indicators can pose challenges; however, it can also provide a broad overview of the social impacts of a producer.

At the national level, broader economic indicators serve as benchmarks for assessing a country’s overall economic health, as well as the contribution of a producer to the local economy (Akarsu, 2023). The production and sale of dairy products, including milk plant-based beverages, influence a country’s gross domestic product (**GDP**) by contributing to the overall value of goods produced, in addition to contributing to a large extent to the local employment rate (FAO, 2016; Dynan & Sheiner, 2018). Monitoring these national economic indicators, often sourced from government reports, economic surveys and statistical analyses, provide a comprehensive understanding of the dairy industry’s role in the country’s economic landscape and has, to some extent, been included in socioeconomic sustainability assessments (Fleurbaey & Blanchet, 2013).

Expanding the scope globally, additional indicators contribute to a nuanced understanding of a country's potential in the international economic arena. The global competitiveness index (**GCI**) evaluates factors such as infrastructure, macroeconomic stability, health and education, offering insights into a nation's competitiveness (Qazi, 2023). The World Happiness Report considers citizen well-being, including income, social support and life expectancy (Helliwell et al., 2012). The global innovation index assesses a country's innovation capacity, providing valuable information about its economic potential (Brás, 2023). These global indicators collectively paint a holistic picture of a nation's economic position on the world stage (Reich et al., 2023). However, to relate this to a specific industry or product may be challenging as the economic and social positioning of a product is intertwined with a variety of other factors and industries. This then summarises the complex nature of socioeconomic measurements and the extent to which they can or cannot be included in sustainability assessments, such as elaborated on below.

Shortcomings and recommendations

While the indicators mentioned provide valuable insights into a holistic economic view, some limitations still exist. Firstly, if only reliant on quantifiable economic indicators, such as profitability and GDP contribution, assessments may fail to consider the social impact and improvement, or potential negative effects associated with the production of specific goods (Fleurbaey & Blanchet, 2013). However, the collection of quantitative data through surveys or in-person assessments can be timely, restricted by ethical clearance hurdles, or provide subjective results and yield qualitative measures which yield sustainability assessments ineffective (Norrman et al., 2020; ul Haq, 2020). Hence, existing metrics like the NRFPI which solely considers consumer affordability may be the most efficient, especially with nutritional supply as the main objective (Silvaa et al., 2020). If, however, a metric aims to assess future sustainability competitiveness in the market or social impacts, the complexity of qualitative measures may be warranted.

Another limitation lies in the variability of national contexts and their impact on indicator relevance. Different countries exhibit distinct socioeconomic structures, agricultural practices, and consumer behaviours, influencing the significance of certain indicators within that context (Gonzalez-Garcia et al., 2018). Therefore, a one-size-fits-all approach may not accurately capture the diverse challenges and opportunities within the global dairy industry or food system (Saleh, 2017). Future research should explore region-specific adaptations of indicators to provide insights into the socioeconomic sustainability of dairy production on a global scale (Ridoutt et al., 2021). Furthermore, the mentioned indicators may not fully encapsulate emerging challenges and opportunities within the dairy and substitute product industry (Lehtonen et al., 2007; Saleh, 2017). As the sector undergoes transformative changes, including advancements in technology, shifts in consumer preferences and evolving environmental concerns, future indicators must adapt to remain relevant which may involve the consideration of growth potential, improvement in efficiency, or even reward expenses and temporary reductions in profit for the benefit of improvements in production capability (Paul et al., 2020; Koutouzidou et al., 2022).

In addition, and in spite of the complexity of including qualitative social indicators, there exists an opportunity to integrate more socially focused indicators into the evaluation of socioeconomic sustainability. Such factors include those related to fair labour practices, community engagement, gender-equality, social justice and the well-being of dairy farmers which could provide a more comprehensive understanding of the industry's social impact and future capability (Cuesta et al., 2019). To overcome challenges of reporting this data, advancements in data analyses, artificial intelligence and technology could enable real-time monitoring and reporting of both qualitative and quantitative measures, which may further enable the accuracy and timeliness of sustainability assessments.

Conclusion

Based on the pressure faced by the dairy sector to reduce emissions and the potential nutritional and socioeconomic consequences to be faced if a holistic approach is not implemented to measure its sustainability, sustainability in the dairy and plant-based beverage industry necessitates a comprehensive and localised approach. This entails one considering various readily available indicators across nutritional, environmental and socioeconomic dimensions. While existing methods like standard front-of-pack labelling and nutrient profiling systems play a valuable role in conveying nutrient information, these often fall short of offering a holistic view of a product's overall healthfulness. Novel approaches, such as the PURE Healthy Diet Eating Pattern and priority micronutrient density score, address these limitations by considering dietary and health outcomes within whole food groups or focusing on essential nutrients, promoting a more holistic perspective on dietary choices. However, the absence of food-group-specific nutrient indexes tailored to dairy foods or proteins highlights a significant gap, emphasising the need for more specialised metrics. Additionally, environmental sustainability assessment, relying on quantitative measures like life-cycle analysis (LCAs), oversimplifies the complex nature of sustainability. Future developments should focus on transparent and holistic evaluations that consider different production systems, geographical locations and alternative units of expression beyond carbon equivalents. Socioeconomic sustainability assessment requires a balanced approach, acknowledging that affordability alone does not represent economic sustainability. The intricate dynamics of different contexts demand contextualisation and consideration of qualitative measures. In essence, sustainability cannot be distilled into a singular metric, emphasising the need for multifaceted evaluation frameworks that prioritise transparency, detailed and comprehensive education efforts for consumers, producers and policymakers. For instance, whilst dairy is often found to be less environmentally friendly than its plant-based counterparts, it is more affordable and nutritious than non-fortified plant-based beverages. Thus, should metrics like affordability and nutrition be taken into account in addition to environmental footprint, a collective sustainability assessment may yield different results. In this context, a holistic and localised sustainability assessment framework, integrating nutritional, environmental and socioeconomic indicators, is imperative for fostering informed consumer choices, promoting industry resilience, and ensuring the long-term sustainability of the dairy and plant-based beverage sector.

Ethics approval

No ethical approval was required for the purposes of this literature review.

Data and model availability statement

All data used is included in this article. None of the data were deposited in an official repository. The data that support the study findings are available from the authors upon request.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used ChatGPT in order to detect and correct clear understandability concerns, as well as Grammarly for the correction of spelling and grammar mistakes. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication, spelling and grammar errors.

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Table 1: Nutrient content (ranges) of bovine milk and plant-based beverages

The average content ranges of nutrients within dairy milk and plant-based beverages as sourced from literature.

Nutrient	Bovine Milk	Almond beverage	Oat beverage	Soy beverage	Rice beverage	Coconut beverage
Energy (kJ)	197–284	36–155	128–200	132–256	181-284.51	119-238
CHO (g)	4.65–4.8	0–3.4	5–7.5	0.2–2.5	7.1-11.8	0-4.6
Protein (g)	3.1–3.62	0.62–1.67	0.6–1.2	2.78–3.7	0.33-0.8	0.13-1.43
Lipid (g)	1.6–3.67	1.15–2.71	1.5–2.2	1.57–4.35	0.83-1.17	1.59-2.61
Dietary fibre (g)	0	0.61–1.25	0.64–4.4	0.2–1.7	0.06-0.12	0.27-0.63
Ca (mg)	110–121	90–206	70–140	100–123.24	0.09-0.005	0.07-0.13
Fe (mg)	0.11	0.02–0.23	0–0.38	0.30–0.56	<0.05	0.14-0.16
Mg (mg)	10–11.5	7.9–8.02	3.37–12.4	13–20.9	0.003-0.005	0.004-0.008
Na (mg)	42–44	48–74.4	35.1–56	36–52.05	57.14-85.52	24.98-56.02

P (mg)	10	5	7	9	0.02-0.06	0.04-0.01
Vitamin D (µg)	0	0.4–0.9	0.3–0.6	0.3–0.47	-	0-0.5
Vitamin E (µg)	63.6–93.1	1 101.6–2 422	484–631	282–2 856	382.60-558.20	-
Vitamin B2 (µg)	108.3–190	54.9–119.46	14–91.56	57.8–160.71	0.8-1.6	0.1-1.4
Vitamin B9 (µg)	3.2–9.27	0.99–1.9	2.3–5.82	17.7–24.33	1.2-2.0	0.4-0.7
Vitamin B12 (µg)	0.44–0.45	0–0.44	0.18–0.48	0.32- 1.08	-	0.0-0.10
Vitamin A (IU)	158	148.8	106.8	201.2	-	-

Sources: Craig & Fresán (2021); Sunidhi et al. (2021); Singh-Povel et al. (2022); Vanga and Raghaven (2018); Paul et al. (2020); Fructuoso et al. (2021); Smith et al. (2022b); Walther et al. (2022)

Table 2: Nutrient profiling systems of foods

A summary on currently used methods of measuring and conveying key nutrient and health related information of food products, including positive and negative remarks and a brief description of how each metric functions.

Measure/metric	Description & aim	Nutrient or food group encouraged	Nutrient or food group limited	Cons	Pros	Reference
Basic nutrient label	Provides nutrient content per 100 ml or 100 g and/or serving size; in relation to daily requirements	Energy, carbohydrates, fat, protein, cholesterol, vitamins and minerals, incl. vitamin D, iron, potassium, calcium, and B vitamins, among others	Fat, sugar, sodium, cholesterol	Simplifies complex nutritional information. Does not consider bioavailability or food matrix effects.	Practical and measurable perspective on nutrient intake.	FDA (2017)
FSA nutrient label	As above, including a colour code to indicate high to low concentrations of nutrients	Energy, carbs, fat, protein, cholesterol, vitamins and minerals, incl. vitamin D, iron, potassium, calcium, and B vitamins, etc.	Fat, sugar, sodium, cholesterol	May be irrelevant depending on dietary goals. Does not consider bioavailability or food matrix effects.	Clear indication of specific nutrients to avoid.	FSA (2016)
Nutri-Score	Assign a letter grade based on nutritional content, penalising and rewarding specific factors	Fruit, vegetables, fibre, protein (with varying points	Energy, sugar, saturated fat, sodium	Questions raised on scientific backing.	Aligns consumer perceptions with healthier choices.	UNICEF (2021); Peters

depending on source), nuts, seeds, seed-oils	Does not consider bioavailability or food matrix effects.	& Verhagen (2022); Van der Bend et al. (2022); Scientific Committee of the Nutri-Score, 2022 and 2023

Health star rating	Assign a star rating (1–5) based on overall nutritional quality	Fruits, vegetables, nuts, legumes	Energy, sugar, saturated fat, sodium	No effect on consumer behaviour. Misrepresents healthfulness of packaged foods.	Improves adherence from manufacturers to the label.	WHO (2019); Bablani et al. (2022)
Food compass	Assess healthfulness across 54 attributes and provide a score of 1–100	Various nutrients, minerals and vitamins & health attributes	Processing, additives, added sugar and negative attributes	Does not consider bioavailability or food matrix effects.	Flexible and comprehensive.	Reedy et al. (2019); Mozaffarian (2021); Tufts (2023)
Healthy eating index	Evaluate how well a set of foods aligns with recommended dietary guidelines	Fruits, vegetables, whole grains, dairy, protein foods, etc.	Added sugar, saturated fat, sodium	Guidelines potentially outdated. Does not consider bioavailability or food matrix effects.	Promotes a balanced diet based in general.	USDA (2023)
DASH Diet	Emphasise nutrient rich foods to prevent and manage high blood pressure	Fruits, vegetables, whole grains, lean proteins, low sodium	Sodium, full-fat meat or dairy	Outcome specific, thus may be irrelevant for other health goals.	Proven effective in managing hypertension.	NHLBI (2021)

Nutrient Rich Food Index (NRFi)	Rank and classify foods or diets based on essential nutrients and nutrients to limit	Carbohydrates, fat, protein, vitamins and minerals, incl. vitamin D, iron, potassium, calcium, and B vitamins, etc.	Added sugar, sodium, saturated fat	Does not consider bioavailability or food matrix effects. Nutrients to limit non-contextual.	Measurable. Indicator of nutrient density and supply.	Drewnowski (2022)
PURE Healthy Diet score	Emphasise six food categories for a balanced and nutrient-rich diet	Fruits, vegetables, nuts, legumes, fish, dairy, red meat, poultry	None	Recent study, hence a potential for critique.	Evidence based (epidemiological study). Balanced diet approach.	Mente et al. (2023)
EAT-Lancet Planetary Health Diet	Combine nutrient recommendations with environmental sustainability	Fruits, vegetables (up to half the plate), legumes, lean protein	Animal-sourced foods, starchy vegetables, added sugars	Criticised for predicted micronutrient shortfalls.	Balances nutrient recommendations with environmental concerns.	Willet et al. (2019); Beal et al. (2023)

EWG Food Scores	Provide an overall product score based on nutrition, ingredient concerns, and processing	Fruit, vegetable, nuts, fibre, protein	Calories, fats, sugars, additives, contaminants, hormones	Rewarded components may be outdated. Environmental scores may be out of context. Does not consider bioavailability or food matrix effects.	Comprehensive assessment considering nutrition, ingredients, and processing.	EWG (2023)

Table 3: Carbon footprint of bovine milk and plant-based beverages and the respective raw materials

The ranges of carbon footprints of dairy milk and the most prevalent plant-based beverages, i.e. almond beverage, soy beverage and oat beverage, expressed as carbon equivalents per unit of product (litre or kilogram).

	Carbon footprint (ranges) of bovine milk and plant-based beverages
Final Product	

Unit	Almond beverage	Soy beverage	Oat beverage	Dairy milk	Sources & comments
kgCO_2eq/kg		0.31	0.21	0.84–1.74	Helsing et al., 2019, De Lima et al, 2022
kgCO_2eq/L	0.467	0.438–0.53	0.301	1.56	Coluccia et al., 2022; Sing-Povel et al., 2022
kgCO_2eq/kg	0.8	1.05	0.95	3.1	Sunidhi et al., 2021
kgCO_2eq/kg	0.39–0.58	0.24–1.21	0.54	1.7–1.97	Winans et al., 2020
Average*	0.49	0.61	0.50	1.66	*based on number of results obtained across studies

Raw Material

Unit	Almonds	Soybean	Oats	Raw dairy milk	Source & comments
kgCO_2eq/kg	1.03–2.077				Marvinney et al. (2020); Volpe et al. (2015); Kendall et al. (2015); Marvinney et al. (2015)
kgCO2eq/kg	0.35–1.03				Martin-Gorriz et al. (2020)

kgCO2eq/kg		0.3–1.93			Blignaut et al. (2019); Escobar et al. (2020); Raucci et al. (2014); Maciel et al. (2016)
kgCO2eq/kg			0.33–0.59		Blignaut et al. (2019); De Kock et al. (2018)
kgCO2eq/kg				0.49–1.1.43	Reinecke & Casey (2017)
Average*	1.23	1.09	0.42	0.89	*based on number of results obtained across studies

Table 4: Retail prices of bovine milk and plant-based beverages in America and South Africa

A comparison between the retail prices of dairy milk, almond beverage, soy beverage and coconut milk as representatives of the most prominent milk and plant-based beverages, with South Africa and America as examples.

Item	Unit	Average	Minimum	Maximum
Cow’s milk	USD/liter	$1.04	$1.00	$1.08

Almond beverage	USD/liter	$1.65	$1.61	$1.69
Almond beverage	ZAR/liter	R48.20	R29.95	R126.00
Soy beverage	USD/liter	$1.76	$1.72	$1.80
Soy beverage	ZAR/liter	R32.86	R19.66	R60.00
Coconut beverage	USD/liter	$1.81	$1.72	$1.90
Coconut beverage	ZAR/liter	R77.94	R44.98	R299.75

Sources: Johnston & Pretorius (2020); Skorbianksy (2022)

Figure captions

Fig. 1. Simplified process diagram of life-cycle analysis for almond production (Winans et al., 2020)

The inputs and outputs of almond production as measured and portrayed in a cradle-to-gate assessment in which case transport from the factory to the shelf are not included, but cultivation and processing are.

Fig. 2. Summarised process flow of bovine milk production, inputs and outflows

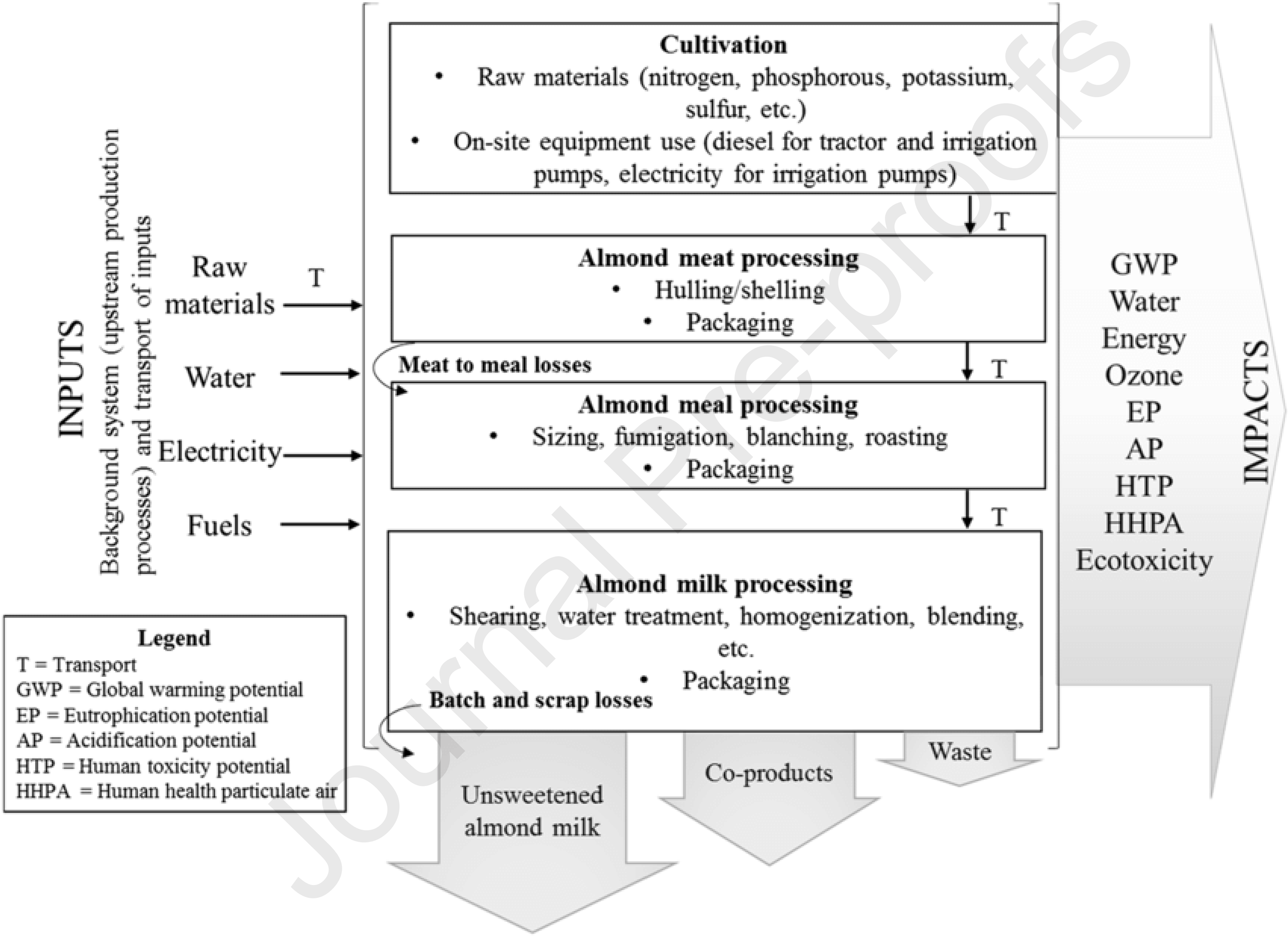
The inputs and outputs of dairy production as measured and portrayed in a cradle-to-gate assessment in which case the system boundaries end before distribution.

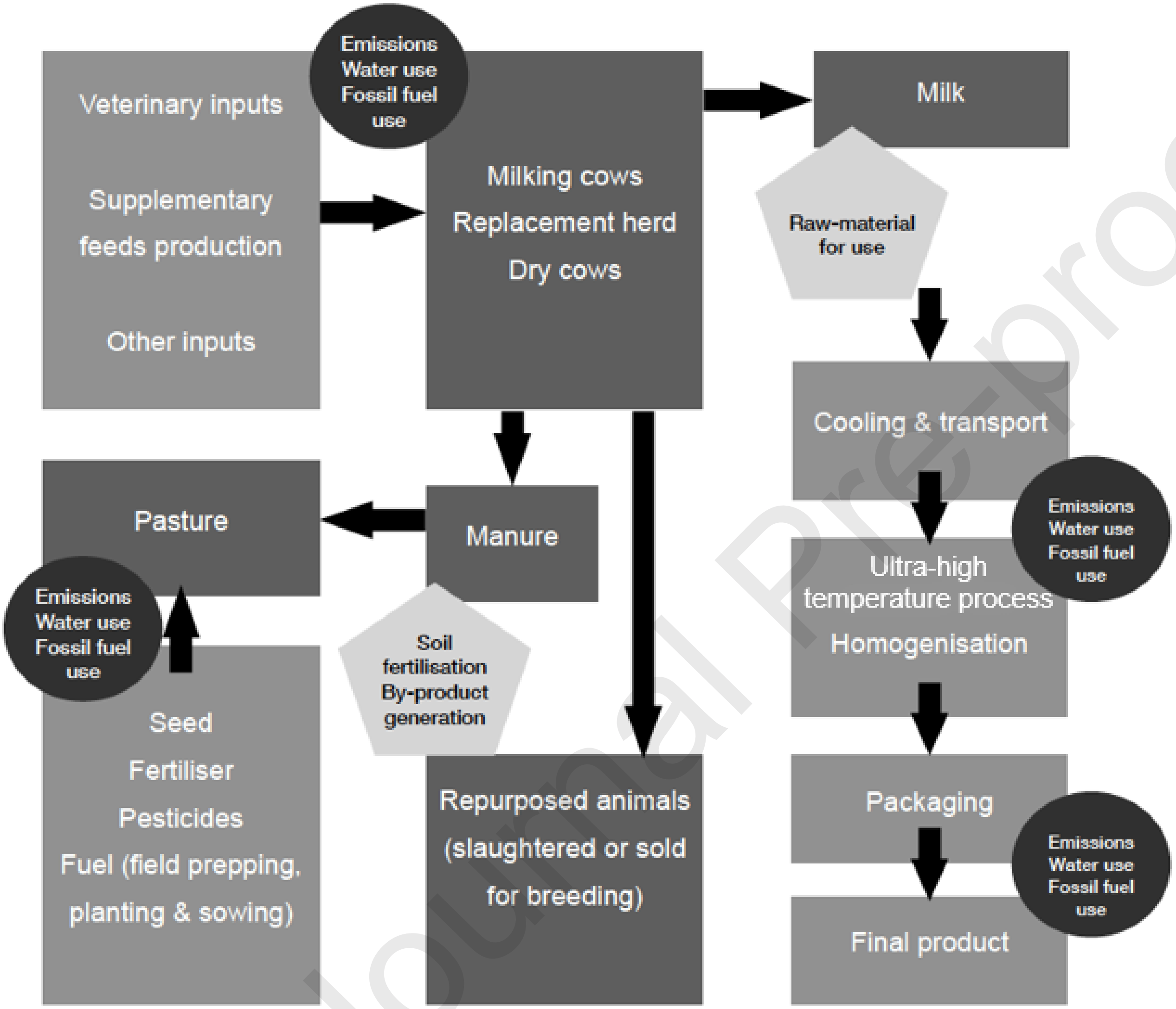
Fig. 3. Share of population unable to afford a healthy diet (Ederer et al., 2023)

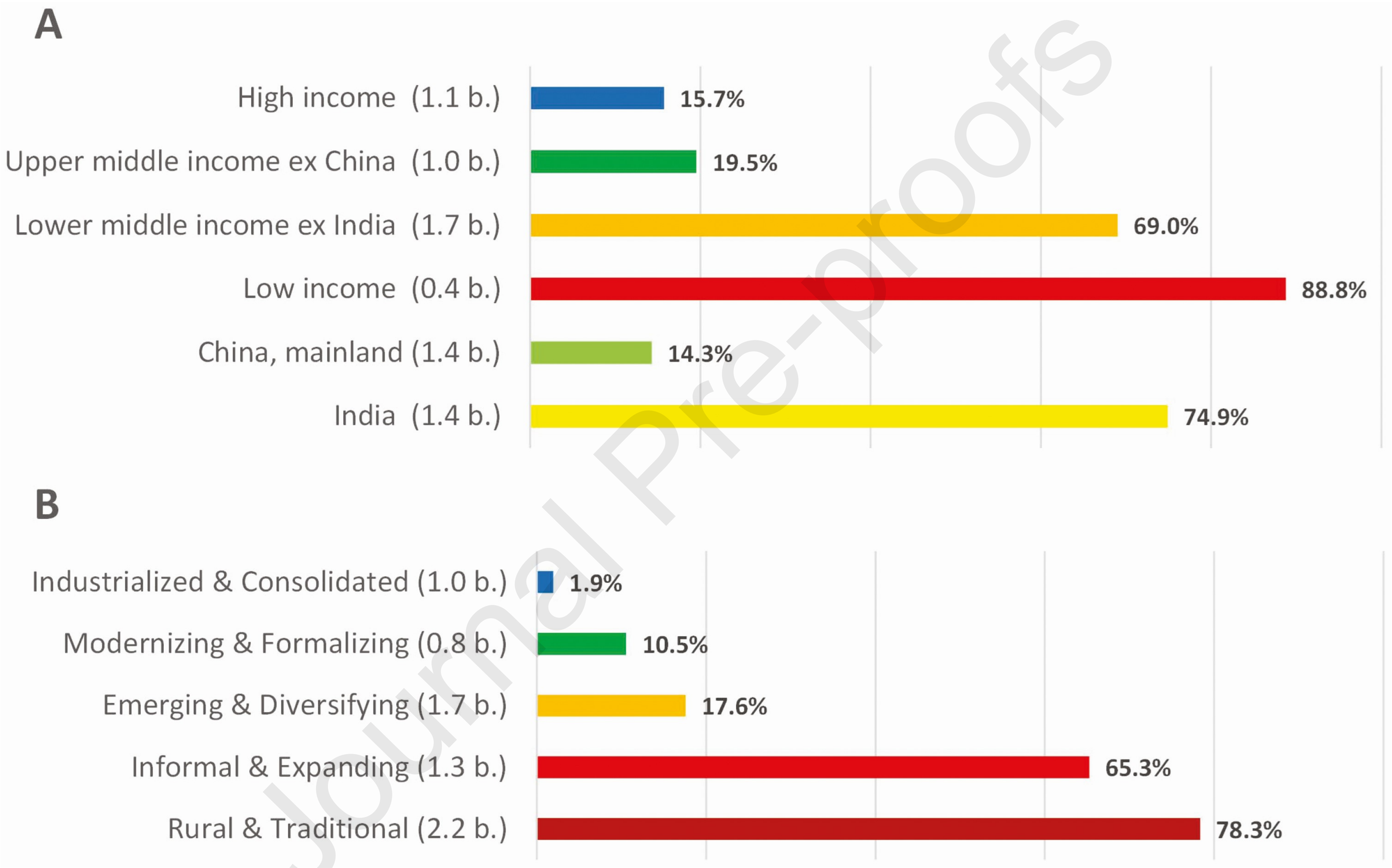
The percentage within each income group unable to afford a healthy diet.

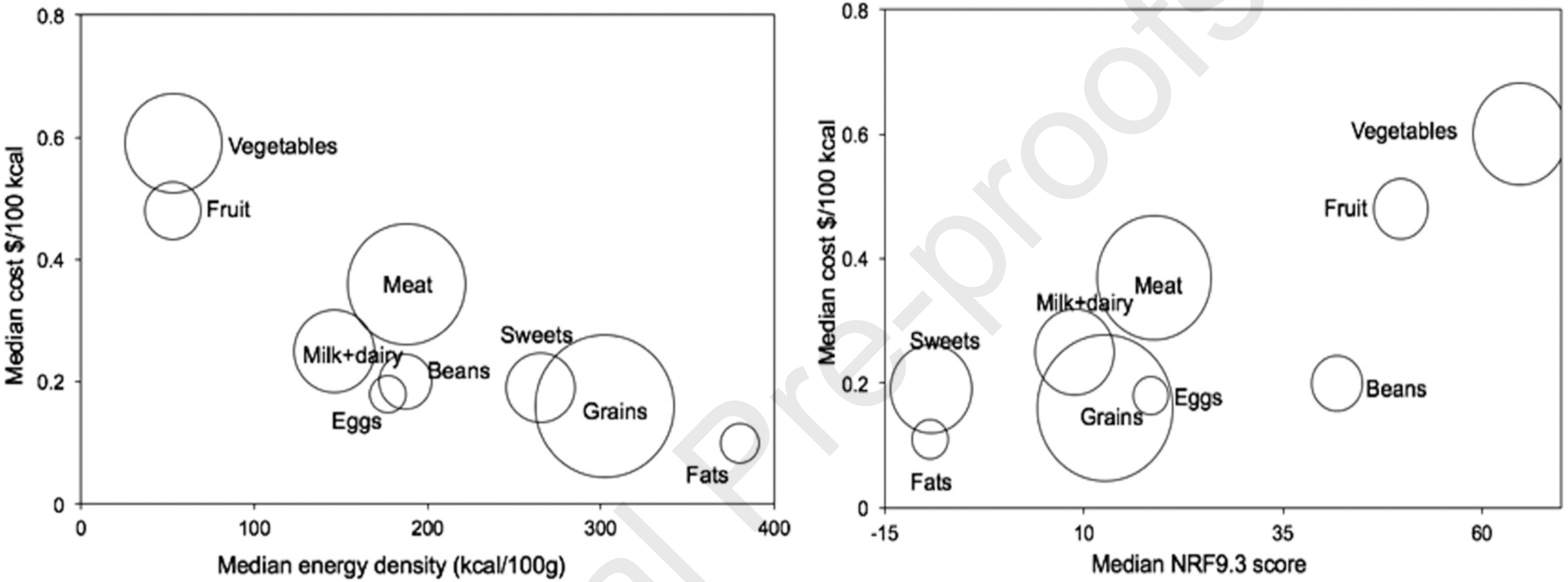
Fig. 4. The relationship between median energy density (kcal/100 g) and median cost per 100 kcal ($/100 kcal) in comparison to the relationship between median NRF9.3 score and median cost ($/100kcal) (Drewnowski, 2018)

A) The relationship between median energy density (kcal/100 g) and median cost per 100 kcal ($/100 kcal) for foods in the Food and Nutrient Database for Dietary Studies 2009–2010 dataset aggregated to 9 major US Department of Agriculture food groups. B) The relationship between median nutrient density (Nutrient-Rich Foods 9.3 score) and median cost per 100 kcal ($/100 kcal) for foods in the Food and Nutrient Database for Dietary Studies 2009–2010 dataset aggregated to 9 major US Department of Agriculture food groups. The size of the bubble represents the number of foods within each group. Abbreviation: NRF9.3, Nutrient-Rich Foods 9.3.


Cultivation
Raw materials (nitrogen, phosphorous, potassium, sulfur, etc.)
On-site equipment use (diesel for tractor and irrigation pumps, electricity for irrigation pumps)
T
Almond meat processing
Hulling/shelling
Packaging
Meat to meal losses
T
Almond meal processing
Sizing, fumigation, blanching, roasting
Packaging
T
Almond milk processing
Shearing, water treatment, homogenization, blending, etc.
Packaging
Batch and scrap losses
Unsweetened almond milk
Co-products
Waste
INPUTS
Background system (upstream production processes) and transport of inputs
Raw materials
T
Water
Electricity
Fuels
IMPACTS
GWP
Water
Energy
Ozone
EP
AP
HTP
HHPA
Ecotoxicity
Legend
T = Transport
GWP = Global warming potential
EP = Eutrophication potential
AP = Acidification potential
HTP = Human toxicity potential
HHPA = Human health particulate air


Veterinary inputs
Supplementary feeds production
Other inputs
Emissions Water use Fossil fuel use
Milking cows
Replacement herd
Dry cows
Milk
Raw-material for use
Cooling & transport
Emissions Water use Fossil fuel use
Ultra-high temperature process
Homogenisation
Packaging
Emissions Water use Fossil fuel use
Final product
Pasture
Manure
Emissions Water use Fossil fuel use
Seed
Fertiliser
Pesticides
Fuel (field prepping, planting & sowing)
Soil fertilisation By-product generation
Repurposed animals (slaughtered or sold for breeding)


A
High income (1.1 b.)
15.7%
Upper middle income ex China (1.0 b.)
19.5%
Lower middle income ex India (1.7 b.)
69.0%
Low income (0.4 b.)
88.8%
China, mainland (1.4 b.)
14.3%
India (1.4 b.)
74.9%
B
Industrialized & Consolidated (1.0 b.)
1.9%
Modernizing & Formalizing (0.8 b.)
10.5%
Emerging & Diversifying (1.7 b.)
17.6%
Informal & Expanding (1.3 b.)
65.3%
Rural & Traditional (2.2 b.)
78.3%


Median cost $/100 kcal
0.8
0.6
0.4
0.2
0
0
100
200
300
400
Median energy density (kcal/100g)
Vegetables
Fruit
Meat
Milk+dairy
Beans
Eggs
Sweets
Grains
Fats
Median cost $/100 kcal
0.8
0.6
0.4
0.2
0
-15
10
35
60
Median NRF9.3 score
Vegetables
Fruit
Meat
Milk+dairy
Sweets
Eggs
Beans
Grains
Fats