An environmental, economic and nutrient index for milk and plant-based beverages in South Africa

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Sustainable decision-making in the food sector is critical in addressing global challenges, such as climate change, resource scarcity, and malnutrition. Particularly, the milk and plant-based beverage sectors lack a comprehensive sustainability index tailored to assess economic, nutritional, and environmental impacts. We developed a specialised sustainability model for milk and plant-based beverages, adaptable to different countries. The Dairy Index for Environment, Economics, and Nutrition (DiEET) revealed that bovine milk scored 3.67 (nutritional), 0.161 (environmental), and 1.543 (economic); almond beverages scored 1.55, 0.172, and 1.103; soy beverages scored 2.21, 0.193, and 1.277; and oat beverages scored 1.204, 0.165, and 1. 083. These findings highlight the need to balance nutrition, economic viability, and environmental sustainability in food choices. The model, based on scientific data and requiring minimal user input, provides a practical tool for stakeholders to assess and compare sustainability across products. By enabling informed decision-making, this study promotes a more sustainable future, advocating for practices that consider all dimensions of sustainability in the food sector. Continuous refinement and validation of the model are essential to maintain its relevance amidst evolving data and industry practices, ensuring its effectiveness in guiding stakeholders towards sustainable dietary choices.

Significance:

This study provides a comprehensive sustainability index for milk and plant-based beverages, addressing critical gaps in current assessments. By integrating environmental, economic, and nutritional indicators, the DiEET offers a holistic approach to evaluating food products. The findings highlight the trade-offs between nutritional quality, economic viability, and environmental impact, emphasising the need for balanced decision-making in agricultural production. This model serves as a practical tool for stakeholders, promoting consumer education and guiding industry practices towards sustainability. Its application can enhance sustainability evaluations and contribute to global efforts in monitoring sustainable development goals.

Introduction

In the face of global challenges, such as climate change, resource depletion and nutrient distribution imbalances, sustainable decision-making in the food sector has become a pressing concern.[1,2] The global food supply, while generally meeting demand, still suffers from inefficiencies, such as food waste, logistical issues and affordability constraints, impeding equal access to nutritious food.[3-6] This issue is particularly acute in the dairy industry and plant-based beverages (PBBs), where the need to balance environmental, economic, and nutritional aspects is paramount. Current methods of assessing the sustainability of dairy and PBBs often lack a holistic perspective.[7] Standard labelling and nutrient-profiling systems, while informative, do not capture the overall healthfulness of products. This gap is notable in the absence of specific nutrient indexes for dairy foods or proteins. Moreover, environmental sustainability assessments relying on single-metric results from life cycle analyses (LCAs) tend to oversimplify the complex sustainability landscape.[8] These challenges underscore the necessity for more detailed and context-specific sustainability evaluations that consider various production systems, geographical locations, and broader impact metrics beyond carbon footprints.

South Africa faces unique challenges regarding nutrient deficiencies and changing consumer and market trends, which can have adverse effects on vulnerable populations, particularly the poor and malnourished.[4,9] Rapid shifts in dietary preferences, influenced by global trends, local economic conditions, and consumer trends that alter the nutritional landscape, can potentially exacerbate nutrient deficiencies and health disparities.[10] The dairy industry and the emerging market for PBBs are central to these changes, making it critical to understand and assess their sustainability in the South African context. This study aimed to develop a tailored sustainability index for milk and PBBs in South Africa, evaluating environmental sustainability, economic viability, and nutritional impact in a manner specific to the industry and country. By addressing the complexities of sustainability within the South African dairy and PBB industries, and integrating nutritional, environmental, and socio-economic indicators, this initiative seeks to foster informed consumer choices, enhance industry resilience, and ensure long-term sustainability. The goal was to create a comprehensive evaluation framework that prioritises simplicity, replicability, and thus transparency and education for both consumers and producers.

Research method

A systematic and comprehensive literature review was undertaken to conduct a data analysis on the subject of sustainability and sustainability modelling. Databases such as ResearchGate and Google Scholar were systematically searched for peer-reviewed articles, research reports, and studies published over the past two decades (2000–2023), encompassing the indicators mentioned (i.e. nutrition, economics, and the environment) related to the sustainability of milk and PBBs, as well as how these indices were measured. Peer-reviewed methods of measuring the indicators were identified and adopted according to the aims of this study. Subsequently, an index named Dairy Index for Environment, Economics, and NuTrition (DiEET) was developed to comprehensively evaluate the environmental, nutritional, and economic profiles of milk and PBBs. The development of the model is elaborated on in the next section, and the process flow is represented in Figure 1.

Model development overview

The Nutrient Rich Food (NRF) index, proposed by Drewnowski et al.[11] and later adapted by Drewnowski and Fulgoni[12] to the NRFh (hybrid), which includes nutrients to be encouraged and makes provision for adherence to recommended food groups, served as a foundational principle guiding the current model. Additional refinements were made, such as in the NRF for adequate intake (NRF-ai), which incorporates the prevalence of inadequate and excessive nutrient intake within populations, by means of weighting factors and subgroups to measure intake according to stratified population requirements.[13] In addition to this, digestible indispensable amino acid score (DIAAS) values inspired the inclusion of protein quality.[14] Beal et al.[15] discussed the concept of priority micronutrient density in foods as a basis for classifying foods in terms of their supply towards recommended intakes of key identified priority nutrients. The Delta Model® as developed by the Sustainable Nutrition Initiative[16] uses the supply of nutrients to deliver an understanding of food groups within the food system. These methodologies provided the foundational framework for the nutritional component of the DiEET model, shaping the implementation of the approaches taken, along with adaptations and refinements to suit a South African context.

The environmental component, being recognised as a sustainability indicator globally, is incorporated into the sustainability index as a key component by means of focusing on major contributing indicators, such as land use, electricity usage, efficiency, waste, and water use.[17-19] Records of expenditures are maintained on farms and factories, whether by automatic management tools or manually by perusing invoices or weighbridge slips. Thus, the model was built with the goal of leveraging existing data for evaluating environmental impact as a midpoint between precision of data and data availability as provided by farmers. Ideally, thorough (LCAs) would be used for all relevant farms, yet a simplified method was used for the purposes of the model that accounts for a more realistic and industry-level availability of data.[20] This method entailed the use of shared indicators amongst distinct products and processes, despite differences in farming operations and relying on data that are generally measured in everyday practice. From an economic perspective, the model incorporated consumer cost as a factor that was evaluated against the poverty levels of the entire population, considering various income groups in South Africa. In addition, the economic health of the producers was assessed by revenue, employment rates, and contribution to gross domestic product (GDP).[21]

Data collection

In order to populate the model, as well as adapt indicators to be relevant to South Africa, both peer-reviewed sources and local online databases were used to source the most relevant information on local population demographics, nutrient requirements, prices, and market preferences. Comparisons and scenarios previously drawn to compare the nutrient profiles of milk and PBBs were used to populate comparisons.[22-27] Beverages were chosen to represent their broad possible classification; thus, a beverage of each relevant class was chosen, i.e. legume (soy beverage), wheat (oat beverage), nut (almond beverage), and ruminant (bovine milk), of which bovine milk consisted of full fat milk (long life and fresh). Financial constraints and relevance to local market preferences excluded rice and coconut milk, as well as fat-free or low-fat milk. Local market reports and scrutiny of local supplier websites offered guidance in terms of which studies and data sets were most applicable, e.g. most South African almond milk is produced using almonds from California, and hence Californian LCAs were used to draw information on the respective indicators.[28] Similarly, data on oats are rarely available in South Africa, and thus data from wheat crops need to be inferred.[29-31] Industry members and local processors were consulted for guidance as well; however, because of non-disclosure agreements with the industry members, the exact data collected were only used for guidance purposes. Literature-based sources were mostly used to compile hypothetical scenarios, solely to validate the efficacy of the model and provide guidance pertaining to different parameters employed.

Model outline

The DiEET model is the first iteration of a conceptual Sustainability index for the Environment, Economics, and Nutrition (SiEEN) model that currently applies only to dairy and potential alternatives. The model does not use the traditional expression of a single score for sustainability but rather scores each component separately, to avoid masking of a poor score for one indicator with a good score for another indicator. The three scores are expressed by means of shorthand notation. The following notations are used: NS, nutrient score; ps, protein score; EnS, environmental score; EcS, economic score. To simplify the interpretation of the results, the environmental and economic components were inverted to allow all increasing values to be favourable. The components are summarised in Figure 2.

Nutrient component

Based on the core nutrients highlighted by the NRFi and NRFh models[12], as well as the suggested nutrients to be included in nutrient indexing by Beal et al.[15], the nutrients included in the model were potassium, dietary polyunsaturated and monounsaturated fats (PUFA+MUFA), saturated fats, iron, sodium, magnesium, calcium, protein, vitamin B12, vitamin E, vitamin A, folate (vitamin B9), and zinc[11,12,15]. Fibre and vitamin C were deliberately excluded because of their natural absence in dairy.[32] Additionally, because of their relevance in the functioning of calcium, e.g. in the mineral complex formed during bone formation, phosphorus was included. Vitamin B2 was further included because of the prevalence of deficiencies in developing countries, such as African countries.[33] Amino acids were included as individual nutrients but were also considered as a subcomponent of protein quality in a separate subscore. The above nutrients were expressed as content per 100 mL, as a percentage of the population nutrient requirements as reported in Supplementary table 1; however, the values were not capped at 100% DV as with the NRFi.[11,14,34]

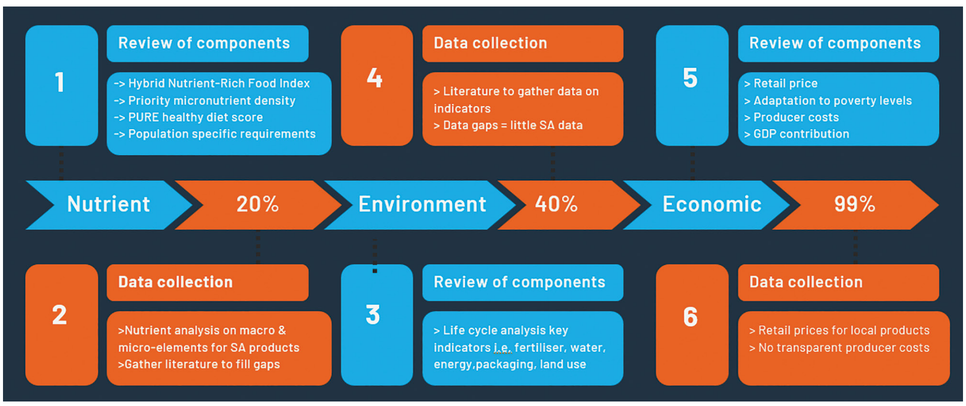

Figure 1: Model development overview and components included.

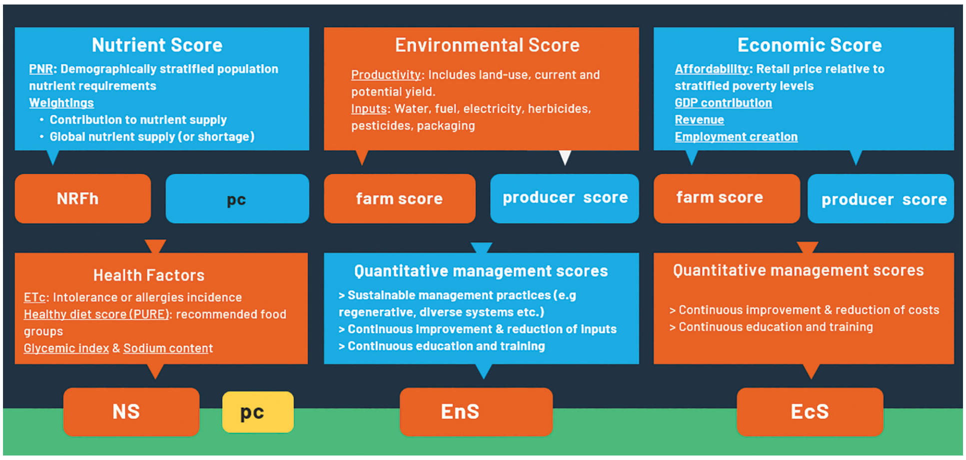

Figure 2: Model outline and summary of main factors included.

The nutrient requirements provided in Supplementary table 1 were synthesised from different sources to synthesise daily recommended intakes[14,35,36], with some supplementation from more recent epidemiological studies in terms of protein and fat intake[37]. Energy requirements are based on moderate physical activity, i.e. a physical activity level factor of 1.8, and average extra daily requirement for the whole pregnancy.[35] Considerations were given to specific requirements within each age and gender group, such as being pregnant or ill.[38] To manage lactation data challenges, pregnant and breastfeeding women are grouped together, with pregnancy assumed to last 9 months and lactation 3 months. In cases of non-lactation, higher nutritional demands were considered throughout postpartum recovery. As a result of their marginal impact, multiple births were excluded, assuming the nutritional needs of such cases to be equivalent to nonpregnant women. Recommendations were adjusted based on population age and gender demographics, as reported in Supplementary table 2, including the percentage of pregnant or lactating women as calculated in Supplementary table 3 for estimating average nutritional requirements. Fortified nutrients, important for sustainable food systems and common in products, were not excluded.

The subscores and subsequent formulas employed are summarised in Table 1. Weighting factors were applied to the nutrients based on existing deficiencies in supply, where a deficiency in the supply of a nutrient warrants an increase in weighting of the nutrient, as calculated by the supplementation coefficient (Sc), which is based on Supplementary table 4.[16] Iron, vitamin A, and zinc were exceptions, where local deficiencies surpass global deficiencies and the prevalence of deficiencies in adolescents was used, with values of 29%, 42% and 63%, respectively.[38-40] Similarly, a weight factor (contribution coefficient) is assigned to each product based on the fraction that each food group ((1) milk, excluding butter; (2) soya beans; (3) nuts and products; and (4) oats) contributes to the global supply of a specific nutrient, which is then adapted to the percentage of each raw material in the final product, as reported in Supplementary table 5 and Supplementary table 6. Protein quality (protein score or ps) is assessed as an additional score by calculating the indispensable amino acid score of each amino acid and, contrary to DIAAS, in which only the most limiting amino acid is highlighted, summed for a total view of protein quality.[14,41,42] The amino acid scoring pattern has been adapted according to demographic strata as reported in Supplementary table 7.

The NRFh utilisation of My Plate Food Groups has been replaced with the latest PURE Healthy Diet recommended intakes (g/day) of each food group in the healthy diet contribution coefficient (HDCc)[12,37], i.e. legumes (48 g/day), nuts (28.20 g/day), dairy (185.50 g/day), and whole grains (40.90 g/day). Additionally, based on recent research on saturated fat and the latest insights on the food matrix effect pertaining to saturated fat, the limiting nutrient score (LIMz) has been removed.[37,43] Limiting factors employed were sodium content, sugar content, and associated diseases or allergies, with some adaptations that are as follows: sugar content was used to calculate the glycaemic index coefficient (Glc), which penalises food based on high glycaemic index (above 55) or low glycaemic index

Table 1: Nutrient score formulas and subscores

Element	Formula
Nutrient sufficiency score (NSs)	NSs = sum [(nutrient content/stratified nutrient requirements) × Sc × Cc]
Supplementation coefficient (Sc)	Sc = 1 + (shortage/population nutrient requirements)
Contribution coefficient (Cc)	Cc = 1 – (contribution ratio)
Protein score (ps)	ps = (sum (IAA))/10
Healthy diet contribution coefficient	HDCc = recommended intake/100
Glycaemic index coefficient (Glc)	Glc = sugar content/100 × [(GI-55)/100] Note only if GI >0; if <0, Glc – 0
Sodium (adjusted)	Sodium(adj) = (target sodium content/(sodium content × serving size)), serving = 120 mL[47]
Exclusion threshold coefficient (Etc)	Etc = 1 – sum [allergy prevalence for product × % of raw material in final product]
Nutrient score (NS)	NS = NSs + HDC – GI corr added sugar – GI corr natural sugar –/+ sodium(adj)

(below 55), based on the type of sugar present in the food, e.g. sucrose (GI:65), maltose (GI:105), and lactose (GI:46).[44,45] Sodium was either a limiting or a contributing nutrient, depending on the content per standard serving, in order to avoid deficiencies of sodium. In the adjusted sodium level (Sodium(adj)), an upper limit was imposed where sodium was limited (deducted) from the nutrient score if the distance from target exceeded 50%, i.e. if the content was more than 50% of the recommended daily intake, and contributed positively to the score when the sodium content was 49% or less.[46] An exclusion threshold was applied, based on the prevalence of allergies or intolerances to each product type, as reported in Supplementary table 8. The full equations and subscores are presented in Table 1.[47]

Environmental component

The common and major contributing indicators identified to be of importance in environmental footprint assessments were blue water (i.e. service and groundwater), fertiliser, fuel, pesticide, and land use.[18,29] Although not all encompassing, these indicators offer a general idea regarding the impact on emissions, water use, and eutrophication or acidification potential. All inputs were adjusted for weight or litre (in the case of raw milk or final product) and adjusted for percentage raw material in the final product during the final calculation. On farm and factory levels, an additional point system was employed as a qualitative measure of the longevity and sustainability of the production system, such as the frequency of soil analyses, cropping type (e.g. monocropping or regenerative), the frequency of sustainability assessments, and others.[48] A simplified scale approach assigned points to the variant applied within each of these indicators, recognising varying degrees of environmental impact or benefit in each of the qualitative measures. A summary of the indicators and user input required is presented in Table 2, in which quantitative scores are awarded points from 0.06 or 0.05 to 0.01, with higher scores being less favourable. These inputs, along with the scenarios in Supplementary tables 9–12, were used in the calculations summarised in Table 3 to contribute to the final environmental score.

Economic component

Inspired by the NRFPI, price was a key component in the economic score.[49] In the current economic score, the price of a product was adapted according to local poverty lines and the amount a person within the poverty levels has each day for food into poverty-adjusted prices.[7] The poverty levels a, b, and c account for 18.9%, 37.60%, and 57.10% of the population, which have ZAR22.10, ZAR29.67, and ZAR44.5/ca/day for food, respectively.[4,36] An additional poverty level (diet-bound poverty level) was created to account for 65% of the population unable to afford a healthy diet, with ZAR57.13 to their availability, which was adapted from a recent publication by Ederer et al.[50] on purchasing power parity base.[36,51] Additional inputs for both farm and factory levels include (1) gross profit, (2) wages, (3) taxes, (4) subsidies, (5) expenses, (6) income from repurposing by-products or waste, (7) employee numbers, and (8) production potential. These were used to assess, amongst others, the extent to which a producer contributes to the GDP of South Africa and to the workforce, as well as the overall financial health of the producer.[21,52] The calculations employed are reported in Table 4.

Table 2: Environmental score user inputs

Farm and factory inputs	Farm-only inputs
Product yield	Fertiliser use
By-product yield	Pesticides use
Quantity recycled	Cropping type (mono < rotational <inter <cover <regenerative < agroforestry)
Quantity repurposed	Livestock use (mixed pasture < single pasture < total mixed ration+ fodder carry, post-harvest grazing < total mixed ration(no fodder carry) < none)
Production potential	Soil type (sandy < clay < loam < silt < peat)
Fuel use	Soil test frequency (never < 5–10 y < 2–5 y < yearly < 2xyear)
Electricity use	Water test frequency (never < 5–10 y < 2–5 y < yearly < 2xyear)
Blue water use	Crop health/livestock welfare assessment (never < 5–10 y < 2–5 y < yearly < 2xyear)
Sustainability training or education frequency (never < 5–10 y < 2–5 y < yearly < 2xyear)	**Factory-only inputs**
Improvement in efficiency yearly (none < 1–2% < 2–5% < 5–10% < 10%+)	Not 100% recycled packaging used
Input reduction yearly (none < 1–2% < 2–5% < 5–10% < 10%+)	

Table 3: Environmental score formulas and subscores

Element	Formula
Farm productivity score (FPs)	FPs = net yield – potential lost – net land use
Potential lost	Production potential – yield
Net yield	Repurposed by-produced + yield
Net land use	1/net yield
Farm footprint score (FFs)	FFs = [sum(input per hectare)/net yield]/1000
Farm management score (FMs)	FMs = sum of qualitative management indicator points
Farm environmental score	FEs = (FFs × % raw material) FPs + FMs
Factory footprint score (FFs)	FaFs = [sum(input)/net yield]/1000
Factory management score (FMs)	FaMs = sum of qualitative management indicator points
Factory environmental score	FaEs = FaFs + FaMS
Environmental score (EnS)	EnS = 1/(FaEns + FEns)

Table 4: Economic score formulas and subscores

Element	Formula
Poverty factor (Pf)	Pf = (Poverty line a, b, c, or d/3 meals)
Poverty-adjusted price (Pap)	Pap = ZAR/100 mL × pf
Producer GDP contribution	(Gross profit + wages + taxes – subsidies)/agriculture GDP contribution (2.7%)
Cost of production	(Expenses – income from repurposing materials)/total production Income from production = gross profit/total production
Cost: income factor	(Cost of production/income from production)/10
Workforce contribution	(number of employees/agricultural employment number (840 000) × 100) × (1 + unemployment rate (32.90%))
Potential lost	[(production potential – total production)/production potential]/100
Economic score (producer or processor)	EcS (producer or processor) = GDP contribution – Cost:Income ratio – Potential lost + Workforce contribution
Economic score total	EcS = 1/(EcS producer + EcS processor – Pap)

Model implementation

Nutrient profiles sourced from literature comparisons[22-27] and previous local nutrient analysis data[53] were used to compile the varying scenarios for a nutrient comparison as reported in Table 5. Protein quality could only be assessed from locally sourced data as sufficient published literature was unavailable. The main subscores and final nutrient score are shown in Table 5, with the full nutritional score outline used is reported in Supplementary table 13.

Table 5: Nutrient score comparison

		Local data analysis	Local label info	#1 Literature scenario	#2 Literature scenario	Average
Bovine milk	**NSs**	1.993	1.938	1.970	1.789	1.932
	ps	1.186				
	NS	**3.771**	**3.679**	**3.713**	**3.525**	**3.672**
Almond beverage	**NSs**	0.740	1.321	1.103	1.755	1.230
	ps	0.909				
	NS	**1.088**	**1.626**	**1.391**	**2.084**	**1.547**
Soy beverage	**NSs**	1.301	1.848	1.1310	2.237	1.629
	ps	1.257				
	NS	1.854	2.377	1.863	2.73	**2.206**
Oat beverage	**NSs**	0.521	1.158	0.758	0.626	0.766
	ps	0.795				
	NS	**0.971**	**1.583**	**1.206**	**1.057**	**1.204**

Scenario: (1) local primary analysis (Maree et al.[53]); (2) South African products' label information (Maree et al.[53]), supplemented with local primary analysis results; (3) literature results, supplemented with local results (Smith et al.[16]; Walther et al.[27]); (4) literature results, supplemented with local results (Fructuoso et al.[24]).

The quantitative inputs used in the environmental score were inferred from literature scenarios as follows: (1) oat and soya bean that are regeneratively produced, based on published available data, although not representative of all production systems in South Africa; (2) dairy production, based on pasture-based systems that represent a large majority of South Africa's production systems[54]; and (3) conventionally produced almonds from California, representing 75% of globally produced almonds, including the majority of brands in South Africa[28,55]. On the processor level, some adaptations have been made to be representative of a South African production system where a single processor is responsible for multiple beverage types.

Qualitative measures were purely hypothetical and have been kept close to similar in all products to avoid the incorrect portrayal of results. Table 6 reports the main subscores. Major differences included between scenarios were only in the cropping type and use of livestock, where bovine milk utilised cover-cropping and pasture-based systems; almond production used monocropping without postgrazing or integration of livestock but used chicken manure, and therefore has been indicated as postharvest grazing in the form of manure spreading (because manure spreading is not an option itself at this point); soy used rotational cropping and no livestock; and oat milk utilised regenerative agriculture and postharvest grazing. The quantitative scenarios and numerical inputs used are reported in Supplementary table 9–12, based on inputs and outputs per year, whereas the full environmental score outline used is reported in Supplementary tables 14 and 15.

Pertaining the economic score, large data gaps and differences between local and international data sets lead to insufficient data to populate the model. Hence, a decision was made to focus on locally available information (which is retail price), preventing skewed results. To scrutinise the effect of price on the economic score, a hypothetical scenario was thus created in which the same producer processes milk and PBBs, with results reported in Table 7. All other factors remained equal across all products, with retail price being the only differing factor.

Table 6: Subscores and environmental score results of bovine milk and plant-based beverages

Parameter	Bovine milk	Almond beverage	Soy beverage	Oat beverage
Farm productivity score	0.911	0.403	0.427	0.724
Farm footprint score	0.001	0.080	0.004	0.000
Management score	0.290	0.765	0.290	0.310
(1) Farm environmental score	1.203	2.250	0.722	1.034
Factory footprint score	4.859	4.905	4.866	4.870
Management score	0.130	0.130	0.130	0.130
(2) Factory environmental score	4.989	5.035	4.996	5.000
Environmental subscore	6.192	5.799	5.171	6.034
Final environmental (inverted) score	**0.161**	**0.172**	**0.193**	**0.165**

Table 7: Comparison of retail price effect in the economic score results of bovine milk and plant-based beverages

Parameter	Bovine milk	Almond beverage	Soy beverage	Oat beverage
Price for reference poverty level:	0.130	0.389	0.265	0.405
RM: GDP contribution	0.229	0.229	0.229	0.229
RM: cost/income ratio	0.31	0.31	0.31	0.31
Raw material producer economic score	–0.08	–0.08	–0.08	–0.08
RM: GDP contribution	0.728	0.728	0.728	0.728
RM: cost/income ratio	0.13	0.13	0.13	0.13
Processing producer economic score	0.6	0.6	0.6	0.6
Economic subscore	0.648	0.907	0.783	0.923
Final (inverted) economic score	1.543	1.103	1.277	1.083

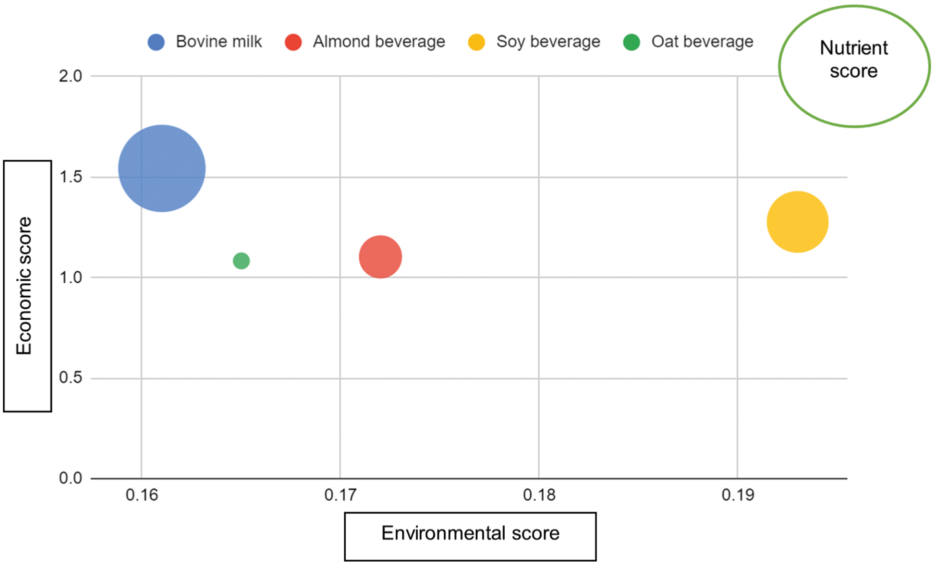

Figure 3: DiEET results for bovine milk and plant-based beverages (bubble size: nutritional score).

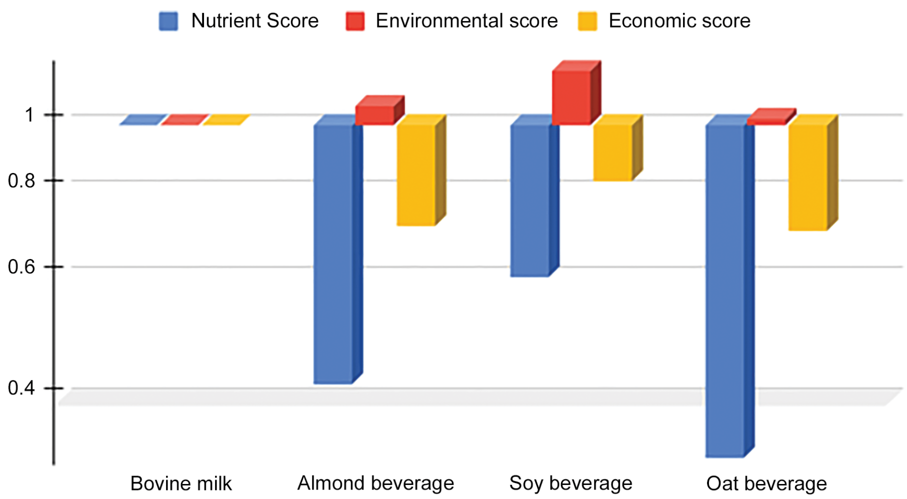

Figure 4: DiEET results of plant-based beverages in relation to bovine milk.

The fourth (diet-bound) poverty level was selected for the comparison of retail prices. The economic component outline is reported in Supplementary table 16.

The results of the main scores (excluding protein score), according to the DiEET model, are shown in Figure 3. Considering the relationship between each component and one another, it is clear that a trade-off exists between the scores when aiming to achieve a high score on more than one parameter. When comparing each score of the PBBs, as a percentage of that of bovine milk as shown in Figure 4, a clear relationship emerges in which the magnitude of differences between the nutrition score and economic score appears, as well as the direction and component in which bovine milk needs to improve.

Discussion

The developed model, including nutritional, environmental, and economic scores as separate indicators, offers variations and scope beyond standard measures, such as the NRFh[12], NRFPI[49], nLCA[8], or other single-metric indexes. This is, in general, a deviation from common practice and can provide opportunity for transparency in consumer decision-making and education. The environmental footprint simplifies comparisons by focusing on key indicators of environmental footprint rather than a single environmental footprint. On the one hand, this is an improvement to standard measures, such as an LCA[8], as it represents a broad range of outcomes other than carbon footprint, specifically considering the ongoing debate regarding the use of carbon dioxide equivalents in current metrics[30,56]. It further allows for industrial application by farmers and producers because of the simplicity of data required.

In the DiEET model results reported in Table 6, mostly similar trends in environmental scores compared to standard units of measure were observed. Notably, the environmental score of bovine milk was consistently lower than all PBBs. Factory inputs for the environmental score remained similar, especially in cases where processors handle both milk and PBBs on the same production line. However, it is essential to acknowledge that raw material processing, which typically occurs off-site for PBBs, is not fully represented in the environmental score calculation and may be under-represented. This highlights a data gap and the potential for increased industry collaboration and data sharing. Yet, it underscores the improvement required in better reporting on matters, such as carbon sequestration, as well as the overall decrease in the environmental footprint of bovine milk.

The DiEET nutrient score in Table 5, both as a subscore and in the final score after accounting for additional health factors, indicated that bovine milk offers a more favourable nutrient profile. This aligned with nutrient profiling but provided less variation than the NRFi, as results using the

NRFi are largely dependent or influenced by fortification. Protein quality, as assessed by protein score, however, showed that soy beverage contained more amino acids per gram of protein than bovine milk or other PBBs, although per 100 mL this might not be the case. This suggests that soy beverage could serve as a valuable protein supplement when considering gram-to-gram protein quality. It further sheds light on the limitations in the use of DIAAS, which does not provide an indication of the overall dietary supplementation that could be achieved by a product but solely focuses on digestibility, neglecting that amino acids in their singular form could act as supplements to an otherwise lacking diet.[14] The model also provided a broader and country-specific contextualised view of the nutrient profiles of milk and PBBs.

From an economic perspective, the model results in Table 7 suggest that bovine milk has a more favourable economic score compared to other beverages when only taking affordability into account, making it more affordable for a larger portion of the population. Based on the nutritional score, this consequently allows for more affordable, high-quality nutrition. Although hypothetical data were used to populate the remaining values in the economic scores, the economic score in general provides a holistic view of economic sustainability by taking both consumer affordability and producer viability into account. Application in industry and consequent validation of these results with ground-truth data can provide further insights into the results and trends reported in this study.

As is, the model is a stepping stone towards more holistic and transparent sustainability measures, recognising that the scientific accuracy and data supporting the model requires more in-depth research and validation. Ideally, in subsequent iterations of the intended SiEEN model, subscores would apply where each production system (e.g. crops, livestock, mixed, intensive, and extensive) has their own analysis which contributes to the final scores.

Additional data sets need to be collected and made available by producers to validate the model and gain accurate results, as well as measure the alignment with current methods and trends to prevent any form of bias generated by the model. The model's complexity requires careful interpretation but serves as a potential tool for decision-makers in the food industry, researchers, and policymakers, as well as consumer educators. To realise this, rapid adoption of the tool by stakeholders is needed to ensure validation and continuous improvement of the model, as well as for data collection to improve the accuracy of results. Such conclusions will aid policymakers in making recommendations on production systems and dietary inclusions and provide a holistic perspective on sustainable production and consumption, moving away from often one-dimensional policies.

Critical evaluation

Limitations in the model exist because of multiple factors, such as the omission of nutrient bioavailability[57], which was an initial goal yet requires much more extensive research to include accurately. Limited research is currently available on the contribution of PBBs to global nutrient supply; hence, overestimations or underestimations are possible and require verification when considering the current weightings applied to nutrient supply and contribution of PBBs.

While the NRFh approaches used provide a useful framework for evaluating the nutrient density of foods, its application is limited by the inability to fully capture the complexities of individual dietary needs and the synergistic effects of whole diets. This model, focused on quantifying the nutritional value of single food items, overlooks the broader context of dietary patterns and the interplay between different foods and nutrients that influence health outcomes. Consequently, it may not adequately address the variability in nutritional requirements amongst individuals or the holistic nature of dietary health. Future research should, therefore, pivot towards exploring the impacts of whole diets and food groups within these diets to offer more comprehensive and personalised dietary recommendations.

From an environmental perspective, although requiring simplified data, the model risks oversimplification of the environmental impact of products and requires large-scale studies to verify the relationships between these indicators with outcomes, such as eutrophication potential, acidification, or biodiversity loss. This is especially relevant to the qualitative measures employed in the environmental component in which a scaling point system is used at equal intervals, whereas ground-truth data may indicate that the scaling intervals change according to different size intervals or based on the environmental impact of each production system (such as regenerative in comparison to conventional). A larger variety of options are further required to represent more diverse production systems.

In the economic component, verification is lacking in the results observed, particularly from a processor level, and consequently requires further research to investigate the relevant economic parameters in more detail. The lack of information from a processor perspective further eliminates room for comment on the success of the measures of economic parameters other than affordability.

Statistically, the model results are limited because of the availability of local data and consequent verification thereof. Thus, the results only provide an indication of whether the model can be implemented in industry, based on the general trends observed in the results and how well it compares to that found in the literature. The results should not be reported as definitive indications of the sustainability of milk and PBBs. In the future, the application of the model and collection of ground-truth data will provide sufficient data sets to validate the model and the results from an industry perspective and a statistical perspective.

Conclusion

The DiEET model's approach has advanced the existing understanding of the sustainability of bovine milk versus plant-based alternatives, such as almond, soy, and oat beverages. This research emphasised the need for a holistic view of sustainability, incorporating nutrient density, bioavailability, environmental impacts through comprehensive life cycle assessments, and the socio-economic implications for food security in South Africa. It further indicated that the potential trade-off to be made between environmental sustainability and nutrient density or affordability, however, to shed light on the potential for the dairy industry to reduce its environmental impact. This is relevant to all beverages, as the use of regenerative practices has a clear impact on the final environmental score. In the aim towards sustainable food systems, the necessity for collaborative research, policy innovation, and informed decision-making is underscored. As a first step, this involves implementing the model in South Africa and continuing improvements based on producer and user feedback in order to inform policy and consumer choices.

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Data availability

All the data supporting the results of this study are included in this manuscript.

Declarations

The project was funded by Milk South Africa and conducted through an independent research organisation, ASSET Research, as part of an MSc degree. The funders had no direct involvement in the project's design, data collection, analysis, or interpretation. All project results and conclusions were finalised prior to any report to the funders. Authors affiliated with the funders were excluded from the conclusion development and were given reviewer access only, without any influence on the final outcomes. After writing the first draft, ChatGPT version 4.0, Open AI was used for an initial language screening or to shorten lengthy sentences using the following two prompts: "Correct the language and grammar in this paragraph: [inserted paragraph]" or "Shorten this text to 50 words: [inserted text]." All resulting text was revised for accuracy before inclusion and submission to an official language editor.

Authors' contributions

E.M.: Investigation, writing – original draft, writing – review and editing. J.N.B.: Writing – review and editing, supervision. C.J.L.D.T.: Writing – review and editing, supervision. H.H.M.: Writing – review and editing, supervision.

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