

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

by

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Declaration

I, Enrike Maree, hereby declare that this thesis, submitted for the MSc (Agric) Animal Science degree at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at any other University.



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All honour and glory to God forever and ever... (1 Tim. 1:17).

Abstract

Amidst growing global concerns over sustainability, the imperative for sustainable agriculture has become increasingly important. This urgency is propelled by heightened awareness among consumers and policymakers, the pressing demands of an increasing global population, and the critical influence of dietary choices on environmental sustainability. Recognising a gap in the literature, this study aimed to contextualise the sustainability of milk and plant-based beverages within the South African milieu, evaluating their nutritional profiles, environmental footprints and economic affordability through a comprehensive literature review. The investigation challenged the prevailing one-dimensional approach in climate-aware consumer choices and policymaking, advocating for a new, contextually relevant perspective.

Central to this research is the development of a sustainability model, the dairy index for the environment, economics and nutrition (DiEET) designed to provide a holistic assessment of the economic, nutritional and environmental dimensions of milk and plant-based beverages. Based on the model results, milk held a superior nutritional and economic profile with scores of 1.932 and 0.848, respectively, in comparison to plant-based beverages with nutritional scores of 0.766-1.629 and economic scores of 0.574-0.713. Soy beverages obtained the highest scores between the plant-based beverages. Environmental scores highlighted bovine milk, with a score of 0.161, as the least environmentally sustainable beverage in comparison to plant-based beverages with scores of 0.165 to 0.193, showing an environmental trade-off of producing an affordable and nutritious product.

In contrast to the nutrient rich food index (NRFi), the model results are less impacted by fortified nutrients. Using NRFi, the study showed that almond beverage has the highest nutrient score (32.573-64.808) in comparison to bovine milk with a maximum score of 8.288, which conflicts with nutrient comparisons and the results of the DiEET model. Environmental and economic results obtained from literature followed similar trends to the results obtained by the DiEET model. The study's findings, both from literature and using the new DiEET model, underscore the complexity of achieving sustainability in the food system and highlights the trade-offs between nutritional value, environmental impact and affordability. This model is an initial step towards integrating multifaceted sustainability indicators into country-specific sustainability policies, thereby informing consumers and promoting a more sustainable, nutritionally adequate and economically viable food system in South Africa and beyond.

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List of abbreviations

AB	Almond beverage
BM	Bovine milk
BF	Bovine milk (fresh)
BLL	Bovine milk (long life)
Cc	Contribution coefficient
DASH	Dietary approaches to stop hypertension
DALRRD	Department of Agriculture, Land Reform and Rural Development
DIAAS	Digestible indispensable amino acid score
DiEET	Dairy index for the environment, economics and nutrition
DV	Daily (recommended) value
EcS	Economic score
Etc	Exclusion threshold coefficient
ES	Environmental score
EWG	Environmental working group
FAO	Food and Agriculture Organisation
FFs	Farm footprint score or Factory Footprint score
FMs	Farm management score
FPS	Farm productivity score
FDA	Food and drug organisation
FOP	Front of pack
FSA	Food standards agency
GCI	Global competitiveness index

GDP	Gross domestic product
GHGe	Greenhouse gas emissions
GI	Glycaemic index
GLEAM	Global livestock environmental assessment model
GWP	Global warming potential
LCA	Life cycle analysis (or assessment)
LIMz	Limiting nutrient score
nLCA	Nutritional life cycle analysis
MRV	Maximum recommended value
MUFA	Monounsaturated fatty acids
NHLBI	National Heart, Lung, and Blood Institute
NRF-ai	Nutrient rich food index for adequate intake
NRFh	Nutrient rich food index hybrid
NRFi	Nutrient rich food index
NRFPI	Nutrient rich food price index
NRx	Nutrient richness score
NS	Nutrient score
NSs	Nutrient sufficiency score
OB	Oat beverage
Pap	Poverty-adjusted price
Pf	Poverty factor
Pc	Protein completeness score
PBBs	Plant-based beverages
PUFA	Polyunsaturated fatty acids
PURE	Prospective urban rural epidemiology
RF	Radiative forcing

Sc	Supplementation coefficient
SB	Soy beverage
TRACI	Tool for the reduction and assessment of chemical and other environmental impacts
UNICEF	United Nations International Children's Emergency Fund
USDA	United States department of agriculture
WHO	World health organisation

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CHAPTER 1 General introduction

1.1 Background

The intersection of agriculture, nutrition and environmental sustainability is at the forefront of modern global sustainability challenges. In South Africa, a unique mixture of socioeconomic factors, agricultural practices and environmental imperatives necessitates a new understanding of the food system, particularly in the context of dairy and plant-based beverages (Drewnowski, 2018; Martinho, 2022; Singh-Povel et al., 2022; Mubangizi, 2023).

Consumer trends in South Africa, mirroring global patterns, indicate an increase in consumption of plant-based diets (Keri et al., 2021). This shift, driven by dietary preferences, environmental concerns and ethical considerations, has augmented the market presence of plant-based beverages, such as soy, oat and almond beverages (Willett et al., 2019; Skorbiansky et al., 2022). The motivation behind these consumer choices is diverse (Keri et al., 2021). While some consumers are driven by personal health concerns, such as lactose intolerance or cow's milk protein allergy (Walther et al., 2022), a portion of the shift is attributed to the belief that animal-based products disproportionately contribute to climate change, and that plant-based alternatives are a tool for climate mitigation and animal welfare (Kundu et al., 2018; Rombach et al., 2023).

However, this perception is not without controversy. The Food and Agriculture Organization (FAO) has previously reported that livestock contributes to 14.5% of anthropogenic greenhouse gas emissions, with recent figures from the Global Livestock Environmental Assessment Model (GLEAM) reporting lower emissions of 12% (Gerber et al., 2013; FAO, 2023). Despite these figures, the environmental impact of livestock is complex, encompassing the complete life cycle of carbon, nitrogen and water, as well as

ecological shifts in different ecosystems and cannot be captured in a single figure (Mitloehner, 2016; Monzano et al., 2023). Thus, a scientific and country-specific assessment of environmental footprint is vital to assess the actual environmental footprint of the dairy industry, particularly in the context of holistic indicators such as nutrition and socioeconomics.

South Africa's agricultural landscape is mostly dominated by crop and livestock farming, shaped by the country's geography, climate and consumer demand. Livestock farming, and dairy production in particular, occupies a critical space in this system. With only 13.6% of the country's land suitable for crops and 68.5% for grazing (DALRRD, 2023), livestock serves not only an economic role but also a nutritional one, converting non-human-edible plant material into nutrient-dense foods (Thompson et al., 2023). This function is crucial in a context where undernutrition and malnutrition are persistent issues (Roser & Ritchie, 2020).

The previously mentioned rising popularity of plant-based alternatives, while offering diversity and market-related benefits in certain contexts, also poses significant challenges. These beverages are often ultra-processed and may not match the nutrient density of dairy milk (Smith et al., 2022b). Moreover, the economic viability of large-scale shifts towards plant-based agriculture for farmers in South Africa is of question, given the lack of financial support and the extensive investment required to alter production systems, in addition to potential negative effects on consumer affordability (Bai et al., 2021; OECD, 2022).

The dairy industry is a contributor of local protein supply, contributing 7.3% of the country's edible protein (GOALSciences, 2023). Any contraction in this industry, prompted by reduced consumer demand or unfeasible policy directives, could exacerbate food insecurity and nutritional deficiencies among the vulnerable populations. Thus, the competitive sustainability of the dairy industry is also of importance. Moreover, adequately measuring the sustainability of dairy and plant-based beverages to accurately inform local producers and consumers in their choices becomes increasingly important.

The need for dynamic, science-based tools to assist producers in making informed decisions that balance environmental, nutritional and economic considerations is clear in that

context. Such tools would need to facilitate a comprehensive analysis of the environmental footprint of dairy in comparison to plant-based alternatives, considering the nutrient density and overall sustainability of these products. The long-term viability of South Africa's dairy and plant-based beverage industry relies on integrative approaches that respect the intricate web of production, consumption and environmental stewardship.

A need was thus identified in the dairy industry for a robust, replicable and consistent measurement tool which can assess not only environmental performance but also socioeconomic performance and contribution to the global and local food system. With changing consumer demands and the concern of climate change, the industry must adapt to meet sustainability expectations while maintaining nutritional adequacy, economic viability, and social acceptance. A comprehensive and localized sustainability measurement index can drive this transformation, aligning the industry with global sustainability goals and securing a sustainable future. By establishing a standardized framework to assess and mitigate sustainability concerns, the industry can identify improvement areas, reduce its environmental footprint, enhance economic viability, and support food security in South Africa.

1.2 Aim and scope

The aim of this study is, therefore, to develop an industry-specific sustainability model which measures the environmental footprint, economic profile and nutritional profile of milk and plant-based beverages in South Africa. The model needs to be developed in such a manner that the values can be compared among products, to determine the sustainability of milk and plant-based beverages in a holistic measure and identify areas of improvement. It should be relevant and practical, for a realistic and accurate comparison which can be utilised by industry members and consumers such as MilkSA, for which the model will be converted into a web-based tool.

The objectives are thus to compare key indicators of milk and plant-based beverages with current methodologies, establish new methodology of measurement for each of the main indicators, with all applicable calculations described or visible, and to verify this by

means of using primary and literature-based data for comparison between products, in the following order:

1) Review of the literature for the current state of knowledge to determine the most suitable methodology and indicators to form the basis of the sustainability model.

2) Source local primary data through nutritional analysis, as well as secondary published data to compile comparisons between milk and plant-based beverages to be used in populating the model.

3) Develop a model which can be used to assess the sustainability of milk and plant-based beverages and populate the model for initial comparisons.

4) Make the model accessible online on the ASSET Research website to be used by MilkSA and other industry members (ASSET Research, PRJ-0346-2023).

Readers note: All of these chapters have been prepared for publication and requires each chapter to be read as a lone standing document, thus repetition among the chapters are inevitable but have been limited as far as possible. To further limit unnecessary repetition, all references, regardless of chapter, appear at the end of the entire document collectively.

CHAPTER 2 Milk and plant-based beverages: a review on the need for holistic, sector-tailored sustainability assessments

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2.1 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: plant-based beverage, dairy milk, nutrient density, sustainability assessments, environmental footprint

2.2 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 the dairy industry (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, the Food and Agriculture Organisation (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 (Gerber et al., 2013; FAO, 2023). In the dairy sector, comparative studies reveal that dairy milk yields 1.586 CO₂eq/kg of product, while beverages such as soy beverage yield 0.48 CO₂eq/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 socioeconomic 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.

2.3 Milk and plant-based beverages in human nutrition

Nutrition and health are crucial in discussions surrounding sustainability, especially considering the status of the global nutrient supply (Drewnowski et al., 2020; Smith, 2021). While global supply of energy is reportedly sufficient to meet global energy demands (Berners-Lee et al., 2018), logistic and accessibility hurdles still lead to hunger and undernourishment, particularly in areas of social instability or conflicts (Roser & Ritchie, 2020; Shekhar & Sharma, 2023). More so, large scale global incidences of malnutrition characterised by specific nutrient deficiencies such as iron, zinc, protein, vitamin B12, vitamin A and calcium are widespread (Sivaprasad, 2019; Smith, 2021; Han et al., 2022; Dave et al., 2023). In light of this, it is crucial to identify foods that address these deficiencies and contribute to global nutrient supply in an adequate manner, while still managing contributions to the economy and the environment.

Table 2.1: Nutrient content (ranges) of milk and plant-based beverages

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

Nutrient per 100ml	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
Carbohydrates (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	-	-

Note: The above ranges include a combination of both fortified and non-fortified beverages, of which calcium, vitamin D and vitamin B12 are the main nutrient fortified.

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); Schönfeldt et al. (2012)

Upon comparing the range of nutrient profiles of dairy milk, and oat, almond and soy beverages, such as summarised in Table 2.1, it is evident that each beverage type offers distinct nutritional characteristics. Cow's milk, an excretion from mammalian udder glands, naturally stands as a primary source for essential nutrients such as calcium, vitamin B2, lysine, and dietary fat (49%, 24%, 1% and 15% of global nutrient availability, respectively). In addition, it contributes 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 (Smith et al., 2022b; Dave et al., 2023).

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 2.1 (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 (Leroy et al., 2020; Abeyrathne et al., 2022; 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 & Orteni, 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 al., 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 (Paul et al., 2020; Fructuoso et al., 2021; Sunidhi et al., 2021), 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, 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 (Shkempi & 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.

2.3.1 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 2.2, mostly reward food items based on specific ingredients or nutrients perceived as healthy and penalises food for “unhealthy” nutrients or nutrients and food groups to limit, such as saturated fat. Exceptions are in specific outcome-related measures such as the 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 (NHLBI, 2021; Beal et al., 2023). Regardless, the common trend is to move past nutrient content and gravitate towards a more holistic view of a product’s nutritional profile, especially focusing on nutrient density and health outcomes. There are, however, still limitations to some of these measures, such as constraints in bioavailability reporting (Fairweather-Tait & Collings, 2010) which recognises the urgency of accurate research in health outcomes of dietary choices and nutrients, such as discussed in the next sub-section.

Table 2.2: Nutrient profiling systems of foods

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.	Food and Drug Administration (2017)
FSA nutrient label	As above, including a colour-code to indicate high- to-low concentration 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.	Food Standards Agency (2016)
Nutri-Score	Assign a letter grade based on nutritional content, penalising and rewarding specific factors	Fruit, vegetables, fibre, protein	Energy, sugar, fat, sodium	Questions raised on scientific backing. Does not consider bioavailability or food matrix effects.	Aligns consumer perceptions with healthier choices.	United Nations International Children's Emergency Fund (2021); Peters & Verhagen (2022); Van der Bend et al. (2022)

Table 2.2: Nutrient profiling systems of foods (continued)

Measure/ metric	Description & aim	Nutrient or food group encouraged	Nutrient or food group limited	Cons	Pros	Reference
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.	World Health Organisation (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. (2018); Mozaffarian et al. (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.	United States Department of Agriculture (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 such as nutrient adequacy or weight control.	Proven effective in managing hypertension.	National Heart, Lung, and Blood Institute (2021)

Table 2.2: Nutrient profiling systems of foods (continued)

Measure/ metric	Description & aim	Nutrient or food group encouraged	Nutrient or food group limited	Cons	Pros	Reference
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, including. 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 et al. (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	Energy, 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.	Environmental working group (2023)

2.3.2 Shortcomings of existing measures 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 policymakers 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 et al., 2023; Beal et al., 2023).

Furthermore, while adaptations to the NRF Index related to carbohydrates exist, there is an absence of food-group-specific nutrient indexes, such as an NRF_i 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 such

as Vitamin E 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.

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 (Aguilera, 2019). Finally, for comparison, it is recommended to tailor nutrient indexes to food groups or types (Kytta et al., 2023).

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). 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 (PBBs) are therefore explored in the following section.

2.4 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 in carbon dioxide equivalents (Dong et al.,

2021). When examining the carbon footprint of milk and PBBs, distinct differences become evident, as highlighted in the comparison in Table 2.3. 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 2.3, 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 kgCO₂eq/kg of the product, the comparability of results is once again questioned, being emphasised by some cases of soy beverage and oat beverage production resulting in 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).

Although a contrast cannot accurately be drawn between on-farm carbon emissions and final product carbon emissions, some differences notable in the two metrics may stem 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, where the water footprint of the final product is much higher than what has been produced on farm. (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).

2.4.1 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, such as summarised from comparative studies in Table 2.3, 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 e.g. carbon dioxide, methane and nitrous oxide are converted into carbon dioxide equivalents (Jungbluth & Meili, 2019; Winans et al., 2020). The water footprint (not reported here) includes categories such as blue water, green water and grey water, which reflect direct and indirect water usage (Hoekstra et al., 2011).

Table 2.3: Carbon footprint of milk and popular plant-based beverages and the respective raw materials, measured in carbon equivalents

Final product					
Unit	Almond beverage	Soy beverage	Oat beverage	Dairy milk	Source & comments
kgCO ₂ eq/kg		0.31	0.21	0.84–2.4	Thoma et al., (2013); Helsing (2019); dos Santos et al. (2022)
kgCO ₂ eq/L	0.467	0.438–0.53	0.301	1.56	Coluccia et al. (2022); Singh-Povel et al. (2022)
kgCO ₂ eq/kg	0.5-0.8	0.66-1.4	0.21-0.95	3.1	Sunidhi et al. (2021); Geburt et al., (2022)
kgCO ₂ eq/kg	0.39–0.58	0.24–1.21	0.54	1.7–1.97	Winans et al. (2020)
Average*	0.54	0.62	0.45	1.64	*based on number of results obtained across studies
Raw Material					
Unit	Almonds	Soybean	Oats	Raw dairy milk	Source & comments
kgCO ₂ eq/kg	1.03–2.08				Marvinney et al. (2020); Volpe et al. (2015); Kendall et al. (2015); Marvinney et al. (2015)
kgCO ₂ eq/kg	0.35–1.03				Martin-Gorriz et al. (2020)
kgCO ₂ eq/kg		0.3–1.93			Blignaut et al. (2019); Escobar et al. (2020); Raucci et al. (2014); Maciel et al. (2016); Potter et al., (2020)
kgCO ₂ eq/kg			0.33–0.59		Blignaut et al. (2019); De Kock et al. (2018); Heusala et al. (2020)

kgCO ₂ eq/kg				0.72 – 1.67	Basset-mens et al (2005); O’Brien et al., 2011; Gollnow et al., (2014); Reinecke & Blignaut, 2021; Galloway et al., 2024
Average*	1.23	1.09	0.49	1.2	*based on number of results obtained across studies

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 & Blignaut, 2021). 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 2.1 and Figure 2.2

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, as well as factors like ingredients, co-products, additives and energy sources (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.

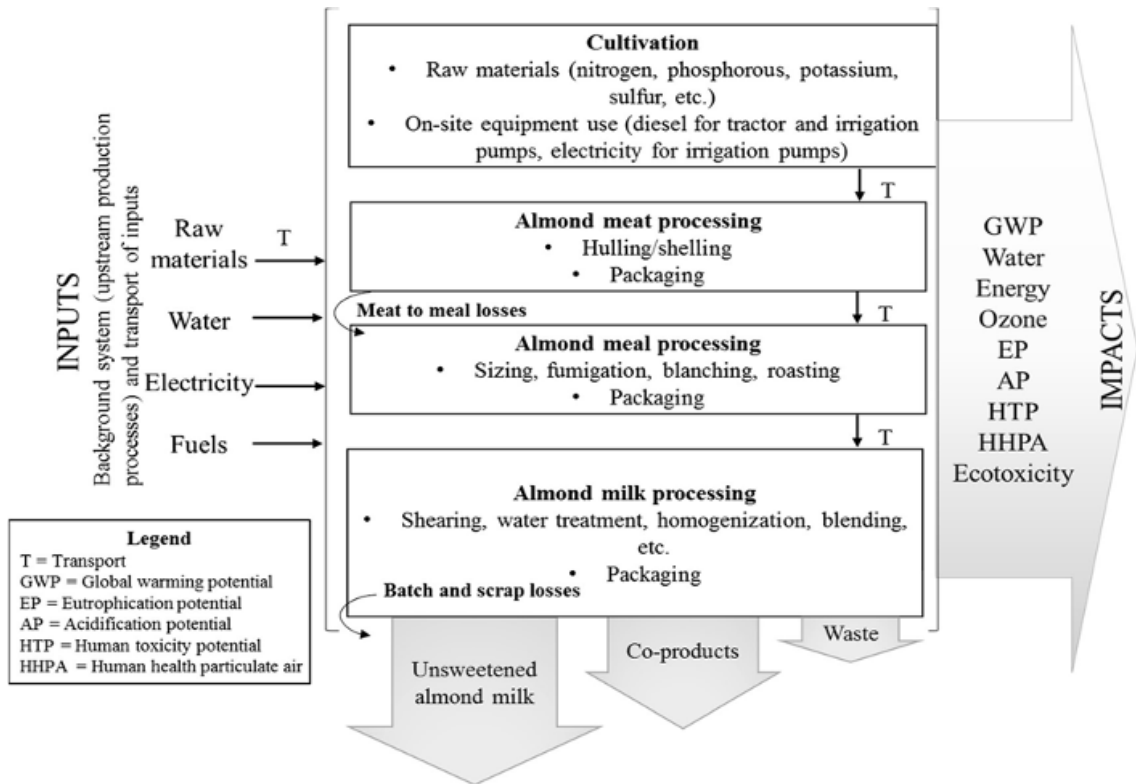


Figure 2.1: Simplified process diagram of a life cycle analysis for almond production (Winans et al., 2020)

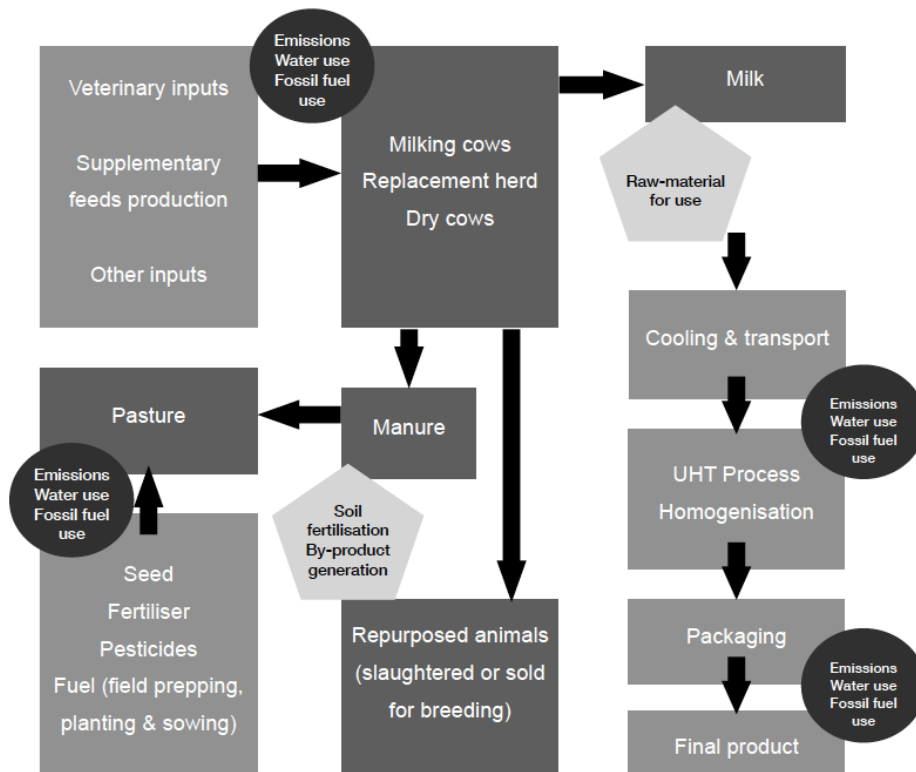


Figure 2.2: Summarised process flow of milk production, inputs and outflow (created by author)

*UHT: Ultra High Temperature

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. An example would be such as a different unit of expression or the inclusion of ecological indicators, land-use, water use, among others in combined metrics (Weidema & Stylianou, 2020; Manzano et al., 2023).

The conventional measure of carbon 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).

2.4.2 Shortcomings of existing measures 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, water-use or land-use, productivity and farmland conditions before and after production may further enrich assessments, especially when tailored to the geographical environment.

As with nutritional 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.

2.5 A socioeconomic view on milk and plant-based beverages

2.5.1 Overview and existing measures

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).

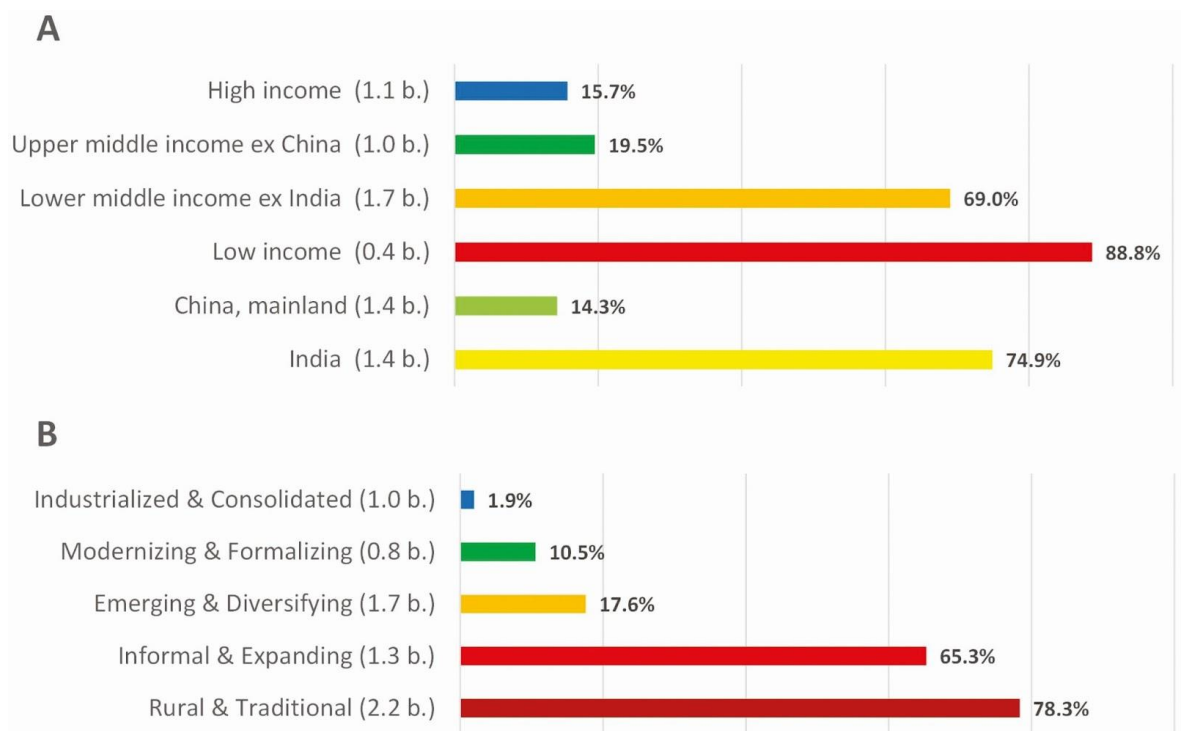


Figure 2.3: Share of population unable to afford a healthy diet (Ederer et al., 2023)

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 energy 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 2.3, 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 2.4 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).

Table 2.4: Retail prices of milk and plant-based beverages in America and South Africa

	Unit	Ave	Min	Max
Cow's milk	USD/liter	\$1.04	\$1.00	\$1.08
	ZAR/litre	R16.31	R13.00	R18.33
Almond beverage	USD/liter	\$1.65	\$1.61	\$1.69
	ZAR/liter	R48.20	R29.95	R126.00
Soy beverage	USD/liter	\$1.76	\$1.72	\$1.80
	ZAR/liter	R32.86	R19.66	R60.00
Coconut beverage	USD/liter	\$1.81	\$1.72	\$1.90
	ZAR/liter	R77.94	R44.98	R299.75

Note: Average PBBs prices reflect fortified and non-fortified products, in which no price differences were noted within the same brand and product. **Sources:** Johnston and Pretorius (2020); Skorbianksy et al. (2022)

However, still in this regard clear definitions and standards need to exist to avoid extreme differences in outcomes. For example, in Figure 2.4 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.

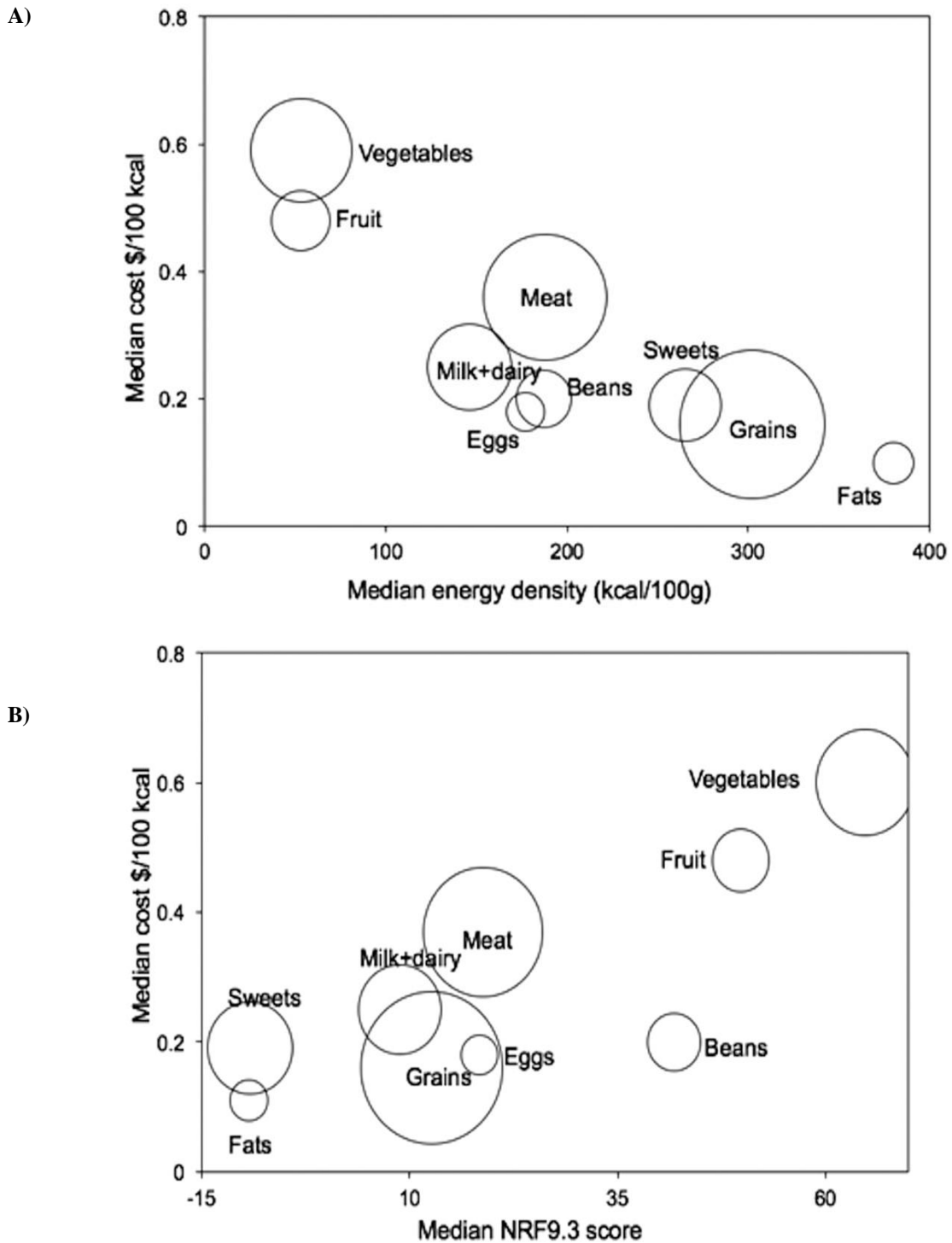


Fig. 2.4. The relationship between A) median energy density (kcal/100 g) and median cost per 100 kcal (\$/100 kcal) in comparison to B) the relationship between median NRF9.3 score and median cost (\$/100kcal) (Drewnowski, 2018)

From a more qualitative measure, social acceptability is often used as one indicator of economic sustainability. This is measured either by means of questionnaires or quantitatively defined by consumption figures and trends. This measure currently reflects 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 (Fleurbay & 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.

2.5.2 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 (Fleurbay & 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.

2.6 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.

CHAPTER 3 A nutrient comparison of milk and plant-based beverages in relation to environmental footprint and price

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3.1 Abstract

In the pursuit of sustainable food systems, a comparative study of milk and plant-based beverages becomes crucial, especially in the context of environmental sustainability, nutritional adequacy and economic viability. This study delves into a data examination, contrasting the nutrient profiles of milk with those of plant-based alternatives, while also considering their environmental footprints and cost-effectiveness. Utilising a comprehensive data collection methodology, this study integrates primary data and extensive literature review to assess the nutritional content, environmental impact and economic affordability of these beverages in South Africa.

The analysis reveals clear variations in the nutrient profiles of milk and its plant-based counterparts. Milk has the highest protein (3.47g/100ml), energy (275kJ/100ml), total amino acids (3.54%), calcium (119.29mg/100ml), phosphorous (85.60mg/100ml), Vit B2 (0.19mg/100ml), Vit B9 (4.70 ug/100ml) and Vit B12 (0.23 ug/100ml). Almond beverage and oat beverage contain fewer macronutrients than the above but contains beneficial micronutrients at higher levels such as Vit E (1.60 ug/100ml) and Vit A (0.06mg/100ml). Soy beverage has a lower yet comparable nutrient profile to bovine milk overall. The nutrient rich food index (NRFi) yielded varying results with oat beverage and almond beverage scoring higher than expected, which signals a potential reevaluation of the weight of fortified nutrients in the final assessment.

Environmental assessments employing life cycle analysis (LCA) methods indicate diverse trends, dependent on production system. Plant-based beverages show lower environmental impacts in the final product than dairy production (0.45- 0.62 kg CO₂eq/L vs. 1.64 kgCO₂eq/L), whereas the raw material production is comparable to dairy (0.49 – 1.23 kg CO₂eq/kg vs. 0.1.23 kg CO₂eq/kg). Economically, bovine milk is approximately two to five times less expensive than plant-based beverages and score better when comparing the costs per nutrient unit.

These findings contribute to the discourse on sustainable dietary choices by providing an understanding of the trade-offs between nutritional value, environmental sustainability and economic accessibility. The results underscore the necessity for a holistic approach to food sustainability assessments, advocating for policies and consumer practices that are informed by comprehensive data on all dimensions of sustainability. It also gives insights into the areas of improvement required for each beverage.

3.2 Introduction

Sustainability within the food system, particularly in the context of South Africa, is anchored in addressing environmental, socioeconomic and nutritional challenges. This is underscored by the stark realities of poverty and nutritional disparities prevalent in the country (Worldbank, 2020). South Africa is characterised by significant income distribution inequality, with a Gini score of 63 in 2021, indicating the highest level of income inequality globally (Roser & Ritchie, 2020). Additionally, the nutritional status of the population is alarming, with 27% of South African children experiencing stunted growth due to malnutrition (Galal, 2022). The combination of these factors, compounded by the current instability in the global economy and increasing poverty rates, heightens the urgency of addressing nutritional wellbeing comprehensively. This includes ensuring the fulfilment of basic energy needs for the population's vulnerable segments while promoting healthier dietary choices for those with sufficient energy.

In this context, the role of dairy production in South Africa is pivotal. Dairy products contribute to the nutritional intake of the local population, accounting for 13.53% of the country's food production by mass, 4.82% of the total kiloJoules, and 8.02% of the total protein produced (GOALSciences, 2023). Although plant-based beverages have not yet been evaluated in terms of global nutrient supply, the sustainability of the dairy and plant-based beverage industry necessitates a detailed examination of their nutritional impact to understand their role in the broader narrative of securing a sustainable supply of nutritious foods.

Reviewing the available literature, however, with a focus on milk and plant-based beverages and their respective environmental impacts, nutrient profiles and economic implications, notable gaps are revealed in localised data. A concern is the scarcity of peer-reviewed and publicly available data from producers regarding nutrient fortification levels and amino acid content of milk and plant-based beverages. This lack of information hinders the accurate calculation of the Nutrient Rich Foods Index (NRFi), a crucial metric for evaluating the sustainability of these products in terms of nutrition.

Moreover, the variability in nutrient content among plant-based beverages, attributed to differing fortification practices and production methods, contrasts with the relatively consistent nutrient profile of bovine milk. Consequently, literature-based assessments of nutrient supply through milk and plant-based beverages fall short without more detailed analysis on local offerings, including data on the Digestible Indispensable Amino Acid Score (DIAAS) for a comprehensive evaluation of their protein quality. In addition, more holistic perspectives pertaining to the environmental cost or consumer costs to obtain a specific nutrient profile is further deficient and may hinder science-based decision-making.

This study aimed to address these information gaps by conducting an in-depth comparison of the nutrient profiles of South African milk and some of the most prominent plant-based beverages in South Africa (soy, almond and oat beverage), thereby evaluating their potential to mitigate malnutrition and enhance nutrient intake among South African consumers. Key objectives included discerning the nutritional variances between milk and plant-based beverages which will contribute to a local dataset on these beverages, evaluating these differences in the context of price and environmental impact, and evaluating the applicability of measures such as the Nutrient Rich Food index (NRFi), Nutrient Rich Food price index (NRFPi) and DIAAS for determining their nutritional efficacy and overall sustainability. Through this comprehensive approach, the study sought to provide critical insights into the nutritional landscape of milk and plant-based beverages in South Africa, offering recommendations to support sustainable beverage choices within the context of the country's unique socioeconomic and nutritional challenges.

3.3 Materials and methods

An initial systemic literature review was conducted to gain general literature-based data on the nutrient profiles of milk and plant-based beverages in South Africa, with focus on key words such as “plant-based milk”, “plant-based beverages”, “oat milk”, “soy milk”, “dairy”, “bovine milk”, “almond milk”, “milk alternatives”, in combination with key words such as “nutritional analysis”, “nutrient profile”, “nutrition”. For use in following stages, similar key words were coupled with “environmental footprint”, “life cycle analysis”, “carbon footprint”, “inputs”, and other deviations of these words. Due to the aforementioned lack of South African data, the findings necessitated supplementation with local labelling

data and primary sourced data to compare along with internationally sourced data. To achieve this, a one litre sealed sample of organic or sugar-free beverage was collected for full fat fresh bovine milk, full fat long-life bovine milk, oat beverage, almond beverage, and soya beverage from the shelf of a local supplier in Gauteng, South Africa. The selection was done based on brand popularity assessed by a local report and by scrutiny of multiple online catalogues to determine the most prevalent brands (Johnston & Pretorius, 2020). Processor locality and scope were considered as well where a single South African processor was selected, responsible for majority of the beverages. Oat beverage was not processed by the specific processor thus another local processor was selected, responsible for oat beverage. The processors will remain anonymous. After industry consultation with some of the relevant processors, an assumption was made that each manufacturer have their own processes in place to ensure product homogeneity between batches to adhere to the nutritional labels as advertised on their products. For this reason, it did not make financial sense to submit multiple repetitions of the same product within the scope, budget and timeframe of this study. General nutrient analysis was performed according to accredited standards, given in Table 3.1, at Mérieux NutriSciences (Stellenryk Building Constantia Square Office Park, 526 16th Street, Randjespark, Midrand, 011 805 4310), an accredited laboratory in Gauteng with SANAS accreditation (Accreditation Nr T0350, according to ISO/IEC 17025:2017). Additional analysis on amino acids were conducted on the same products, sampled in the same manner, through Innovative Research Solutions in Cape Town (Groene Weide Farm, Protea Road, Klappmuts, 021 875 5778) using similar methodologically, however, with lower detectible limits of amino acids.

Table 3.1.1: Local method of analysis for milk and plant-based beverages

Local analysis	Method	Comments/description
Density	SWM.PHY.005	NFV04
Moisture (PBB)	SWM.CHEM.010	NF V04-401, EN12145, ISO712
Moisture (dairy)	SWM.CHEM.001	NF EN ISO3727-1, IDF26A:1993, ISO13580, ISO 6731, IDF21, ISO5536, NFV04-370
Dry matter	SWP.CHEM.030	Calculated based on moisture content
Ash	SWM.CHEM.002 6	AOAC945.46, AOAC930.30, AOAC920.108, ISO936, ISO2171, EN1135, NF V04-404
Sugars	SWM.CHEM.008	IOCC analytical method 34, AOAC980.13, AOAC982.14
Total fat (PBB)	SWM.CHEM.025	ISO1443

Fat (dairy)	SWM.CHEM.014	ISO7208, ISO1736, ISO2450, ISO1737, ISO1211, ISO3727-2, ISO8262-3, ISO1735, IDFS
Fatty acids	SWM.CHEM.011	AOAC996.06, NF V03-030
Protein (PBB)	SWM.CHEM.004	Dumas method, ISO14891, ISO16634-2
Protein (dairy)	SWM.CHEM.003	Kjeldahl method, ISO8968-2, EN12135, IDF20
Carbohydrates	SWP. CHEM.030	Calculated based on sum of sugars (fructose, glucose, lactose, galactose < sucrose, maltose)
Dietary fibre	SWM.CHEM.009	AOAC 985.29, AOAC.991.43
Energy	SWP.CHEM.030	Calculated based on all above as per method listed (calculation not specified by laboratory)
Na, Ca, Mg, Zn, K	SWM.CHEM.005	EN15505, ISO8070, EN1134, EN13805

Table 3.1.2: International method of analysis for milk and plant-based beverages

International analysis	Method	Comments/description
Amino acids	Internal method	
Iodine	Internal method	
Phosphorous	Internal method	Adapted from NF ISO8070
Vitamin A	Internal method	
Vitamin B2	Internal method	Adapted from NF ISO8070
Vitamin B3	Internal method	Adapted from EN 15652
Vitamin B9	Internal method	Adapted from AOAC 992.05
Vitamin B12	PNTA0137	PNTA0137
Vitamin D3	NF EN 12821	NF EN 12821
Vitamin E	Internal method	
Vitamin K1	Internal method	

The nutritional results gained from the above analyses were compared with one another by analysing the mean, deviations from the mean as well the significance of that deviation, in conjunction with directional and magnitude comparisons. Following this, these results were further used with internationally sourced data for a comparison according to the Nutrient Rich Food index (Drewnowski & Fulgoni, 2020). The NRF score (NRF_i) for individual foods is calculated as $100 * (NR_x - LIM_z)$, where NR_x represents the sum of qualifying nutrients to encourage and LIM_z represents the sum of disqualifying nutrients to limit and is calculated as a portion of maximum recommended value (MRV). The NR_x in this case is calculated based in nutrient content per kilojoule, as a portion of daily requirement value (DV). The specific calculations were thus as follows: $NR_x = \sum_{i=1}^n ((Nutrient/energy\ density)_i / DV_i)$ and $LIM_z = \sum_{i=1}^n ((Nutrient/energy\ density)_i / MRV_i)$. The primary dataset obtained from the nutritional analyses was used to

supplement local labelling information and various international datasets in order to compile at least four complete nutrient datasets to compare using the NRFi, on the basis of 100 ml and 100 kJ. Minimum, maximum and average values were used for further comparisons. To assess the affordability of the products, the online catalogues from local suppliers were inspected to identify the prices of the selected beverages as supplied by different brands and shops, between November 2022 and June 2023. This assisted in calculating an average price per 100 ml of the product. Thereafter, the same principle as the Nutrient Rich Food price index (NRFPI) was followed to calculate the affordability of the nutrient profile as follows: $NRFPI = NRFi / Price/100ml$, where a repetition was done for price per 100 kJ (Mendoza-Velázquez et al., 2023). For comparison, cost was calculated for energy and protein as well.

In terms of the environmental component, multiple life cycle analyses (LCAs) for each product were sourced, where available, to gain datasets relevant to South African products from which to draw comparisons for environmental footprint (expressed as carbon dioxide equivalents). The final emission factor, expressed as $gCO_2eq/100$ ml product, was further adapted to $gCO_2eq/100$ kJ and used to divide the NRFi, yielding the NRFi achieved for each gram of carbon dioxide emitted. The same process was repeated for energy and protein content. Since the number of datasets obtained from the above methods were limited and repetitions could not be analysed, the basic prerequisites for elaborate statistical analysis such as ANOVA could not be performed. However, the results could be portrayed in tables to be compared visually, gain magnitude or directional differences (e.g. to determine maximum or minimum values), and to determine the standard deviation between products.

3.4 Results

3.4.1 Nutrient profile results of milk and plant-based beverages

The tables below portray the macronutrient profile of the selected beverages (oat beverage (OB), almond beverage (AB), soy beverage (SB), fresh bovine milk (BF) and long-life bovine milk (BLL). According to Table 3.2, differences are noted in each of the macronutrients between PBBs and bovine milk (BM) with standard deviations of 88.8kJ for energy, 1.61g for protein, 2.88g for carbohydrates and 0.91g for fat per 100 ml, each being greater than 40% of the mean. Bovine milk contains the highest average values for energy, protein and fat in comparison to the plant-based beverages, with average values of 275kJ,

3.41g and 3.4g per 100ml, respectively. Soy beverage's protein value is, however, comparable to that of bovine milk at 3.16g/100ml. No notable differences exist between long-life bovine milk (BLL) and fresh bovine milk (BF) for any of the macronutrients, with standard deviation values for macronutrients less than 5% of the mean between BLL and BF, excluding trans fatty acids with a standard deviation of 9.43% of the mean.

Table 3.2: Macronutrient results of milk and plant-based beverages

Nutrient	Unit	AB	SB	OB	BF	BLL
Moisture	g/100 ml	97.46	94.2	92.4	90.2	90.2
Dry matter	g/100 ml	2.80	7.53	10.4	12.7	12.6
Energy	kJ/100 ml	66.0	154	213	275	274
Protein	g/100 ml	0.69	3.16	0.33	3.47	3.34
Carbohydrates	g/100 ml	<2.50	2.50	8.55	5.37	5.29
Sugar	g/100 ml	<0.50	0.54	3.94	4.21	4.49
- Sucrose	g/100 ml	<0.50	0.54	<0.50	<0.05	<0.05
- Maltose	g/100 ml	<0.50	<0.50	3.94	<0.05	<0.05
- Lactose	g/100 ml	<0.50	<0.50	<0.50	4.21	4.49
Total fat	g/100 ml	1.29	1.78	1.83	3.35	3.45
- Saturated fat	g/100 ml	0.20	0.30	0.33	2.26	2.36
- Monounsaturated fat	g/100 ml	0.39	0.41	0.60	0.84	0.85
- Polyunsaturated fat	g/100 ml	0.70	1.07	0.90	0.10	0.10
- Trans FA	g/100 ml	0.10	0.10	0.10	0.16	0.14
- Omega-3 FA	g/100 ml	0.10	0.15	0.10	0.10	0.10
- Omega-6 FA	g/100 ml	0.61	0.93	0.90	0.10	0.10

F: fresh (full fat); LL: Long life; FA: Fatty acids; Where a value is indicated with a “<” it refers to values below the detectable limit of quantifications.

As a continuation of the comparison of protein profiles, equally notable differences emerged within the amino acid profiles of the different beverages. Table 3.3 (with green depicted essential amino acids) contains the analysis of amino acid results, with Table 3.4 providing more detail on the protein content of the different beverages, as well as the differing protein values of skimmed bovine milk (SBM) (i.e. 1%, 2%, 3% and 4% fat milk

in comparison to full fat milk (BF). The additional analysis of protein content showed the same magnitude differences as above between bovine milk, soy beverage, and the remaining plant-based beverages.

It was further observed that amino acid values between bovine milk differ with a standard deviation of 5.1% or less of the mean. Between plant-based beverages, standard deviations were between 41% and 130% of the mean, showing notable variation within these beverages. This is mostly due to the low amino acid and protein content of oat beverage and almond beverage. Soy beverage contained the highest amino acid values of the plant-based beverages and has 73.1% the total amino acid content of full fat bovine milk.

Regarding essential amino acids, indicated by “*”, both bovine milk and soy beverage exhibited higher content of each essential amino acid than almond and oat beverage. Except for histidine and phenylalanine, bovine milk contained the highest concentration of each essential amino acid. Oat beverage and almond beverage contained less than 30% of the essential amino acids present in bovine milk and soy beverage.

Table 3.3. Amino acid content in mg/100 ml of beverage

Amino acid	1% SBM	2% SBM	3% SBM	4% SBM	BM	SB	AB	OB
Asx	239.85	223.14	197.31	192.29	187.39	133.06	31.26	21.62
Glx	581.71	594.33	576.81	533.42	656.81	242.87	115.29	134.57
Ser	186.33	178.34	176.43	165.74	189.65	179.56	27.35	35.12
His*	109.99	110.56	108.56	98.96	108.07	119.37	19.81	17.20
Gly	32.52	24.39	19.02	10.37	117.73	41.09	12.12	110.72
Thr	100.75	93.21	94.87	85.55	95.62	83.00	10.37	7.89
Arg	139.34	131.24	130.74	114.40	130.08	318.00	87.02	24.44
Ala	119.67	114.91	112.41	101.95	119.33	147.08	30.29	28.58
Pro	618.00	647.34	630.99	602.86	674.16	333.45	54.76	60.31
Tyr	164.45	154.80	151.73	139.14	169.58	125.47	22.19	30.24
Val*	167.44	161.84	158.17	148.06	212.44	148.01	21.29	28.51
Met*	50.11	47.23	49.25	46.99	101.02	44.53	6.57	8.22
Cys	6.16	5.43	6.33	5.36	13.85	32.40	2.46	5.54
Ile*	145.22	136.98	138.86	126.64	156.44	129.50	20.97	18.55
Phe*	140.95	135.80	128.61	116.74	145.90	151.08	34.83	33.49
Leu*	297.66	297.35	289.23	266.13	340.00	244.64	44.14	44.58
Lys*	226.25	235.35	233.94	228.67	275.03	196.10	18.23	21.26
Trp*	29.64	24.82	26.07	28.25	30.28	18.39	1.51	5.34
Sum	3550.34	3508.39	3406.35	3178.39	3948.93	2885.13	622.37	699.45
mg/100g								

Table 3.4.: Local analysis of protein results

Product	Dry matter	Moisture	Protein
1% fat milk	10.38%	89.62%	3.60%
2% fat milk	11.16%	88.84%	3.43%
3% fat milk	12.16%	87.84%	3.43%
4% fat milk	12.54%	87.46%	3.25%
Full Cream Bovine	12.62%	87.38%	3.66%
Soy beverage	7.02%	92.98%	2.77%
Almond beverage	2.88%	97.12%	0.58%
Oat beverage	11.94%	88.06%	0.75%

Similar trends to the macronutrients are observed among the mineral and vitamin results presented in Table 3.5, portraying a generally elevated micronutrient profile in bovine milk, in comparison to plant-based beverages.

Table 3.5: Mineral and vitamin results for milk and plant-based beverages

Nutrient	Unit	AB	SB	OB	BF	BLL
Minerals						
- Sodium	mg/100 ml	65.04	75.50	45.76	48.12	43.00
- Calcium	mg/100 ml	117.00	45.49	1.00	119.29	106.00
- Magnesium	mg/100 ml	6.80	18.62	1.00	11.93	11.40
- Zinc	mg/100 ml	<1.00	<1.00	<1.00	<1.00	<1.00
- Potassium	mg/100 ml	15.00	235.00	167.00	155.79	159.00
- Phosphorous	mg/100 ml	11.20	32.30	65.50	85.60	80.60
- Iodine	mg/100 ml	<0.01	<0.01	0.02	<0.01	<0.01
Vitamins						
- Vit A	mg/100 ml	0.06	0.01	0.01	0.04	0.03
- Vit B2 (riboflavin)	mg/100 ml	0.03	0.11	0.01	0.19	0.13
- Vit B3 (niacin)	mg/100 ml	<0.10	<0.10	<0.10	<0.10	<0.10
- Vit B9 (folate)	ug/100 ml	2.70	4.60	3.20	4.70	3.40
- Vit B12	ug/100 ml	<0.10	<0.10	<0.10	0.23	<0.10
- Vit D3	ug/100 ml	<0.10	<0.10	<0.10	<0.10	<0.10
- Vit E	ug/100 ml	1.60	0.09	0.49	0.12	0.12

- Vit K1	ug/100 ml	0.10	2.80	0.23	0.34	0.32
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Iodine, zinc, vitamin B3 and vitamin D were below the detection limits across all products, indicated by “<”, except for oat beverage which contained 0.02mg of iodine. Only bovine milk had detectable limits of vitamin B12. In bovine milk, the following nutrients were higher in comparison to plant-based beverages: calcium (119.29mg), phosphorous (85.60mg), vitamin B2 (0.19mg), vitamin B9 (4.70mg) and vitamin B12 (0.23mg). Contrary to the clear distinguishable differences between bovine milk and soy beverage, in comparison to almond and oat beverage, some micronutrients were higher in almond beverage. According to the label, almond beverage contained added calcium and thus had comparable levels thereof, yet further exhibited the highest vitamin E levels (1.6ug/100ml), whereas soy beverage contained highest levels of magnesium (18.62mg/100ml), potassium (235mg/100ml) and vitamin K (2.80ug/100ml).

Although similar information could not be sourced for all nutrients from literature, the above values compare well to the information available in the literature, as summarised in Table 3.6. Bovine milk results compare well with a South African dataset (Schönfeldt et al, 2012) In addition, due to the availability of multiple datasets per beverage, the below dataset shows the variation within plant-based beverages of the same type.

Table 3.6: Nutrient content (ranges) of milk and plant-based beverages, sourced from literature.

Nutrients per 100ml	BM (all fat types)	AM	OM	SM
Energy (kJ)	197–284	36–155	128–200	132–256
Carbohydrates (g)	4.65–4.8	0–3.4	5–7.5	0.2–2.5
Protein (g)	3.1–3.62	0.62–1.67	0.6–1.2	2.78–3.7
Lipid (g)	1.6–3.67	1.15–2.71	1.5–2.2	1.57–4.35
Dietary fibre (g)	0	0.61–1.25	0.64–4.4	0.2–1.7
Ca (mg)	110–121	90–206	70–140	100–123.24
Fe (mg)	0.11	0.02–0.23	0–0.38	0.30–0.56
Mg (mg)	10–11.5	7.9–8.02	3.37–12.4	13–20.9
Na (mg)	42–44	48–74.4	35.1–56	36–52.05

P (mg)	10	5	7	9
Vitamin D (µg)	0	0.4–0.9	0.3–0.6	0.3–0.47
Vitamin E (µg)	63.6–89.1	1 101.6–2 422	484–631	282–2 856
Vitamin B2 (µg)	108.3–190	54.9–119.46	14–91.56	57.8–160.71
Vitamin B9 (µg)	3.2–9.27	0.99–1.9	2.3–5.82	17.7–24.33
Vitamin B12 (µg)	0.44–0.45	0–0.44	0.18–0.48	0.32–1.08
Vitamin A (IU)	158	148.8	106.8	201.2

Sources: Vanga and Raghaven (2018); Paul et al. (2020); Fructuoso et al. (2021); Sunidhi et al. (2021); Singh-Povel et al. (2022); Walther et al. (2022); Schönfeldt et al. (2012)

In compiling the above into various scenarios within the Nutrient Rich Food index (NRFi) for a more holistic comparison, the below results can be seen for each beverage type, respectively. In Table 3.7, the local analysis results (Scenario 1), as well as literature-based results which were used together with local analysis results where data was insufficient (Scenario 2, 3 and 4) are visible as a percentage of daily value per 100 kJ, and per 100 ml of beverage. The NRFi (100ml) for each beverage is reported in Annex 6.1. based on the DV for the adult age group where the same values were adapted according to energy content as well to yield the below results. Beverages which include fortification have been denoted with an asterisk (*).

Table 3.7: NRFi comparison of milk and plant-based beverages (per 100 ml and 100 kJ)

	NRFi	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4
Bovine milk	per 100 kJ	8.28	8.71	7.51	7.14
	per 100 ml	22.79	22.33	21.11	19.55
Almond beverage	per 100 kJ	32.57*	39.15*	42.67*	64.81*
	per 100 ml	21.50	48.25*	45.81*	88.92*
Soy beverage	per 100 kJ	9.65	30.35*	12.69*	23.06*
	per 100 ml	14.87	48.31*	21.46*	40.14*
Oat beverage	per 100 kJ	4.13	22.29*	15.11*	3.41
	per 100 ml	8.80	40.89*	25.57*	5.92

Scenario: 1) Local primary analysis; 2) Label information, supplemented with local primary analysis results; 3) Literature results, supplemented with local results (Smith et al., 2022b; Fructuoso et al., 2021), 4) Literature results, supplemented with local results (Walther et al., 2021)

*Indicates fortified nutrients in the product.

The results between differing bovine milk scenarios vary with standard deviations of less than 10% of the mean, both when expressed per energy and per volume unit of beverage. In comparison to the plant-based beverages, bovine milk scores were consistently lower than all fortified plant-based beverages which have been enriched mostly with vitamin D and calcium. In comparison to non-fortified beverages, the beverages were more comparable with one another per 100 kJ, with soy beverage scoring slightly higher. When expressed per 100 ml, bovine milk scored higher than all non-fortified products. The results among the same product or beverage within the different scenarios vary with standard deviation of between 6.5 and 36.4, representing a deviation of 38% to 94% of the mean, which portrays the large difference in nutrient density to be expected when beverages are fortified with additional nutrients. However, these results do not represent the bioavailability of fortified or non-fortified nutrients.

3.4.2 Environmental profile results and nutrient-adjusted comparison of milk and plant-based beverages

A compilation of results, as sourced from mostly comparative studies and based on a variety of production systems which are closely related to South African systems, are seen below in Table 3.8.1 and 3.8.2, and visualised in Figures 3.1. and 3.2.

Table 3.8.1. Environmental footprint of raw milk, almonds, soybean and oats

Unit	Almonds	Soybean	Oats	Raw milk	Source & comments
kgCO ₂ eq/kg	0.35–2.08				Marvinney et al. (2020); Martin-Gorriz et al. (2020); Volpe et al. (2015); Kendall et al. (2015); Marvinney et al. (2015)
kgCO ₂ eq/kg		0.3–1.93			Blignaut et al. (2019); Escobar et al. (2020); Raucci et al. (2014); Maciel et al. (2016); Potter et al., (2020)
kgCO ₂ eq/kg			0.33–0.59		Blignaut et al. (2019); De Kock et al. (2018); Heusala et al. (2020)

kgCO ₂ eq/kg				0.72–1.67	Basset-mens et al (2005); O’Brien et al., 2011; Gollnow et al., (2014); Reinecke & Blignaut, (2021); Galloway et al., (2024)
Average*	1.23	1.09	0.49	1.23	*based on number of results obtained across studies

In comparing the environmental footprint of the raw materials, different production systems such as regenerative, rain-fed, commercial and irrigated, among other differences, yielded varying results. No comparison could be drawn among the raw materials, as it differs based on the production system which is compared, as highlighted and visualised in Figure 3.1.

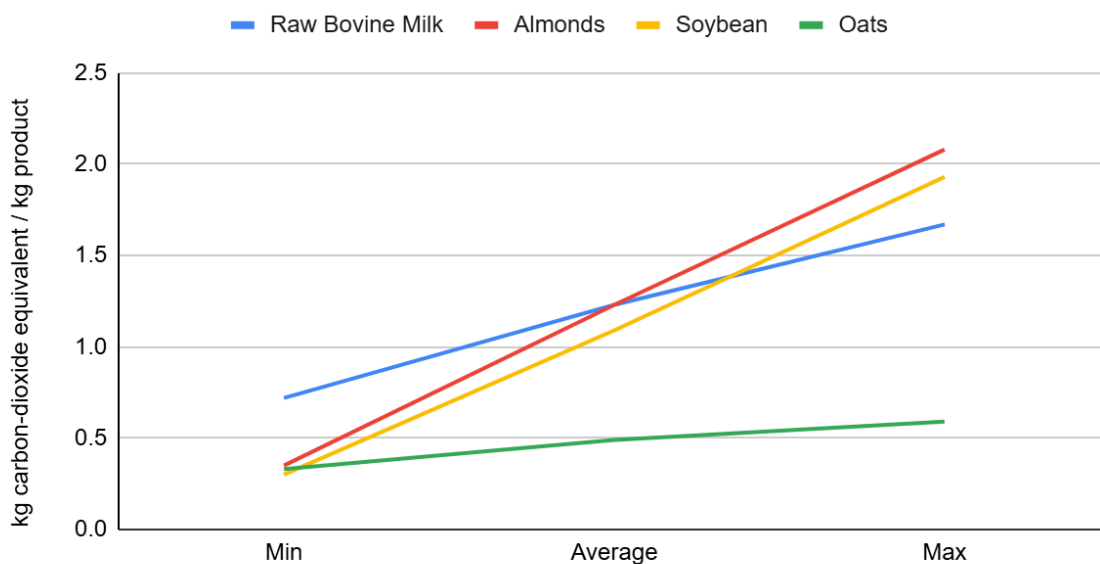


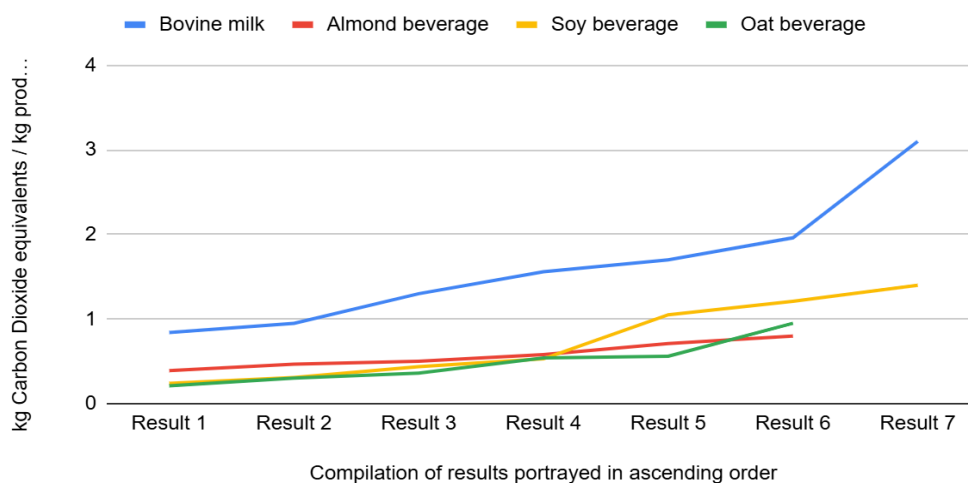
Figure 3.1: Carbon footprint (kg carbon dioxide equivalents per kg of raw product) of milk, almond, soybean and oats

However, the minimum, maximum and average values yielded across previous studies show that if practices like regenerative practices are applied as was the case in the minimum values (Reinecke & Blignaut, 2021; Blignaut et al., 2019), both crop and animal production can have comparably low environmental footprints. Under irrigation and with the use of inorganic fertilisation, the footprints of almonds and soybean are higher than that of bovine milk or non-irrigated oats (Kendall et al., 2015; De Kock et al., 2018).

Table 3.8.2. Environmental footprint of milk and plant-based beverages

Unit	AB	SB	OB	BM	Source & comments
kgCO ₂ eq/kg		0.31	0.21	0.84–2.4	Thoma et al., (2013); Helsing (2019); dos Santos et al. (2022)
kgCO ₂ eq/L	0.47	0.438–0.53	0.30	1.56	Coluccia et al. (2022); Singh-Povel et al. (2022)
kgCO ₂ eq/kg	0.5-0.8	0.66-1.4	0.21-0.95	3.1	Sunidhi et al. (2021); Geburt et al., (2022)
kgCO ₂ eq/kg	0.39–0.58	0.24–1.21	0.54	1.7–1.97	Winans et al. (2020)
Average*	0.54	0.62	0.45	1.64	*based on number of results obtained

Regarding the final products, bovine milk had a consistently higher footprint than plant-based beverages. This may be due to differences in accounting methods, or more likely due to the concentration of the raw materials in the final beverages. Label information showed that concentrations of the raw plant-based ingredients (oats, almond and soybean) compose between 2% and 11% of the final beverage, thus only a percentage of the on-farm footprint is attributed to plant-based beverages, whereas the full footprint of raw milk is attributed to the final product (Coluccia et al., 2022; Singh-Povel et al., 2022). The trend is more clearly seen in Figure 3.2., where the values found in literature from the same studies portrayed in Table 3.8.2, were compiled in ascending order. (Helsing, 2019; Winans et al., 2020; Sunidhi et al., 2021; Coluccia et al., 2022; dos Santos et al., 2022; Singh-Povel et al., 2022).


Figure 3.2: Carbon footprint of milk and plant-based beverages using published values

To gain perspective on the carbon footprint associated with the nutrient profile, the minimum, maximum, and average carbon footprints were compared in relation to the ranges of energy and protein content, respectively, as shown in Table 3.9. The results indicate that the environmental cost of oat beverage in relation to energy is the lowest among all beverages, with a minimum of 0.01 gCO₂eq/100kJ and a maximum of 0.04 gCO₂eq/100kJ. Bovine milk has a slightly higher average environmental cost of 0.06 gCO₂eq/100kJ compared to almond (0.05 gCO₂eq/100kJ) and soy beverages (0.04 gCO₂eq/100kJ).

In terms of protein content, bovine milk has an average carbon footprint of 0.48 gCO₂eq/10g protein, which is lower than almond (0.69 gCO₂eq/10g protein) and oat beverages (0.61 gCO₂eq/10g protein) but higher than soy beverage (0.21 gCO₂eq/10g protein). The minimum values show that soy beverage has the lowest environmental cost per protein content (0.12 gCO₂eq/10g protein), while the maximum values highlight oat beverage's higher variability (1.02 gCO₂eq/10g protein). The variability is less pronounced in bovine milk and oat beverage, indicating more consistent environmental costs compared to almond and soy beverages.

Table 3.9: Carbon footprint in relation to energy and protein

GWP:E (gCO₂eq/100kJ)	Bovine milk	Almond beverage	Soy beverage	Oat beverage
Min GWP: min energy	0.03	0.06	0.02	0.01
Max GWP: max energy	0.08	0.06	0.08	0.04
Average GWP: average energy	0.06	0.05	0.04	0.02
GWP:P (gCO₂eq/10g protein)				
Min GWP: min protein	0.26	0.67	0.12	0.46
Max GWP: max protein	0.01	0.78	0.32	1.02
Average GWP: average protein	0.48	0.69	0.21	0.61

GWP: Global warming potential i.e. carbon footprint (CO₂eq); E: energy; P: protein

Opposite trends are noticed below when utilising the minimum, maximum and averages of both the NRFi and carbon footprint of the final products to draw comparisons which assess the average NRFi gained per gram of carbon dioxide emitted, rather than only focusing on energy and protein. These results are reported in Table 3.10, both per 100 ml

and per 100 kJ. The NRFi obtained for equal carbon equivalents per 100 ml or 100 kJ both indicate that almond and soy beverages exhibit higher nutrient scores per carbon footprint emitted per ml and per kJ. This follows similar trends when comparing product per volume or weight unit yet it is different to the previous analysis, comparing carbon footprint per energy unit basis. This is, once again, most likely due to the fortification of products which initially yielded high results on an NRFi basis, as well as the few datasets available on oat beverage for which the current results mostly portray both regeneratively farmed produce and organic oat beverage. However, these emissions are not calculated per single nutrient and may require further inspection in terms of priority micronutrients (Beal et al, 2023), as well as gathering more complete data sets on non-fortified nutrients to draw similar comparisons.

Table 3.10: Carbon footprint cost in comparison to nutrient rich food index score (calculated on a volume and energy basis)

	Bovine milk	Almond beverage	Soy beverage	Oat beverage
Min NRFi / min GWP (per 100ml)	232.76	551.23	619.44	281.72
Max NRFi / max GWP (per 100ml)	94.97	1111.46	345.09	430.45
Avg NRFi / avg GWP (per 100ml)	130.77	946.64	511.06	450.94
Min NRFi / min GWP (per 100kJ)	217.78	551.24	534.19	274.43
Max NRFi / max GWP (per 100kJ)	102.00	1111.46	377.33	499.65
Avg NRFi / avg GWP (per 100kJ)	130.17	861.49	482.14	460.23

3.4.3 Economic affordability results and nutrient-adjusted comparison of milk and plant-based beverages

The general cost per litre of beverage which was sourced in South Africa during late 2022 and early 2023 are reported in Table 3.11, as well as previous reports on South African beverages from literature, thus it should be considered at the time of publication that these prices might have changed due to inflation or other circumstances.

Table 3.11: Price ranges of milk and plant-based beverages obtained in the South African retail market (Gauteng and Western Cape) and via literature

	Unit	Avg.	Min	Max	Source
Bovine milk	ZAR/litre	R16.31	R13.00	R18.33	Retail prices
Lactose free BM	ZAR/litre	R22.56	R15.49	R29.95	Retail prices
Almond beverage	ZAR/litre	R48.20	R29.95	R126.00	Retail prices
	ZAR/litre	R46.89	R37.99	R79.99	Literature reports
Soy beverage	ZAR/litre	R32.86	R19.66	R60.00	Retail prices
	ZAR/litre	R38.92	R30.47	R64.99	Literature reports
Oat beverage	ZAR/litre	R50.14	R34.99	R69.00	Literature reports
	ZAR/litre	R50.79	R37.49	R74.99	Retail prices

Source: Gauteng market research* (2022); Johnston and Pretorius (2020)

*Averages based on number of samples (weighted average)

In the above, bovine milk was consistently more affordable (price per litre) than any of the plant-based beverages, including lactose free bovine milk. When the above prices were adjusted per 100kJ of energy and per 10g of protein, similar results were noted as reported in Table 3.12, however to a higher degree. The cost of protein and energy in bovine milk is less than half that of soy beverage, which marked the most affordable energy and protein source among the plant-based sources. The cost was more than tenfold for the protein content within some of the same beverages.

Table 3.12: Cost of beverages in relation to their energy and protein content

Energy cost (ZAR/100kJ)	Bovine milk	Almond beverage	Soy beverage	Oat beverage
Min cost of energy	0.51	4.54	1.48	2.07
Max cost of energy	1.07	5.95	3.73	3.52
Average cost of energy	0.71	5.21	2.61	2.87
Protein cost (ZAR/10g)				
Min cost of protein	3.99	51.64	9.50	76.07
Max cost of protein	8.18	80.09	17.19	80.63
Average cost of protein	5.58	68.83	13.98	71.41

Similarly, and in contrast to the trends observed when comparing NRFi to carbon footprint, the NRFi in relation to cost per 100ml and per 100kJ of bovine milk exhibits the highest ratio, as seen in Table 3.13. This translates to bovine milk exhibiting the highest NRFi profile gained per ZAR spent by the consumer. The minimum and maximum costs of

a beverage in relation to the minimum, maximum and average NRFi scores yielded the below NRFPi ratios.

Table 3.13: Nutrient Rich Food Price index (Economic cost in comparison to nutrient score)

NRFPI (NRFi per ZAR)	Bovine milk	Almond	Soy	Oat beverage
		beverage	beverage	
Min NRFi: min cost (per 100ml)	15.04	7.18	7.56	1.69
Max NRFi: max cost (per 100ml)	7.61	10.88	7.43	5.45
Average NRFi: average cost (per 100ml)	11.04	9.45	7.70	3.84
Min NRFi: min cost (per 100kJ)	14.07	7.18	6.52	1.65
Max NRFi: max cost (per 100kJ)	1.01	0.81	1.77	0.28
Average NRFi: average cost (per 100kJ)	2.51	1.21	2.28	0.30

3.5 Discussion

This study's comparative analysis of the nutrient profiles of milk and plant-based beverages offers a comprehensive assessment of their macro- and micronutrient compositions, amino acid profiles, environmental footprints and economic affordability, providing critical insights for consumers and policymakers.

The findings in Table 3.2. indicate a marked difference in the macronutrient composition of bovine milk compared to plant-based alternatives. Bovine milk exhibits a higher content of energy, fat and protein, which is consistent with previous studies that have recognised its nutritional density (Vanga & Raghaven, 2018; Paul et al., 2020). Interestingly, soy beverages demonstrate a protein content comparable to that of bovine milk, affirming soy's potential as a viable protein alternative (Fructuoso et al., 2021). The amino acid analysis in Table 3.3. further underscores the nutritional edge that bovine milk and soy beverages have over almond and oat beverages, which otherwise display low amino acid profiles.

The lack of variance between the nutrient profiles of fresh and long-life bovine milk suggests that processing variations do not substantially affect the micronutrient content, which aligns with the findings of Singh-Povel et al. (2022). The complete amino acid profiles of bovine milk and soy beverage not only highlights its roles as complete protein sources but

also emphasises the potential nutritional inadequacies of almond and oat beverages when consumed without proper dietary supplementation.

The environmental review in Table 3.8.1. and Table 3.8.2. revealed that bovine milk had a higher carbon footprint compared to plant-based beverages (Helsing, 2019; dos Santos et al., 2022). The variances in the carbon footprint of raw materials further accentuate the impact of different farming practices, ranging from regenerative to commercial, on the environmental cost of the final product. Despite the lower environmental impact of plant-based beverages, it is important to note the mentioned percentages of raw material into the final product. This distinction could misrepresent the environmental efficiency when not considered in the context of nutrient density, bioavailability and affordability. However, it sheds light on the potential to improve the efficiency and sustainability of dairy production as well as crop production.

The economic overview provided in Table 3.11. demonstrated that bovine milk remained the most affordable option per litre, particularly when adjusted for nutrient density. This finding is pivotal for consumers making purchasing decisions within budget constraints, especially in regions where dietary choices are heavily influenced by economic factors, such as in underdeveloped countries. The affordability of soy beverage as an alternative source of protein and energy further positions it as an economically viable plant-based alternative. However, the price differences observed within plant-based beverages, influenced by factors like fortification and brand, highlight the complexity of making generalised economic comparisons. The variance further emphasises the need for careful consideration of brand-specific production practices and nutrient fortification when assessing economic affordability.

The Nutrient Rich Food index (NRFi) comparisons in Table 3.7. offered a holistic perspective on the nutrient-to-cost ratio of each beverage type. Fortified plant-based beverages, particularly almond and oat, exhibited higher NRFi scores per carbon footprint, suggesting that fortification significantly elevates the nutrient profile of these beverages when comparing to the nutritional analysis performed. This trend contrasts the NRFi per economic cost, where bovine milk delivered the highest nutrient score per monetary unit, reinforcing its status as a nutrient-dense and cost-effective food item. The discrepancy

between the NRFi and carbon footprint of non-fortified beverages warrants further investigation. It raises critical questions about the environmental cost and financial cost of obtaining a nutrient-equivalent plant-based alternative to bovine milk. However, it highlights the importance of reducing the environmental footprint of dairy production to continue supplying a cost effective and nutrient dense product to consumers. Further questions are raised about the use of NRFi, where fortification is highly favoured.

The variations in nutrient profiles among the same beverage type point to the influence of brand-specific production methods and fortification levels, indicating the need for standardised testing protocols and reporting practices. The nutrient profile analysis conducted in this study further faced challenges due to financial constraints permitting only a single sample per product type. Consequently, the results should be considered preliminary indicators rather than conclusive evidence, reflecting potential alignments with international data but requiring further expansion and statistical validation. The lack of multiple samples precludes robust statistical analysis, underscoring the need for a broader dataset for more definitive comparisons. Moreover, the lack of comprehensive existing datasets on plant-based beverages, particularly for oats, limits the robustness of our comparisons and underscores the necessity for more extensive research in this area.

The findings highlight the complexity of comparing milk and plant-based beverages across multiple dimensions, particularly due to the differing results gained in each comparison type. While plant-based beverages offer environmental advantages and, when fortified, can approach the nutrient content of bovine milk, these often come at a higher economic cost and with potential nutritional shortcomings. These results underscore the importance of a new approach to dietary recommendations and sustainable production, one that considers the multifaceted nature of food production and consumption. Moreover, the absence of standardised metrics for comparing products within the same food group both in South Africa and globally calls for the development of such metrics.

The variations in nutrient profiles and densities revealed by this study, alongside the limitations of the Nutrient Rich Food index (NRFi) such as locality or the inclusion of bioavailability, further bring to light the complex nature of nutritional assessments, particularly within the South African context (Riddout et al., 2021). The NRFi, while a useful

tool for comparing the nutrient content of foods, does not account for nutrient bioavailability—how well a nutrient can be absorbed and utilised by the body. This omission is critical, as it can lead to overestimations of the nutritional value of certain foods, especially those that are fortified. Bioavailability is influenced by numerous factors, including the food matrix, preparation methods, and the presence of enhancers or inhibitors of nutrient absorption (Aguilera, 2019).

In South Africa, where protein and other nutrient deficiencies are prevalent, the importance of bioavailability cannot be overstated (Jiang et al., 2019; Dave et al., 2023). The country faces unique nutritional challenges, and a food’s nutrient profile must be considered in light of these challenges (Jiang et al., 2019). The NRFi’s lack of consideration for population-specific nutrient needs means that it may not always align with the dietary requirements of South Africans, potentially influencing policy decisions in a direction that does not address these key nutritional deficiencies (Vorster et al., 2013).

Moreover, the NRFi does not reflect the role a specific product plays within a food group or its contribution to the global nutrient landscape. For instance, the high protein content of soy beverage may make it a suitable alternative to bovine milk in terms of protein provision; however, without considering the bioavailability of that protein and how it complements the overall diet, such comparisons may be misleading (Dave et al., 2023). Therefore, product comparisons should be made within the same food groups and should consider the importance of that food group in the overall diet (Eccles et al., 2012).

In terms of environmental impact, the reliance on carbon equivalents as the sole indicator of a product’s environmental footprint is increasingly being recognised as insufficient. Life cycle analyses (LCA) often vary in their methodologies, leading to potential bias in comparisons. For example, carbon sequestration, a consequence of proper rangeland or cropland management, is frequently omitted from LCAs, skewing results in favour of systems that do not actively enhance this ecological service. By-product allocation also varies widely; some analyses may allocate environmental impacts solely to the primary product, while others may distribute impacts across all co-products, altering perceptions of a product’s true environmental cost (Mackenzie et al., 2017).

The affordability aspect provides another layer of complexity. While plant-based beverages may appear less economical than bovine milk, the analysis does not consider the sustainability of business operations or market competitiveness. A holistic approach to economic assessment should consider the full spectrum of production costs, market dynamics, and the potential for long-term sustainability of businesses within the industry.

3.6 Conclusion

This study's findings indicate that bovine milk possesses a superior individual nutrient profile and offers greater economic value compared to plant-based alternatives. When using the NRFi for comparisons, fortified plant-based beverages have higher nutrient scores than bovine milk. Despite the financial constraints that might affect consumers' purchasing decisions, bovine milk remains a nutritionally dense and cost-effective choice. For individuals with lactose intolerance or specific dietary preferences, soy beverage emerges as a favourable alternative, presenting a comparable protein content and a more manageable economic and environmental footprint than other plant-based options. Fortification of plant-based beverages stands out as a viable strategy to enhance their nutrient density, potentially bridging the gap towards bovine milk's nutrient content. However, this process inevitably increases both the cost and the environmental footprint, as it involves additional ingredients and extends manufacturing time. It is crucial to consider these trade-offs when evaluating the overall benefits of fortified plant-based beverages.

When drawing comparisons across different beverage options, it is essential to employ a holistic approach that considers the full spectrum of factors, including nutrient bioavailability, economic affordability, environmental impact, and the broader context of dietary needs specific to populations like those in South Africa. This study serves as a preliminary step in developing a comprehensive model for such comparisons, emphasising the need for more extensive datasets and nuanced analyses. Only with a more complete understanding of these complex interrelations can decision-makers formulate policies and recommendations that reflect the nutritional, economic and environmental considerations of food products within their respective groups.

Standard nutrient comparisons, while providing valuable insights, can inadvertently influence policy and consumer choice in ways that do not fully address nutritional needs, environmental sustainability or economic realities. A more holistic approach is essential – one that is tailored to specific regional contexts, considers the complete environmental impact of food production, and acknowledges the role of food within its respective group. Only through such an approach can we make informed decisions that truly contribute to the health of the population and the planet.

CHAPTER 4 An environmental, economic and nutritional index for bovine milk and plant-based beverages (DIEET) – a South African perspective.

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4.1 Abstract

In the context of global challenges such as climate change, resource scarcity and malnutrition, sustainable decision-making in the food sector is increasingly critical. Particularly in the milk and plant-based beverage sector, there is an absence of a comprehensive sustainability index tailored to assess the economic, nutritional and environmental impacts of specific products. This study addressed this gap through the development of a specialised sustainability model for milk and plant-based beverages, adaptable to different countries, and capable of guiding stakeholders towards environmentally responsible, economically viable and nutritionally beneficial practices. The model was inspired by existing frameworks like the Nutrient Rich Food index (NRFi) and integrated a diverse range of other factors. These included demographic-specific dietary needs, global nutrient contributions, allergy associations, protein quality and environmental considerations derived from life cycle analysis (LCA) principles. Parameters such as water usage, land use, energy consumption and waste management were incorporated, providing a comprehensive view of the sustainability of dairy products and their alternatives. The model evaluated both environmental impacts and socioeconomic factors, considering aspects such as product pricing, poverty levels, financial contributions, employment and production efficiencies. The resulting Dairy Index for Environment, Economics and Nutrition (DiEET) yielded the following results for the nutritional score, environmental score and economic score (higher values being more favourable): bovine milk scored 3.67, 0.161 and 1.543, respectively; almond beverages scored 1.55, 0.172 and 1.103, respectively; soy beverages scored 2.21, 0.193 and 1.277, respectively; and oat beverages scored 1.204, 0.165 and 1.083, respectively. This indicated that bovine milk is more nutritious and economically viable than plant-based beverages yet require reduction of environmental impacts. Soy beverages was the most affordable, nutritious and environmentally friendly plant-based beverage alternative. A trade-off between nutrition and the environment was also noted. The model, based on scientific data and requiring minimal user input, provides a simplistic and practical measure for stakeholders to assess and compare sustainability across products. Continuous refinement and validation are essential for maintaining its effectiveness and relevance, particularly in the face of evolving data and industry practices. In conclusion, this study promotes a more sustainable future by enabling informed decision-

making based on a holistic understanding of environmental, economic and nutritional sustainability.

Keywords: sustainability index, plant-based beverage, dairy, nutrient index, climate change

4.2 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 (Roser & Ritchie, 2020; Galal, 2022). The global food supply, while generally meeting demand, still suffers from inefficiencies like food waste, logistical issues and affordability constraints, impeding equal access to nutritious food (Foodsystemsdashboard.org, n.d.; Worldbank, 2020; Berners-Lee et al., 2018, Smith et al, 2022a). 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 (Drewnowski, 2018). 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 (Kayo et al., 2014). 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 (Vorster et al., 2013; Worldbank, 2020). Rapid shifts in dietary preferences, influenced by global trends, local economic conditions and consumer trends which alters the nutritional landscape, can potentially exacerbate nutrient deficiencies

and health disparities (Keri et al., 2021). 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 developing 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 socioeconomic 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.

4.3 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 plant-based beverages, as well as how these indices were measured. Peer-review methods of measuring the indicators were identified and adopted according to the aims of this study. Subsequently, an index named Dairy Index for the Environment, Economics and NuTrition (DiEET) was developed to comprehensively evaluate the environmental, nutritional and economic profiles of milk and plant-based beverages. The development of the model is elaborated in section 4.3.1. and the process flow can be seen represented in Figure 4.1.

4.3.1 Model development overview

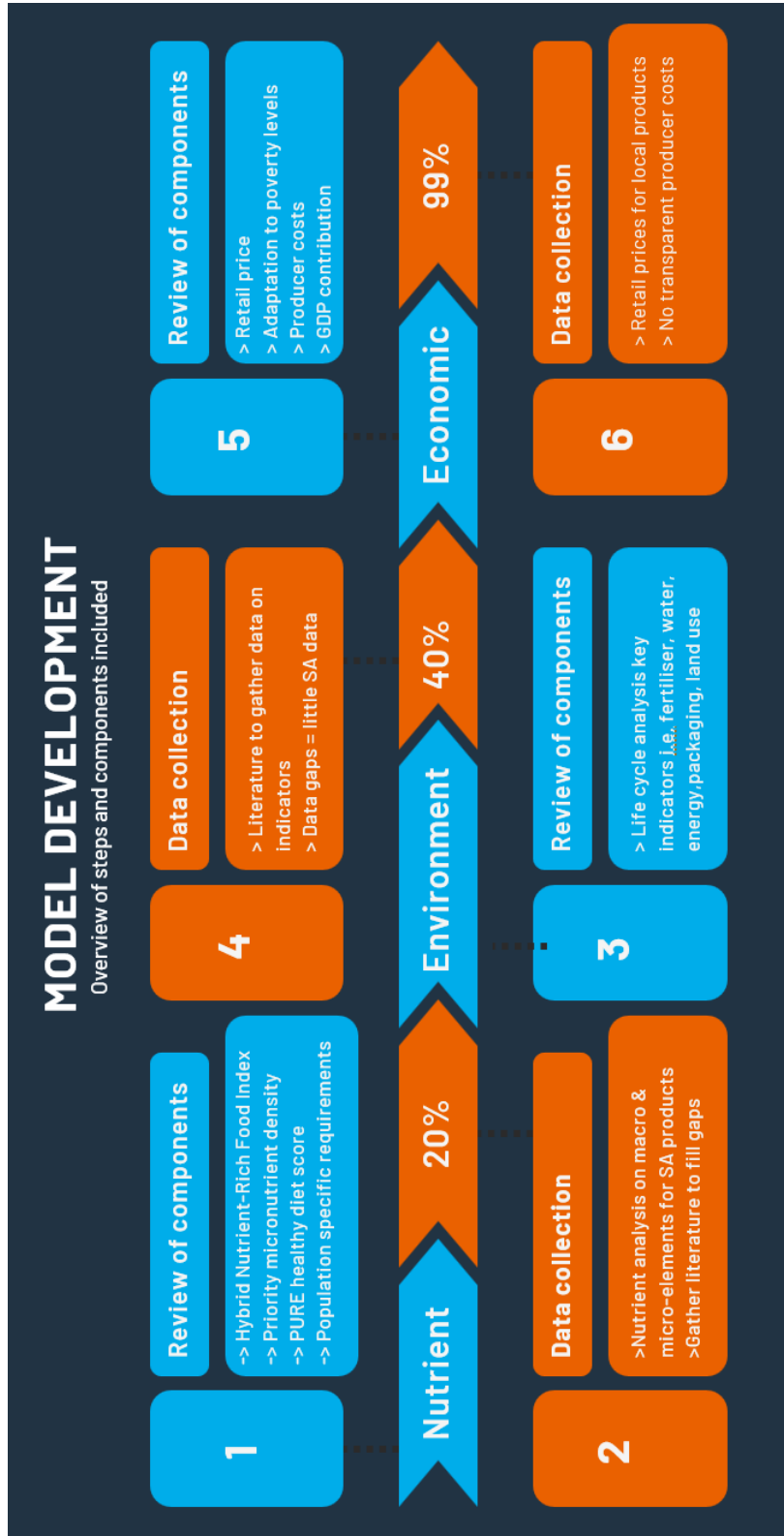


Figure 4.1: Model development overview and components included (created by author)

The Nutrient Rich Food (NRF) index, proposed by Drewnowski et al. (2009) and later adapted by Drewnowski and Fulgoni (2022) 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 (Ridoutt, 2021). In addition to this, digestible indispensable amino acid score (DIAAS) values inspired the inclusion of protein quality (FAO, 2013). Beal et al. (2023) discussed the concept of priority micronutrient density in foods as a basis of 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 (Smith et al., 2022a) uses 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 (De Boer, 2011; Hoekstra et al., 2011; McLaren & Chaudhary, 2021). 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 to leverage existing data for evaluating environmental impact as a midpoint between precision of data and data availability as provided by farmers. Ideally, thorough life cycle analyses (LCAs) would be used for all relevant farms, yet a simplified method was used for the purposes of the model which accounts for a more realistic and industry-level availability of data (Zhang et al., 2021). This method entailed the use of shared indicators among distinct products and processes, despite differences in farming operations, and relying on data that is generally measured in everyday practice.

From an economic perspective, the model incorporated consumer cost as a factor which 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) (Dynan & Sheiner, 2018).

4.3.2 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 more. Comparisons and scenarios previously drawn to compare the nutrient profiles of milk and plant-based beverages were used to populate comparisons (Vanga and Raghaven, 2018; Paul et al., 2020; Fructuoso et al., 2021; Sunidhi et al., 2021; Singh-Povel et al., 2022; Walther et al., 2022). Local market reports and scrutiny of local supplier websites offered guidance in terms of which studies and datasets were most applicable, e.g. most of South African almond milk is produced using almonds from California, hence Californian LCAs were used to draw information on the respective indicators (Marvinney & Kendall, 2021). Similarly, data on oats is rarely available in South Africa thus data from wheat crops needed to be inferred (De Kock et al., 2018; Blignaut et al., 2019; Heusala et al., 2020). Industry members and local processors were consulted for guidance as well, however, due to 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 the different parameters employed.

4.4 Model outline

The DiEET model is a first iteration of a conceptual SiEEN (Sustainability index for the Environment, Economics and Nutrition) model which 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 of another indicator. The three scores are expressed by means of shorthand notation. The notations as follows will be used: NS = nutrient score; PC

= protein completeness 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 4.2.

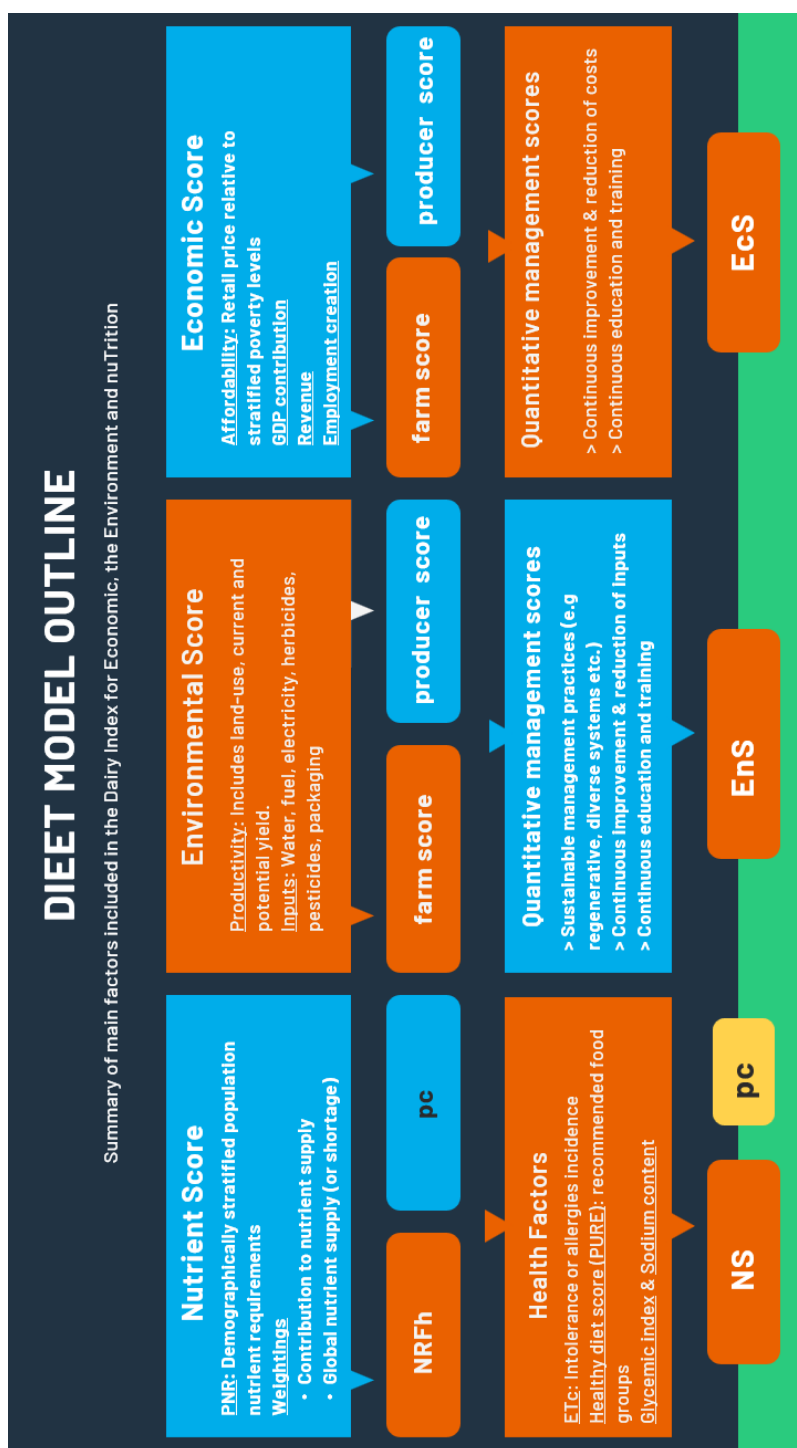


Figure 4.2: Model outline and summary of main factors included (created by author)

4.4.1 Nutrient component

Based on the core nutrients highlighted by the NRFi and NRFh models (Drewnowski & Fulgoni, 2020), as well as the suggested nutrients to be included in nutrient indexing by Beal et al. (2023), 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 B6), and zinc (Drewnowski et al., 2009; Drewnowski & Fulgoni, 2022; Beal et al., 2023). Fibre and vitamin C were deliberately excluded due to its natural absence in milk (Tifrea & Ovidiu, 2011). Additionally, due to its relevance in the functioning of calcium, e.g. in the mineral complex formed during bone formation, phosphorus was included. Vitamin B2 was further included due to the prevalence of deficiencies in developing countries such as African countries (Mahabadi et al., 2023). Amino acids were included as individual nutrients but were also considered as a subcomponent of protein quality in a separate sub-score. The above were expressed as content per 100 ml, as a percentage of the population nutrient requirements as reported in Appendix 6.2.5., however, the values were not capped at 100% DV as with the NRFi (Drewnowski et al., 2009; FAO, 2013; Statista, 2022).

The nutrient requirements in Appendix 6.2.5. were synthesised from different sources to synthesise daily recommended intakes, (NHMRC, 2005; FAO, 2013, USDA, 2020), with some supplementation from more recent epidemiological studies in terms of protein and fat intake (Mente et al., 2023). Energy requirements are based on a moderate physical activity i.e. a physical activity level factor of 1.8, and average extra daily requirement for the full pregnancy (NHMRC, 2005). Considerations were given to specific requirements within each age and sex group, such as being pregnant or ill (StatsSA, 2021). To manage lactation data challenges, pregnant and breastfeeding women were grouped together, with pregnancy assumed to last 9 months and lactation 3 months. Despite recommendations to exclusively breastfeed until 6 months, nearly 30% of babies are not breastfed at all and less than 30% are exclusively breastfed until 6 months, inspiring an adaptation to account for a larger percentage of breastfeeding women during a shorter amount of time (StatsSA, 201). In cases of non-lactation, higher nutritional demands were considered throughout postpartum recovery. Due to their marginal impact, multiple births were excluded, with the nutritional

needs of such cases assumed equivalent to non-pregnant women. Recommendations were adjusted based on population age and sex demographics, as reported in Appendix 6.2.1., including the percentage of pregnant or lactating women as calculated in Appendix 6.2.2. to estimate 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 4.1. 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 (S_c), which is based on Appendix 6.2.6. (SNI, 2022). Iron, vitamin A and zinc were exceptions, where local deficiencies surpass global deficiencies and the prevalence of deficiencies in adolescents were used, thus 29%, 42% and 63%, respectively (Harika et al., 2017; Sivaprasad, 2019; StatsSA, 2022). Similarly, a weight factor (contribution coefficient) is assigned to each product based on the fraction that each food group (1. milk, excluding butter; 2. soybeans; 3. nuts and products; and 4. oats) contributes to global supply of a specific nutrient, which is then adapted to the percentage of each raw material in the final product, as reported in Appendix 6.2.7. and Appendix 6.2.8. Protein quality (protein score or ps) is assessed as an additional score by calculating the indispensable amino acid score (IAAS) 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 (FAO, 2013; CVB, 2016; Reynaud et al., 2021). The amino acid scoring pattern has been adapted according to demographic strata as reported in Appendix 6.2.4.

The NRFh utilisation of My Plate Food Groups have been replaced with the latest PURE Healthy Diet recommended intakes (g/day) of each food group in the healthy diet contribution coefficient (HDCc) (Drewnowski & Fulgoni, 2022; Mente et al., 2023), i.e. legumes (48g/day), nuts (28.20g/day), dairy (185.50g/day) and whole grains (40.90g/day). Additionally, based on recent research on saturated fat and latest insights on the food matrix effect pertaining saturated fat, the limiting nutrient score (LIMz) have been removed (Aguilera, 2019; Mente et al., 2023). Limiting factors employed were sodium content, sugar content and associated diseases or allergies, with some adaptations as follows: sugar content was used to calculate the glycaemic index coefficient (GIc), which penalises a food based

on high glycaemic index (above 55) or low glycaemic index (below 55), based on the type of sugar present in the food e.g. sucrose (GI:65), maltose (GI:105), lactose (GI:46) (Zadow,1984; Qi & Tester, 2020). 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 exceeds 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 (O'Donnell et al., 2020). An exclusion threshold was applied, based on the prevalence of allergies or intolerance to each product type, such as reported in Appendix 6.2.3. The full equations and sub-scores are below.

Table 4.1: Nutrient score formulas and subscores

Element	Formula
Nutrient Sufficiency Score (NSs)	$NSs = \text{Sum} [(\text{Nutrient content} / \text{Stratified nutrient requirements}) \times Sc \times Cc]$
Supplementation coefficient (Sc)	$Sc = 1 + (\text{shortage} / \text{population nutrient requirements})$
Contribution coefficient (Cc)	$Cc = 1 - (\text{contribution ratio})$
Protein Completeness Score (pc)	$pc = (\text{Sum (IAA)}) / 10$
Healthy Diet Contribution coefficient	$HDCc = \text{recommended intake} / 100$
Glycaemic Index coefficient (Glc)	$Glc = \text{sugar content} / 100 \times [(GI - 55) / 100]$ Note only if GI >0; if <0, Glc - 0
Sodium (adjusted)	$\text{Sodium (adj)} = (\text{Target Sodium Content} / (\text{Sodium Content} \times \text{serving size}), \text{serving} = 120\text{ml (Schonfeldt, 2020)})$
Exclusion Threshold coefficient (Etc)	$Etc = 1 - \text{Sum} [\text{Allergy prevalence for product} \times \% \text{ of raw material in final product}]$
Nutrient Score (NS)	$NS = NSs + HDC - GI \text{ corr Added Sugar} - GI \text{ corr Natural Sugar} -/+ \text{ Sodium(adj)}$

4.4.2 Environmental component

The common and major contributing indicators identified to be of importance in environmental footprint assessments were blue water (i.e. service and ground-water), fertiliser, fuel, pesticide and land use (Hoekstra et al., 2011; De Kock, 2018). Although not

all encompassing, these indicators offer a general idea regarding the impact on emissions, water use, eutrophication or acidification potential. All inputs were adjusted to 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 level, 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 (ul Haq & Boz, 2020). 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 4.2, in which quantitative scores awarded point from 0.06 or 0.05 to 0.01, with higher score being less favourable.

Table 4.2: 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 < TMR + fodder carry, post-harvest grazing < TMR (no fodder carry) < none)
Production potential	Soil type (sandy < clay < loam < silt < peat)
Fuel use	Soil test frequency (never < 5–10y < 2–5y < yearly < 2xyear)
Electricity use	Water test frequency (never < 5–10y < 2–5y < yearly < 2xyear)
Blue water use	Crop health / livestock welfare assessment (never < 5–10y < 2–5y < yearly < 2xyear)
Sustainability training or education frequency (never < 5–10y < 2–5y < 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%+)	

The above inputs, along with the scenarios in Appendix 6.3., were used in the below calculations to contribute to the final environmental score, summarised in Table 4.3.

Table 4.3: Environmental score formulas and sub-scores

Element	Formula
Farm Productivity Score (FPs)	$FPs = \text{Net yield} - \text{potential lost} - \text{net land use}$
Potential lost	$\text{Production potential} - \text{yield}$
Net yield	$\text{Repurposed by-produced} + \text{yield}$
Net land use	$1/\text{net yield}$
Farm Footprint Score (FFs)	$FFs = [\text{sum}(\text{input per hectare})/\text{net yield}]/1000$
Farm Management Score (FMs)	$FMs = \text{Sum of qualitative management indicator points}$
Farm Environmental Score	$FEs = (FFs \times \% \text{ raw material}) FPs + FMs$
Factory Footprint Score (FFs)	$FaFs = [\text{sum}(\text{input})/\text{net yield}]/1000$
Factory Management Score (FMs)	$FaMs = \text{Sum of qualitative management indicator points}$
Factory Environmental Score	$FaEs = FaFs + FaMS$
Environmental Score (ES)	$ES = 1/(FaEs + FEs)$

4.4.3 Economic component

Inspired by the Nutrient rich food price index (NRFPI), price was a key component in the economic score (Mendoza-Velazquez et al., 2023). In the current economic score, 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 (Drewnowski, 2010). The poverty levels a, b and c account for 18.9%, 37.60% and 57.10% of the population which have R22.10, R29.67 and R44.5/ca/day for food, respectively (Worldbank, 2020; Statista, 2022). An additional poverty level (diet-bound poverty level) was created to account for 65% of the population unable to afford a healthy diet, with R57.13 to their availability which was adapted from a recent publication by Ederer et al. (2023) on purchasing power parity base (Worldbank, 2022; Knoema, 2023).

Additional inputs for both farm and factory levels included 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, among others, the extent to which a producer contributes to the gross domestic product (GDP) of South Africa and to the workforce, as well as the overall financial health of the producer (Dynan & Sheiner, 2018; CSO, 2023). The calculations employed are reported in Table 4.4.

Table 4.4: Economic score formulas and subscores

Element	Formula
Poverty Factor (Pf)	$Pf = (\text{Poverty line a, b, c, or d} / 3 \text{ meals})$
Poverty Adjusted Price (Pap)	$Pap = R/100ml \times pf$
Producer GDP contribution	$(\text{Gross profit} + \text{wages} + \text{taxes} - \text{subsidies}) / \text{agriculture GDP contribution (2.7\%)}$
Cost of production	$(\text{Expenses} - \text{Income from repurposing materials}) / \text{total production}$ $\text{Income from production} = \text{Gross profit} / \text{Total production}$
Cost:Income factor	$(\text{Cost of production} / \text{Income from production}) / 10$
Workforce contribution	$((\text{number of employees} / \text{agricultural employment number (840 000)} \times 100) \times (1 + \text{unemployment rate (32.90\%)})$
Potential lost	$[(\text{Production potential} - \text{Total production}) / \text{Production potential}] / 100$
Economic score (EcS) (producer or processor)	$\text{EcS (producer or processor)} = \text{GDP contribution} - \text{Cost:Income ratio} - \text{Potential lost} + \text{Workforce contribution}$
Economic score total	$\text{EcS} = 1 / (\text{EcS producer} + \text{EcS processor} - \text{Pap})$

4.5 Model implementation

Nutrient profiles sourced from literature comparisons (Vanga and Raghaven, 2018; Paul et al., 2020; Fructuoso et al., 2021; Sunidhi et al., 2021; Singh-Povel et al., 2022; Walther et al.,

2022) and previous local nutrient analysis data (Maree et al., 2023) were used to compile the varying scenarios for a nutrient comparison as reported in Table 4.5. Protein quality could only be assessed from locally sourced data as sufficient published literature was unavailable. The main subscores and final nutrient score (NS) are visible in Table 4.5., with the full nutritional score outline used reported in Appendix 6.4.1.

Table 4.5: Nutrient score comparison

		Local data analysis	Local label info	#1 Lit. scenario	#2 Lit. scenario	Average
BM	NSs	1.993	1.938	1.970	1.789	1.932
	pc	1.186				
	NS	3.771	3.679	3.713	3.525	3.672
AM	NSs	0.740	1.321	1.103	1.755	1.230
	pc	0.909				
	NS	1.088	1.626	1.391	2.084	1.547
SB	NSs	1.301	1.848	1.1310	2.237	1.629
	pc	1.257				
	NS	1.854	2.377	1.863	2.73	2.206
OB	NSs	0.521	1.158	0.758	0.626	0.766
	pc	0.795				
	NS	0.971	1.583	1.206	1.057	1.204

Scenario: 1) Local primary analysis (Maree et al, 2023) 2) South African products' label information (Maree et al., 2023), supplemented with local primary analysis results 3) Literature results, supplemented with local results (Smith et al., 2022b; Walther et al., 2022) 4) Literature results, supplemented with local results (Fructuoso et al., 2021).

The quantitative inputs used in the environmental score were inferred from literature scenarios as follows: 1) oat and soybean which 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 which represent a large majority of South Africa's production systems (Gertenbach, 2024) and 3) conventionally produced almonds from California, representing 75% of globally produced almonds, including

majority of brands in South Africa (Marvinney & Kendall, 2021; Johnston & Pretorius, 2020). 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 incorrect portrayal of results. Table 4.6 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 mono-cropping without post-grazing or integration of livestock, but used chicken manure and therefore has been indicated as post-harvest grazing in the form of manure spreading; soy used rotational cropping and no livestock; and oat milk utilised regenerative agriculture and post-harvest grazing. The quantitative scenarios and numerical inputs used are reported in Appendix 6.3, based on inputs and outputs per year, whereas the full environmental score outline used is tabled in Appendix 6.4.2.

Table 4.6: Subscores and environmental score results of bovine milk and plant-based beverages

Parameter	BM	AB	SB	OB
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 sub-score	6.192	5.799	5.171	6.034
Final environmental (inverted) score	0.161	0.172	0.193	0.165

Pertaining the economic score, large data gaps and differences between local and international datasets 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 scrutinize the effect of price on the economic score, a hypothetical scenario was thus created in which the same producer processes milk and plant-based beverages, with results reported in Table 4.7. All other factors remained equal across all products, with retail price being the only differing factor. The fourth (diet-bound) poverty-level was selected for the comparison of retail price. The economic component outline is reported in Annex 6.4.3.

Table 4.7: Comparison of retail price effect in the economic score results of bovine milk and plant-based beverages

Parameter	Bm	Ab	Sb	Ob
Price for reference poverty level:	0.130	0.389	0.265	0.405
Raw material producer: GDP contribution	0.229	0.229	0.229	0.229
Raw material producer: cost/income ratio	0.31	0.31	0.31	0.31
Raw material producer economic score	-0.08	-0.08	-0.08	-0.08
Processor: GDP contribution	0.728	0.728	0.728	0.728
Processor: cost/income ratio	0.13	0.13	0.13	0.13
Processing producer economic score	0.6	0.6	0.6	0.6
Economic sub- score	0.648	0.907	0.783	0.923
Final (inverted) economic score	1.543	1.103	1.277	1.083

The results of the main scores (excluding protein score) according to the DiEET model, are visualised below in Figure 4.1. In viewing the relationship between each component to 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.

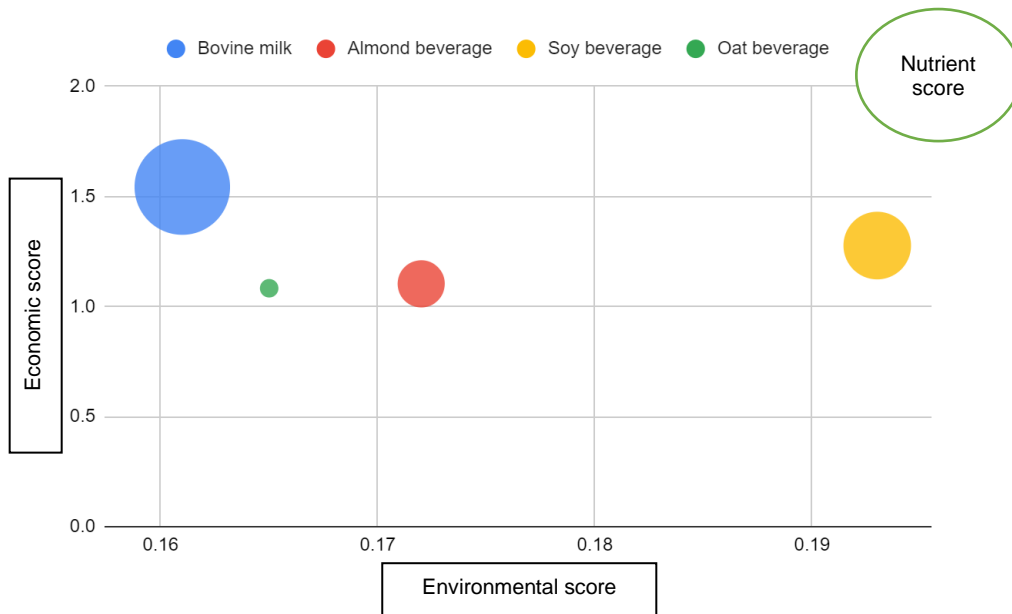


Figure 4.1: DiEET results for bovine milk and plant-based beverages (bubble size: nutritional score)

When comparing each score of the plant-based beverages, as a percentage of that of bovine milk in Figure 4.2, a clear relationship emerges in which the magnitude of differences between nutrition score and economic score emerges, as well as the direction and component in which bovine milk needs to improve.

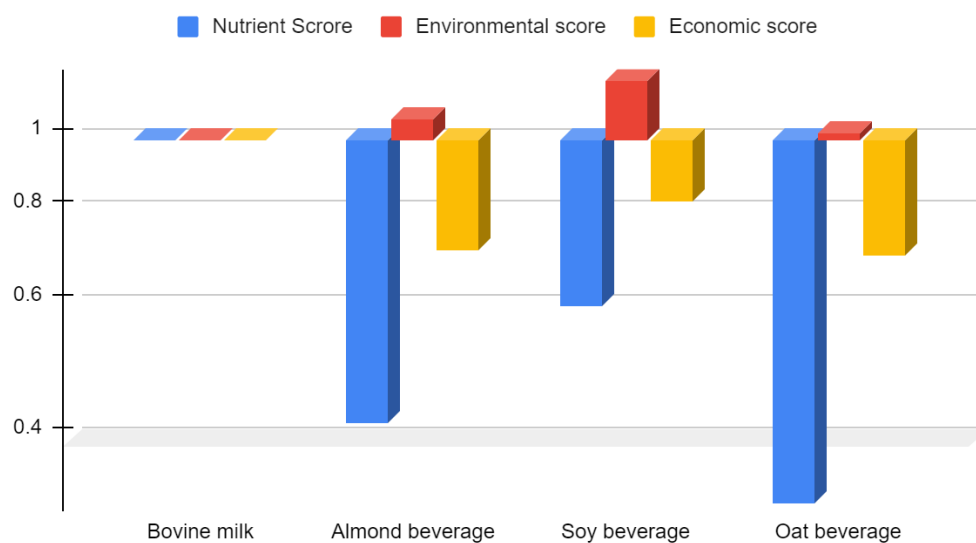


Figure 4.2. DiEET results of plant-based beverages in relation to bovine milk

4.6 Discussion

The developed model, including nutritional, environmental and economic scores as separate indicators, offer variations and scope beyond standard measures such as the NRFh (Drewnowski & Fulgoni, 2020), NRFPI (Mendoza-Velazquez et al., 2023), nLCA (Thompson et al., 2023) 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 one hand, this is an improvement to standard measures such as an LCA (Kayo et al., 2014) 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 (Blignaut et al., 2022; Manzano et al., 2023). It further allows for industry application by farmers and producers, due to the simplicity of data required.

In the DiEET model results reported in Table 4.6, mostly similar trends in environmental scores (ES) compared to standard units of measure were observed. Notably, the ES of bovine milk was consistently lower than all plant-based beverages. Factory inputs for the environmental score remained similar, especially in cases where processors handle both milk and plant-based beverages on the same production line. However, it is essential to acknowledge that raw material processing, which typically occurs off-site for plant-based beverages, is not fully represented in the ES calculation and may be underrepresented. 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 overall decrease in environmental footprint of bovine milk.

The DiEET nutrient score (NS) in Table 4.5, 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 is 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 plant-based beverages, although per 100 ml this was not 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 protein or amino acid deficient diet (FAO, 2013). The model further provided a broader and country-specific contextualised view of the nutrient profiles of milk and plant-based beverages.

From an economic perspective, the model results in Table 4.7 suggested 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 was 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, sub-scores would apply where e.g. each production system (crops, livestock, mixed, intensive, extensive,) has their own analysis which contributes to the final scores.

Additional datasets need to be collected in order 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 it offers a holistic approach to sustainability assessments. The model serves as a potential tool for decision-makers in the food industry, researchers and policymakers, as well as consumer educators, emphasising the need for ongoing efforts to create a more sustainable future for food production and consumption.

4.7 Critical evaluation

Limitations in the model exist due to multiple factors such as the omission of nutrient bioavailability (Dave et al., 2023), which was an initial goal yet requires much more extensive research to include accurately. Limited research is currently available on the contribution of plant-based beverages to global nutrient supply; hence, over or underestimations are possible and require verification when considering the current weightings applied to nutrient supply and contribution of plant-based beverages.

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, overlooking 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 among 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 in 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 systems (such as regenerative in comparison to conventional).

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 more in depth. The lack of information from a processor perspective further eliminates room for comment on the success of the measures of economic perimeters other than affordability.

Statistically, the model results are limited due to 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 plant-based beverages. In future, the application of the model and collection of ground-truth data will provide sufficient datasets to validate the model and the results from an industry perspective and a statistical perspective.

4.8 Conclusion

The DiEET model's approach has advanced the existing understanding of the sustainability of bovine milk versus plant-based alternatives like 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 socioeconomic implications for food security in South Africa. It further indicated the potential trade-off to be made between environmental sustainability and nutrient density or affordability, however, it 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 had 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, offering a foundation for future strategies to enhance food system resilience and equity globally.

CHAPTER 5 **General discussion & conclusion**

5.1 Discussion

Amidst growing global concerns over sustainability, the imperative for sustainable agriculture has become increasingly significant. This urgency is propelled by heightened awareness among consumers and policymakers, the pressing demands of a growing global population, and the influence of dietary choices on environmental sustainability (Keri et al., 2021; Thompson et al., 2023). This thesis aimed to contextualize the sustainability of milk and plant-based beverages within the South African milieu, evaluating their nutritional profiles, environmental footprints, and economic affordability through a comprehensive literature review and empirical study (Drewnowski, 2018; Drewnowski & Fulgoni, 2020; Mendoza-Velazquez et al., 2023). In addition, the study developed a tool for the evaluation and comparison of milk and plant-based beverages.

The investigation commenced with a literature review that identified a gap in the existing literature pertaining to South African data, and a further gap regarding the complexity of global sustainability assessments. Traditional approaches such as an LCA primarily focuses on environmental metrics such as carbon footprint analyses, often neglecting the equally critical economic and nutritional dimensions (Kayo et al., 2014; Thompson et al., 2023). Some, however, incorporate nutrition into the analyses such as with an nLCA or LCAai. Additionally, the nutrient rich food index (NRFi) also include price in some versions (NRFPI), yet no metric was identified to compare all three indicators (i.e. environmental footprint, affordability and nutritional profile) at once (Mendoza-Velazquez et al., 2023).

The study initially compared the existing literature values using these established methodologies, revealing large differences in the nutritional and environmental profiles of milk versus plant-based beverages, with milk being the most nutritious yet with the highest environmental footprint. However, these assessments were limited by their one-dimensional focus and more specifically the scarcity of localised South African data (Vanga and Raghaven, 2018; Paul et al., 2020; Fructuoso et al., 2021; Sunidhi et al., 2021; Singh-Povel et al., 2022; Walther et al., 2022). Due to the focus on finding comparative studies in an aim to be equally representative of each beverage, the literature review lacked sufficient global data and statistically sound datasets. In addition, a lack of accurate data collection at farm level provided challenges in accurate comparisons.

Label information and published data gathered was insufficient, hence limited primary data was consequently sourced via laboratory analysis, industry consultation and further scrutiny of online available label information. This data still requires expansion for comprehensive and statistically accurate analysis. The lack of comprehensive data highlighted the difficulty in achieving a balanced understanding of sustainability, thereby underscoring the need for a more holistic tool, which assesses multiple sustainability indicators. Regardless, the findings remained similar to that in literature where nutrient profile of milk is more favourable, whereas fortified plant-based beverages may score equal or better, with milk consistently being the most affordable.

To bridge the gap in assessments, the study introduced the development of the Dairy Index for Environment, Economics, and Nutrition (DiEET). This newly developed model integrated economic, nutritional, and environmental dimensions, providing a holistic assessment of beverage sustainability. The application of DiEET to empirical data revealed that while dairy products generally offer higher nutritional benefits and economic viability, their environmental impact is greater compared to plant-based alternatives. Conversely, plant-based beverages, although environmentally less burdensome, require enhancements in nutritional content and economic viability to be truly sustainable.

The empirical findings from the model application also emphasised the complex trade-offs involved in sustainability assessments. The model was populated with primary and published data and, even though comprehensive, statistically significant primary analysis was constrained by financial limitations and the availability of local data. However, the

model's initial application has been instrumental in comparing key sustainability indicators—nutrition, economics, and environment—albeit challenged by the limited availability of published South African data. Despite these advancements, the study encountered limitations. The reliance on generalized environmental data and the preliminary nature of its economic analysis highlighted the need for further refinement. The model, currently accessible online via the ASSET research website (<https://assetresearch.org.za/environmental-footprint-of-milk-and-plant-based-alternatives/>) and utilized for consumer education, requires broader engagement with industry members to enhance its practical utility.

The future directions for this research include a more aggressive marketing strategy to engage a wider array of stakeholders, which is crucial for the ongoing refinement and validation of the DiEET model. Collecting more extensive user data will help tailor the model more precisely to local needs and conditions, ensuring its relevance and effectiveness in promoting sustainable practices within the food sector.

5.2 Conclusion

This thesis successfully developed a framework for assessing the sustainability of milk and plant-based beverages in South Africa, through the Dairy Index for Environment, Economics, and Nutrition (DiEET). This multifaceted approach highlighted that while dairy remains an affordable and nutritionally rich option, soy beverages present a viable alternative, balancing nutritional content with economic feasibility and environmental footprint. However, the environmental impact of all beverage types, including dairy and plant-based alternatives, can be substantially improved. Despite achieving promising insights, the study faced limitations such as reliance on generalized environmental data and financial constraints, limiting extensive primary data collection. This underscores the ongoing need for localised research, accurate data collection on-farm, and enhanced sustainability practices across the beverage industry to reduce environmental impacts while maintaining nutritional and economic viability. The development of the DiEET model marks a great step towards integrating sustainability into the food sector, setting the stage for future enhancements and broader stakeholder engagement to refine and validate this essential tool.

CHAPTER 6 Appendix

6.1 Nutrient rich food index (NRFi) of bovine milk and plant-based beverages

6.1.1. Bovine milk nutrient rich food index (NRFi)

Nutrient	unit	DV	Local analysis	SA label avg.	Smith et al. (2022b)	Walther et al. (2022)
Protein	g	50	0.073	0.068	0.070	0.065
Dietary Fibre	g	28	0.000	0.000	0.000	0.000
Vitamin A	mcg	900	0.000	0.000	0.000	0.000
Vitamin B12	mcg	2.4	0.096	0.096	0.096	0.083
Vitamin D	µg	20	0.000	0.000	0.000	0.000
Vitamin E	µg	15	0.008	0.008	0.008	0.006
Folate	mcg	400	0.012	0.012	0.012	0.008
Calcium	mg	1300	0.092	0.092	0.085	0.086
Iron	mg	18	0.001	0.001	0.001	0.001
Potassium	mg	4700	0.036	0.036	0.034	0.036
Magnesium	mg	420	0.028	0.028	0.024	0.024
MUF+PUF	g	58	0.016	0.013	0.016	0.016
NRx			0.362	0.354	0.345	0.325
Sat fat	g	20	0.113	0.112	0.113	0.113
Sodium	mg	2300	0.021	0.019	0.021	0.015
Added sugar	g	50	0.000	0.000	0.000	0.002
LIMz			0.134	0.131	0.134	0.130
NRFi			22.792	22.333	21.109	19.552

6.1.2. Almond beverage nutrient rich food index (NRFi)

Nutrient	unit	DV	Local analysis	SA label avg.	Fructuoso et al., (2021)	Walther et al. (2022)
Protein	g	50	0.012	0.013	0.018	0.020
Dietary Fibre	g	28	0.000	0.017	0.045	0.000
Vitamin A	mcg	900	0.000	0.060	0.000	0.000
Vitamin B12	mcg	2.4	0.000	0.167	0.000	0.083
Vitamin D	µg	20	0.000	0.047	0.000	0.002
Vitamin E	µg	15	0.107	0.100	0.107	0.735
Folate	mcg	400	0.007	0.007	0.007	0.005
Calcium	mg	1300	0.090	0.079	0.095	0.050
Iron	mg	18	0.000	0.000	0.078	0.007
Potassium	mg	4700	0.003	0.003	0.003	0.003
Magnesium	mg	420	0.016	0.016	0.100	0.023
MUF+PUF	g	58	0.019	0.031	0.019	0.019
NRx			0.253	0.538	0.471	0.947
Sat fat	g	20	0.010	0.014	0.010	0.010
Sodium	mg	2300	0.028	0.013	0.003	0.023
Added sugar	g	50	0.000	0.029	0.000	0.025
LIMz			0.038	0.056	0.013	0.058
NRFi			21.498	48.247	45.812	88.917

6.1.3. Soy beverage nutrient rich food index (NRFi)

Nutrient	unit	DV	Local analysis	SA label avg.	Fructuoso et al., (2021)	Walther et al. (2022)
Protein	g	50	0.055	0.063	0.041	0.076
Dietary Fibre	g	28	0.000	0.019	0.029	0.000
Vitamin A	mcg	900	0.000	0.000	0.000	0.000
Vitamin B12	mcg	2.4	0.000	0.167	0.000	0.004
Vitamin D	µg	20	0.000	0.040	0.000	0.002
Vitamin E	µg	15	0.006	0.006	0.006	0.188
Folate	mcg	400	0.012	0.012	0.012	0.004
Calcium	mg	1300	0.035	0.092	0.095	0.065
Iron	mg	18	0.000	0.000	0.000	0.033
Potassium	mg	4700	0.050	0.050	0.050	0.050
Magnesium	mg	420	0.044	0.044	0.044	0.048
MUF+PUF	g	58	0.026	0.025	0.016	0.016
NRx			0.228	0.518	0.294	0.486
Sat fat	g	20	0.047	0.013	0.047	0.047
Sodium	mg	2300	0.033	0.022	0.033	0.010
Added sugar	g	50	0.000	0.000	0.000	0.028
LIMz			0.079	0.035	0.079	0.084
NRFi			14.867	48.312	21.463	40.141

6.1.4. Oat beverage nutrient rich food index (NRFi)

Nutrient	unit	DV	Local analysis	SA label avg.	Fructuoso et al., (2021)	Walther et al. (2022)
Protein	g	50	0.015	0.019	0.016	0.009
Dietary Fibre	g	28	0.000	0.017	0.074	0.000
Vitamin A	mcg	900	0.000	0.000	0.000	0.000
Vitamin B12	mcg	2.4	0.000	0.158	0.000	0.004
Vitamin D	ug	20	0.000	0.049	0.000	0.002
Vitamin E	ug	15	0.033	0.033	0.033	0.034
Folate	mcg	400	0.008	0.008	0.008	0.001
Calcium	mg	1300	0.001	0.087	0.092	0.038
Iron	mg	18	0.000	0.000	0.000	0.005
Potassium	mg	4700	0.036	0.033	0.036	0.036
Magnesium	mg	420	0.002	0.002	0.002	0.001
MUF+PUF	g	58	0.030	0.023	0.030	0.030
NRx			0.124	0.430	0.291	0.159
Sat fat	g	20	0.017	0.012	0.017	0.017
Sodium	mg	2300	0.020	0.010	0.019	0.017
Added sugar	g	50	0.000	0.000	0.000	0.066
LIMz			0.036	0.021	0.036	0.100
NRFi			8.795	40.893	25.565	5.916

6.2 Sources used for determining the model nutritional subcomponents

6.2.1. South African population, age and sex distribution (including the nutrient brackets each category was applied to) (Statisa, 2022)

Age (Daily recommended intake bracket)	Male	%	Female	%
0–4 (0–3, divided equally)	2 884 691	4.76%	2 809 831	4.64%
5–9 (4–8)	2 837 833	4.68%	2766 037	4.56%
10–14 (9–13)	2 890 269	4.77%	2 824 108	4.66%
15–19 (14–18)	2 566 719	4.24%	2 534 956	4.18%
20–24 (19–30)	2 351 752	3.88%	2 327 273	3.84%
25–29 (19–30)	2 626 342	4.33%	2 577 765	4.25%
30–34 (30–50)	2 833 963	4.68%	2 761 813	4.56%
35–39 (30–50)	2 583 697	4.26%	2 546 286	4.20%
40–44 (30–50)	1 990 106	3.28%	2 043 181	3.37%
45–49 (30–50)	1 607 584	2.65%	1 699 172	2.80%
50–54 (50–70)	1 262 718	2.08%	1 419 523	2.34%
55–59 (50–70)	999 048	1.65%	1 261 065	2.08%
60–64 (50–70)	777 905	1.28%	1 068 241	1.76%
65–69 (50–70)	578 724	0.95%	858 302	1.42%
70+	833 531	2.81%	1 482 557	4.79%

6.2.2. South African birth numbers and percentage of pregnancies per age group

Birth rate	1.79%
Number of births	1 087 526
% of females	3.51%
Age groups	Percentage pregnancies per group
10–19 (14–18)	13.12%
20–30	47.00%
30+	39.88%

Sources: statssa.gov.za (2021); Statista (2022)

6.2.3. Global allergy and disease incidence specific to milk and plant-based beverages

Allergy or disease	Product	Prevalence (fraction)
Milk allergy	Milk	0.005
Maltase-glucoamylase deficiency	Oats	0.020
Sucrase-isomaltase deficiency	Soybean	0.001
Almond nut allergy	Almond	0.010
Soybean allergy	Soybean	0.017
Lactose intolerance*	Milk	0.810

Sources: Wiederstein et al. (2023); Qi and Tester (2020); Mandalari and Mackie (2018); Ahn et al. (2003); Storhaug et al. (2017)

6.2.4. Amino acid scoring pattern, adapted to yield a population scoring pattern

Amino acid	IDc	Infants	1-2yrs	3-10yrs	11-14yrs	15-18yrs	>18yrs	Population scoring pattern
His	0.900	20.0	18.0	16.0	16.0	16.0	15.0	16.21
Ile	0.910	32.0	31.0	30.0	30.0	30.0	30.0	31.27
Leu	0.920	66.0	63.0	61.0	61.0	61.0	59.0	62.29
Lys	0.940	57.0	52.0	48.0	48.0	48.0	45.0	48.41
Met + Cys	0.860	27.0	25.0	23.0	23.0	23.0	22.0	23.48
Phe + Tyr	0.890	52.0	46.0	41.0	41.0	41.0	38.0	41.28
Thr	0.850	31.0	27.0	25.0	25.0	25.0	23.0	24.97
Trp	0.770	8.5	7.0	6.6	6.6	6.6	6.0	6.55
Val	0.900	43.0	41.0	40.0	40.0	40.0	39.0	41.03

Source: FAO (2013); CVB feed table (2016: Table 4.3); Reynaud et al. (2021)

Note: nearest age group percentiles used.; IDc = Ileal digestibility coefficient

6.2.5. South African nutrient requirements based on demographic strata (PNR: population nutrient requirement)

Nutrients	Unit	PNR Total
Energy	kJ/d	10 494.30
Carbohydrates*	g/d	354.42
Fibre	g/d	28.51
Protein*	g/d	108.09
Fat*	g/d	75.44
- PUFA*	g/d	15.31
- MUFA*	g/d	26.44
- Omega 3 (alpha l)	g/d	1.28
- Omega 6 (lin)	g/d	12.99
- Sat fat*	g/d	24.77
- Trans fat	g/d	2.76
Potassium (K)	mg/d	2 799.84
Iron (Fe)	mg/d	12.73
Sodium (Na)	mg/d	1 381.29
Magnesium (Mg)	mg/d	321.73
Calcium (Ca)	mg/d	1 064.09
Phosphorous (P)	mg/d	723.21
Vit A	µg /d	794.60
Vit B2 (Riboflavin)	mg/d	1.13
Vit B12	µg /d	2.20
Vit B9 (Folate)	µg /d	379.46
Vit D	µg /d	15.63
Vit E	mg/d	13.92
Zinc	mg/d	9.06
Iodine	µg /d	157.96
Amino acids	mg/d	
- Histidine	mg/d	1 659.90
- Leucine	mg/d	6 446.57
- Lysine	mg/d	4 972.00
- Methionine (+cystine)	mg/d	2 416.50
- Threonine	mg/d	2 557.22
- Tryptophan	mg/d	735.83
- Isoleucine	mg/d	3 247.26
- Phenylalanine (+tyr)	mg/d	4 220.12
- Valine	mg/d	4 250.95

Dietary Reference Intakes (DRIs) and FAO (2013); Amino acids are adapted according to scoring patterns and protein requirement; *Macro requirements based on PURE Healthy Diet (Mente et al., 2023); Energy based on moderate physical activity and average extra daily requirement for the whole pregnancy; M: male, F: female, P/L: pregnant and/or lactating

6.2.6. Global nutrient supply of nutrients based on the 2020 baseline setting of the Delta model (SNI, 2022) in relation to population nutrient requirements (PNR).

Nutrient	Unit/day	Supply*	Daily requirement	Supplement needed
Energy	kJ	11 208.98	10 494.30	-714.68
Carbohydrates	g	401.51	354.42	-47.10
Fibre	g	26.26	28.51	2.25
Protein	g	64.62	108.09	43.46
Fat	g	83.80	75.44	-8.36
Potassium (K)	mg	3 239.47	2 799.84	-439.63
Iron (Fe)	mg	12.66	12.73	0.07
Sodium (Na)	mg	424.32	321.73	-102.58
Magnesium (Mg)	mg	622.82	1 064.09	441.27
Calcium (Ca)	mg	1 383.25	723.21	-660.04
Phosphorous (P)	µg	645.68	794.60	148.92
Vit A	mg	1.61	1.13	-0.48
Vit B2 (Riboflavin)	µg	3.93	2.20	-1.73
Vit B12	µg	385.02	1 381.29	996.27
Vit B9 (Folate)	µg	2.68	379.46	376.77
Vit E	µg	8.99	15.63	6.64
Zinc	mg	10.53	9.06	-1.47
- Histidine	mg	1 678.77	1 659.90	-18.86
- Leucine	mg	4 886.96	6 446.57	1 559.61
- Lysine	mg	3 512.51	4 972.00	1 459.49
- Threonine	mg	2 343.99	2 557.22	213.23
- Tryptophan	mg	751.15	735.83	-15.32
- Met + cys	mg	2 348.22	2 416.50	68.28
- Methionine	mg	1 364.83	2 416.50	1 051.66

6.2.7. Percentage of raw material in final product, based on market investigations in Gauteng

Product	Number of brands used	Average percentage raw material
1) Oat beverage	8.00	11.21%
2) Soy beverage	4.00	6.75%
3) Almond beverage	9.00	2.40%
4) Bovine milk	10.00	100.00%

* information was gathered from labelling or website information provided by the different anonymous brands in Gauteng

6.2.8. Nutrient contribution ratios per food group (adjusted to content in final product)

Nutrient	Milk	Oats	Adj	Soybean	Adj	Nuts	Adj
Energy	0.0669	0.0027	0.0003	0.0041	0.0003	0.0058	0.0001
Carbohydrates	0.0378	0.0034	0.0004	0.0022	0.0001	0.0017	0.0001
Fibre	0.0000	0.0072	0.0008	0.0082	0.0006	0.0080	0.0002
Protein	0.1654	0.0041	0.0005	0.0116	0.0008	0.0066	0.0003
Fat	0.1288	0.0017	0.0002	0.0069	0.0005	0.0184	0.0002
Potassium (K)	0.1183	0.0021	0.0002	0.0120	0.0008	0.0050	0.0003
Iron (Fe)	0.0107	0.0060	0.0007	0.0224	0.0015	0.0082	0.0005
Magnesium (Mg)	0.1144	0.0089	0.0010	0.0174	0.0012	0.0155	0.0004
Calcium (Ca)	0.3192	0.0009	0.0001	0.0073	0.0005	0.0029	0.0002
Phosphorous (P)	0.4409	0.0151	0.0017	0.0254	0.0017	0.0193	0.0006
Vit A	0.1076	0.0000	0.0000	0.0002	0.0000	0.0002	0.0000
Vit B2 (Riboflavin)	0.3335	0.0015	0.0002	0.0101	0.0007	0.0054	0.0002
Vit B12	0.2597	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Vit B9 (Folate)	0.0409	0.0029	0.0003	0.0303	0.0020	0.0039	0.0007
Vit E	0.0004	0.0000	0.0000	0.0009	0.0001	0.0160	0.0000
Zinc	0.0894	0.0061	0.0007	0.0090	0.0006	0.0081	0.0002
- Cystine	0.1297	0.0087	0.0010	0.0186	0.0013	0.0099	0.0004
- Histidine	0.3097	0.0074	0.0008	0.0245	0.0017	0.0114	0.0006
- Leucine	0.2854	0.0058	0.0007	0.0191	0.0013	0.0085	0.0005
- Lysine	0.2999	0.0039	0.0004	0.0203	0.0014	0.0058	0.0005
- Methionine	0.3658	0.0076	0.0008	0.0149	0.0010	0.0100	0.0004
- Threonine	0.3257	0.0057	0.0006	0.0264	0.0018	0.0098	0.0006
- Tryptophan	0.3848	0.0097	0.0011	0.0313	0.0021	0.0137	0.0008

Sources: Delta Model (SNI, 2022) based on standard settings for 2020, baseline scenario

Note: average raw material content is used, however, if a single product is measured with a known raw material percentage, this can be replaced.

Ratios reflect the portion of global supply to which each food group contributes.

6.3 Environmental footprint of raw materials for milk and plant-based beverages

6.3.1. Environmental footprint of almond cultivation (Marvinney and Kendall, 2021)

Indicator	Unit	Value	Comment
Fuel	kg/ha	20 365.91	Diesel + gasoline
Propane gas	kg/ha	98.9871	
Electricity	kWh/ha	83 156.86	
Pesticide	kg/ha	4 167.77	Nursery + orchard
Fertiliser N	kg/ha	3 614.00	Nursery + orchard
Fertiliser P	kg/ha	4 142.56	Nursery + orchard
Fertiliser K	kg/ha	224.6913	Nursery + orchard
Total synthetic fertiliser	kg/ha	21 075.32	Nursery + orchard
Blue water (irrigation)	kL/ha	2 986 840	
Yield	t/ha	2.33	Lifetime average per year
Maximum yield	t/ha	2.742	Based on maximum achieved in the area per year (lifetime avg./year)
Average age at removal	years	21.533	
Additional material input	kg/ha	1 147.81	Planting + irrigation
Density	trees/ha	312.4028	(Sapling required: 170.81 kg/ha)
Co-product generated	kg/ha	3401.71	Biomass, tree loss, hulls etc. (lifetime total averaged per year)
Recycled into farm	kg/ha	1295.741	Soil mulch, etc. (lifetime total averaged per year)
Sold/repurposed	kg/ha	1709.11	Dairy feed, energy generation (lifetime averaged per year)
In-field burning	kg/ha	396.8569	(lifetime total averaged per year)

6.3.2. Environmental footprint results of oat cultivation

Indicator	Unit	Value	Comment
Fuel	kg/ha	50.3	Transport to silo 3.6 L, 5.5 L
Electricity	kWh/ha		Only farm maintenance (security, housing) – not recorded
Fertiliser N	kg/ha	77.75	
Fertiliser P	kg/ha	18.85	
Fertiliser K	kg/ha	6.25	
Lime	kg/ha	425	
Fungicide	kg/ha	0.4	
Insecticide	kg/ha	0.41	
Herbicide	kg/ha	1	
Blue water (irrigation)	kL/ha	0	Winter wheat planted in winter rainfall area
Yield	t/ha	2.95	
Maximum yield	t/ha	3.3	
Co-product generated	t/ha	2625.5	Crop residues
Recycled into farm	t/ha	172.42	29.8% residues left – 1% burnt
Sold/repurposed	t/ha	1844.525	70.2% residues removed
In-field burning	t/ha	7.81	1% burnt

Source: De Kock et al. (2018); GrainSA (2022) – based on wheat grown in South Africa

6.3.3. Environmental footprint of soybean cultivation

Indicator	Unit	Value	Comment
Fuel	kL/ha	189.2	
Electricity	kWh/ha	2091.68	Drying beans = 133.88
Fertiliser N	kg/ha	60	
Fertiliser P	kg/ha	7	
Fertiliser K	kg/ha	19	
Lime	kg/ha	5.7	Both before and after harvest
Pesticide	CO ₂ eq/ha	628.6	Input not provided, only carbon eq.
Blue water (irrigation)	kL/ha		Not under irrigation
Yield	t/ha	1.8	
Maximum yield	t/ha	2.38	
Co-product generated	t/ha	2.94	crop residues
Recycled into farm	t/ha	1.0584	36% residues remaining
Sold/repurposed	t/ha	1.65	56% residues collected or repurposed
In-field burning	t/ha	0.235	8% burnt

Source: Tongwane et al. (2016); Blignaut et al., (2019); Kuboń et al. (2021); Pannar (2006)

6.3.4. Environmental footprint results of dairy production

Indicator	Unit	Value
Farm size	ha	310
Herd	nr	1 188
Of which dairy	nr	588
Milk production	l/year	5 730 000
Per cow per year	l/year	9 744.897959
Feed produced	ton/year	12 960
Feed purchased	ton/year	3 360
N fertiliser	kg/ha	68
P fertiliser	kg/ha	0
Electricity	kWh/year	335 000
Fuel use	L/year	128 600
Milk production	l/year	6 546 500
Water	l/l	0.046
Electricity	kWh/L	0.056

Source: Owusu-Sekeyre et al. (2016); dos Santos et al. (2022)

6.4 Model outline

6.4.1. Nutrient score outline

Nutrient score						
Milk (milk type selected by user)	Content	Population nutrient req.	Supplement coefficient	Contribution coefficient	Nutrient content sufficiency	
Nutrient	Unit/100ml	100ml	PNR (/day)	Sc	Cc	NSs
Energy	mg		10 494.300	1.000	1.067	
Carbohydrates*	mg		354.418	1.000	1.038	
Fibre	mg		28.511	1.079	1.000	
Protein*	mg		108.085	1.402	1.165	
Fat (count if type unknown)	mg		75.436	1.000	1.129	
- PUFA*	mg		15.310	1.000	1.000	
- MUFA*	mg		26.445	1.000	1.000	
- Omega 3 (alpha l)	mg		1.285	1.000	1.000	
- Omega 6 (lin)	mg		12.991	1.000	1.000	
- Sat. fat*	mg		24.774	1.000	1.000	
- Trans fat	mg		1.682	1.000	1.000	
Potassium (K)	mg		2 799.838	1.000	1.118	
Iron (Fe)	mg		12.735	1.330	1.011	
Magnesium (Mg)	mg		321.733	1.000	1.114	
Calcium (Ca)	mg		1 064.088	1.415	1.319	
Phosphorous (P)	mg		723.207	1.000	1.441	
Vit A	mg		794.602	1.330	1.108	
Vit B2 (Riboflavin)	mg		1.131	1.000	1.333	
Vit B12	mg		2.195	1.000	1.260	
Vit B9 (Folate)	mg		379.459	1.721	1.041	
Vit D	mg		15.633	1.993	1.000	
Vit E	mg		13.922	1.425	1.000	
Zinc	mg		9.061	1.330	1.089	
Iodine	mg		157.962	1.000	1.000	
Amino acids						
- Histidine	mg		1 659.902	0.989	1.310	

6.4.1 Nutrient score outline continued

- Leucine	mg		6 446.566	1.242	1.285	
- Lysine	mg		4 972.003	1.294	1.300	
- Methionine (+cystine)	mg		2 416.498	1.028	2.495	
- Threonine	mg		2 557.216	1.083	1.326	
- Tryptophan	mg		735.833	0.979	1.385	
- Isoleucine	mg		3 247.257	1.000	1.000	
- Phenylalanine (+tyr)	mg		4 220.116	1.000	1.000	
- Valine	mg		4 250.946	1.000	1.000	

1: Nutrient sufficiency score total

Amino acids	Unit	AA %	IAA
- Histidine	mg/g		
- Leucine	mg/g		
- Lysine	mg/g		
- Methionine (+cystine)	mg/g		
- Threonine	mg/g		
- Tryptophan	mg/g		
- Isoleucine	mg/g		
- Phenylalanine (+tyr)	mg/g		
- Valine	mg/g		

1.1: Protein completeness factor

IAA (summed)

(pc)

Health factors	Coefficient	PNR (/day)	Sub-factors
Added sugar (only added)	g		
Natural sugar	g		
Sodium (Na)	mg	1 381.292	
Exclusion threshold	Etc		
Healthy diet contribution	HDCc		
Nutrient score			NS

Meaning	Color
User input	Green
Variable based on milk type	Purple
Automatic calculated value	Orange
Automatic calculated score	Blue

6.4.2. Environmental score outline (green:user input; orange: calculated value; blue: subscore calculated value)

Parameter	Unit	Usage	Unit/ton
Total land	Ha		
Yield	kL /ha		
By-product yield	Ton/ha		
Of which recycled into farm	Ton/ha		
Of which yielding a product or electricity	Ton/ha		
Production potential	Ton/ha		
Potential lost	Ton/ha		
Land use	Ha/ton		
Net yield (yield-by-product) per ha	Ton/ha		
Net land use	Ha/ton		
Farm productivity score			
Total synthetic fertiliser	Ton/ha		
N fertiliser	Ton/ha		
P fertiliser	Ton/ha		
K fertiliser	Ton/ha		
Lime	Ton/ha		
Pesticides (if type not known)	Ton/ha		
Herbicides	Ton/ha		
Insecticides	Ton/ha		
Fungicides	Ton/ha		
Fuel (inc. Material transport)	Kl/ha		
Electricity	Kwh/ha		
Blue water	kL/ha		
Farm input & footprint score			
Management & environmental indicators (see Appendix 6.4.2.B for input options)			
Cropping type			
Livestock use			
Soil type			
Soil test frequency			
Water test frequency			
Formal sustainability assessment (f)			
Crop health and/or livestock welfare assessment (f)			
Environmental score outline continued			
Sustainability training or education (f)			

Improvement in efficiency yearly			
Reduction of inputs yearly			
Management score			
1) farm environmental score			
Total litres produced at factory	kL		
Of which product in question	kL		
By-product yield	L/L		
Of which recycled into processing	L		
Of which a product or electricity	L		
Fuel (excluding distribution)	L/L		
Fuel (distribution)	L/L		
Electricity	Wh/L		
Blue water	L/l		
Are product specific inputs accurately measured in the factory?			
Total litres of final product at factory	L/year		
By-product yield	Kg/year		
Of which repurposed	Kg/year		
Of which a product or electricity	Kg/year		
Packaging used	Kg/year		
Fuel (excluding distribution)	L/year		
Fuel (distribution)	L/year		
Electricity	Kw/L/year		
Blue water	L/year		
Factory input & footprint score			
Management & environmental indicators (see			
Formal sustainability assessment (f)			
Sustainability training or education (f)			
Improvement in efficiency yearly			
Reduction of inputs yearly			
Management score			
2) factory environmental management score			
Environmental score	ES		

6.4.2.B. Qualitative indicators question and user input options

Question/qualitative indicator	Options					
Cropping type	<ul style="list-style-type: none"> Mono-cropping Rotational-cropping Inter-cropping Cover-cropping Regenerative cropping Agroforestry 					
Livestock use	<ul style="list-style-type: none"> None (if crops only without integration of livestock) TMR (no fodder carry) Post-harvest grazing (not for milking) TMR with Fodder carry Pasture based (single crops; with or without supplements) Pasture based (mixed veld, with or without supplements) 					
Soil type	<ul style="list-style-type: none"> Sandy Clay Loam Silt Peat 					
<table border="1" style="width: 100%; text-align: center;"> <tr><td>Soil test frequency</td></tr> <tr><td>Water test frequency</td></tr> <tr><td>Formal sustainability assessment (f)</td></tr> <tr><td>Crop health and/or livestock welfare assessment (f)</td></tr> <tr><td>Sustainability training or education (f)</td></tr> </table>	Soil test frequency	Water test frequency	Formal sustainability assessment (f)	Crop health and/or livestock welfare assessment (f)	Sustainability training or education (f)	<ul style="list-style-type: none"> Never 5-10 years 2-5 years Yearly Twice or more per year
Soil test frequency						
Water test frequency						
Formal sustainability assessment (f)						
Crop health and/or livestock welfare assessment (f)						
Sustainability training or education (f)						
<table border="1" style="width: 100%; text-align: center;"> <tr><td>Improvement in efficiency yearly</td></tr> <tr><td>Reduction of inputs yearly</td></tr> </table>	Improvement in efficiency yearly	Reduction of inputs yearly	<ul style="list-style-type: none"> None 1-2% 2-5% 5-10% More than 10% 			
Improvement in efficiency yearly						
Reduction of inputs yearly						

6.4.1. Economic score outline (green: user input; orange: calculated value; blue: subscore)

PARAMATER	Unit/Factor	
CONSUMER COST		
Affordability		
COST	R/100ml	
FPL	pf1	
LBLP	pf2	
UBPL	pf3	
DBPL	pf4	
Price for reference poverty level:	Poverty Level	
PRODUCER ECONOMIC INDICATORS		
Raw material producer		
Gross profit (whole farm)	R/year	
Wages (whole farm)	R/year	
Taxes (whole farm)	R/year	
Subsidies (whole farm)	R/year	
RM: GDP (agriculture) contribution		
Total expenses	R/year	
Income gained from repurposing waste	R/year	
Total production	kg/year	
Holistic cost of production	R/kg	
Holistic income from production	R/kg	
RM: Cost/Income Ratio		
Employees on farm		Nr employees
Production potential	ton/year	
Potential lost	ton/ton	
Raw material producer economic score		
Final product producer		
Gross profit (whole factory)	R/year	
Wages (whole factory)	R/year	
Taxes (whole factory)	R/year	
Subsidies (whole factory)	R/year	
RM: GDP (agriculture) contribution		

Economic score outline continued

Total expenses	R/year	Green
Income gained from repurposing waste	R/year	Green
Total production	kg/year	Green
Holistic cost of production	R/kg	Yellow
Holistic income from production	R/kg	Yellow
RM: Cost/Income Ratio		Blue
Employees on factory	Nr employees	Green
Production potential	ton/year	Green
Potential lost	ton/ton	Yellow
Processing producer economic score		
ECONOMIC SCORE	ES	Blue

CHAPTER 7 References

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