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Bridging Nutritional and Environmental Sustainability Within Planetary Boundaries in Food Life Cycle Assessments: SWOT Review and Development of the Planet Health Conformity Index

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Abstract: To promote sustainable food choices, it is essential to provide easily understandable information that integrates health, environmental impacts and planetary boundaries. For this purpose, the Planet Health Conformity Index (PHC) was developed and tested. Current labels, such as the Nutri-Score for health and the Eco-Score for environmental impacts, provide separate information, which may result in consumers receiving conflicting messages. The PHC combines these dimensions into a single label, aligning with consumer demand for clearer guidance and fostering sustainable food consumption and development. Methods: The PHC assesses 18 nutrients and five environmental impacts—Global Warming Potential (GWP), cropland use, freshwater use, nitrogen application (N-min) and phosphorus application (P-min)—within the framework of planetary boundaries. Six different algorithm designs, varying in capping and weighting, were tested on 125 food products from the German market. The analysis compared mass-, energy- and multi-nutrient-based functional units. Results: Under mass- and energy-based units, many products meet planetary boundaries. However, incorporating nutrient profiles often leads to exceeding these boundaries (exceedance rate PHC: GWP: 38% of products transgressed the boundary, cropland use: 41%, freshwater use: 27%, N-min: 34%, P-min: 71%). Accordingly, the PHC contextualizes nutritional strengths and weaknesses environmentally. Moreover, it disaggregates the Planetary Health Diet (PHD) at the nutrient level, facilitating adaptation to individual nutritional needs. Conclusions: Traditional food Life Cycle Assessments should include nutrients in the functional unit and consider planetary boundaries to enable more accurate food comparisons. The PHC presented here takes these aspects into account. In addition, its dual-factor approach, integrating health and environmental metrics, ensures broad applicability. Thus, the PHC Index can be applied not only to single food items but also to recipes, dishes, menus and entire diets.

Keywords: life cycle assessment (LCA); multi-nutritional LCA; nutritional functional unit; planetary boundaries; planetary health diet (PHD); Planet Health Conformity Index (PHC); food profiling; Nutri-Score; Eco-Score; SWOT analysis; review

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1. Introduction

In recent decades, food systems have become more efficient and technologically advanced, providing food for a growing world population. However, sustainable food systems based on environmentally friendly, healthy, ethically responsible, everyday-appropriate, socio-cultural and economically viable diets are still far from being realized [1]. Therefore, maintaining healthy diets within planetary boundaries remains a key sustainability issue, particularly as scarce resources such as land, biodiversity, freshwater, nitrogen and phosphorus are overexploited, and greenhouse gases and pollutants are emitted [2–6]. The concept of planetary boundaries, as defined by the Stockholm Resilience Centre, is essential for sustainable development. It delineates ecological limits within which humanity can operate safely, thereby ensuring that critical Earth system processes are maintained. Today, six of the nine planetary boundaries are already being exceeded, and one of the main drivers of overshooting planetary boundaries is agriculture, the basis of food production [7,8].

In recent years, the approach of Nutritional Life Cycle Assessment (nLCA) has evolved with the aim to integrate the diverse core functions of nutrition (nourishment, health promotion, ecosystem protection, etc.) by measuring the corresponding impacts of food products, recipes and whole diets [9–16]. Although several nLCA approaches have been developed for specific research tasks, the following challenges persist in nLCA, which hinder sustainable choices at the point of sale: (i) a limited scope of considered environmental impact categories, (ii) a limited scope of considered foods/nutrients and health endpoints and (iii) a lack of alignment with planetary boundaries (see SWOT analysis of reviewed studies conducted within this research (Supporting Information 1, Table S1)).

For these reasons, it is currently impossible for consumers and other stakeholders to identify the combined environmental and health benefits of foods along the life cycle from agriculture to retail [17]. In order to inform consumers about the health and environmental impacts of foods, the information must be transparent, understandable and comparable [18]. A label is such an instrument with the potential to provide understandable and credible information [19]. However, to date, only mono-dimensional food labels have achieved a certain level of market penetration, with the five-level Nutri-Score label being the most widely recognized in European countries [20]. However, this label only addresses the "health" dimension and overlooks the ecological quality and food processing levels. While the Nutri-Score label is already present on many foods [21], environmental labels are still in the experimental phase. There are discussions about options that integrate various environmental impacts (e.g., Eco-Score, Planet-Score and French Environmental Labels) or labels that focus solely on one environmental impact (e.g., climate label) [22].

If ongoing initiatives such as the EU-PEF (Product Environmental Footprint [23]) are implemented, foods could be labeled with both scores: a health-related score (such as the Nutri-Score) and an environmental score (such as the Eco-Score or EU-PEF). This could potentially result in conflicting messages. This would be the case, for example, if a product is rated A in the Nutri-Score but only D in the Environmental Score [24].

Goals of the study: Against this background, this study aims to develop a novel index that encompasses 18 public health-relevant nutrients and five environmental impacts, contextualized within the framework of the "planetary boundaries". The new index, called the Planet Health Conformity Index (PHC), assesses whether a food product can provide sufficient nutrients while preserving planetary boundaries. Thus, by aligning nutrient intake with environmental limits, foods can contribute to both individual health and planetary health, promoting diets that are nutritious and minimize ecological impact. The index, thus, fills a gap in existing indices and labels by taking into account both nutritional needs as well as environmental limits. Six distinct algorithm designs were tested, including variations in capping and weighting, and applied to 125 food products within the German market (including imported foods). Subsequently, the results of the PHC were compared with indices based on mass-, energy- and nutrient-based functional units.

2. Materials and Methods

2.1. Scope and System Boundaries

The PHC Index was developed and tested to assess environmental impacts across the five key dimensions of the planetary boundaries framework, namely greenhouse gas emissions, cropland use, freshwater use, mineral nitrogen application and mineral phosphorus application (Willet et al., 2019 [25]). These boundaries cover solely the agricultural sector, including upstream processes such as emissions from fertilizer production and land-use change (LUC) while excluding downstream activities such as food processing, transport, packaging and cooking. Accordingly, we used the same cradle-to-farmgate system boundaries for this analysis.

From a health perspective, the nutrients selected by Forner et al. (2021) [26] were included in the PHC Index due to their public health relevance in Germany (Table 1). However, the design of the PHC Index follows a universal approach, which allows the inclusion of further relevant environmental or nutrient/health parameters.

Table 1. Average daily nutrient recommendations per person.

	Nutrient	Unit	Minimum/ Optimum	Value *	Source
	Energy	kcal	opt	2000	[27]
Macronutrients	Protein	g	min	56	[28]
	SFAs **	g	opt	22	[26]
	MUFAs + PUFAs ***	g	opt	43	[26]
	Dietary fiber	g	min	30	[27]
Vitamins	Thiamine	mg	min	1.2	[27]
	Riboflavin	mg	min	1.4	[27]
	Vitamin B6	mg	min	1.5	[27]
	Folate	mg	min	0.3	[27]
	Vitamin B12	µg	min	4	[27]
	Vitamin C	mg	min	110	[27]
	Vitamin D	µg	min	5	[27]
	Vitamin E	mg	min	14	[27]
Minerals	Salt	g	opt	3.75	[27]
	Calcium	mg	min	1000	[27]
	Magnesium	mg	min	350	[27]
	Iron	mg	min	15	[27]
	Zinc	mg	min	10	[27]
	Iodine	µg	min	200	[27]

* If values for males and females were different, the higher value was taken. ** Saturated fatty acids. *** Monounsaturated fatty acids + polyunsaturated fatty acids.

2.2. Design of the Planet Health Conformity Index

The design process of the PHC Index followed the conceptual steps ("points of differentiation") proposed by Green et al., 2023 [10]:

(i) Nutrient selection (see Supporting Information 1);
(ii) Algorithm design (see Supporting Information 1);
(iii) Weighting (see Supporting Information 1);
(iv) Energy standardization (see Supporting Information 1);
(v) Capping (see Supporting Information 1);
(vi) Selection of analyzed food products (see Supporting Information 1);
(vii) Dietary context of the target population (see Supporting Information 1).

The nutrients selected comprised micro- and macronutrients that are included in the NutriRECIPE Index due to their high public health relevance [26,29]. Whereas the nutriRECIPE Index comprises 19 nutrients (16 encouraging and 3 limiting) and the energy content of foods, the PHC was set up based on 18 nutrients and the energy content (Table 1). Sugar as a limiting nutrient has been excluded from this selection, as only a maximum value has been defined for its intake [27]. The remaining limiting nutrients salt and saturated fatty acids (SFAs) were included. Despite their average excessive consumption, minimum and optimum values for their intakes are defined and were, thus, used as a reference point [27]. In its basic framework, the PHC assumes that the primary function of food is to nourish by providing adequate amounts of nutrients. Consequently, nutrients were not divided into encouraging and limiting nutrients, as has been implemented for several nutritional scores [30,31]. Instead, to account for the specific nutritional requirements, the daily nutrient recommendations for the German population were utilized as a reference point [27]. Where available, the minimum or maximum values were substituted for the optimum values (Table 1).

The calculation of the PHC Index is given in Equations (1)–(4).

$$(a) PHC\_am = \bar{x}\sum_{n=1}^{18}\left(\frac{P_{envi}}{P_{nutrient}} / \frac{RDA_{envi}}{RDA_{nutrient}}\right) \quad (1)$$

$$(b)\ PHC\_amw = \bar{x}\sum_{n=1}^{18}\left(\frac{P_{envi}}{P_{nutrient}} / \frac{RDA_{envi}}{RDA_{nutrient}} \times W_n\right) \quad (2)$$

$$(c)\ PHC\_m = \tilde{x}\sum_{n=1}^{18}\left(\frac{P_{envi}}{P_{nutrient}} / \frac{RDA_{envi}}{RDA_{nutrient}}\right) \quad (3)$$

$$(d)\ PHC\_mw = \tilde{x}\sum_{n=1}^{18}\left(\frac{P_{envi}}{P_{nutrient}} / \frac{RDA_{envi}}{RDA_{nutrient}} \times W_n\right) \quad (4)$$

Here, the following hold true:
PHC: Planet Health Conformity Index;
am: arithmetic mean $\bar{x}$;
m: median $\tilde{x}$;
n: nutrient;
w: weighting;
P_{envi}: environmental impact per 100 g of product P;
$P_{nutrient}$: nutrient content per 100 g of product P;
RDA_{envi}: recommended daily allowance of environmental impact per person based on planetary boundary;
$RDA_{nutrient}$: recommended daily allowance of nutrient per person;
W_n: weighting factor for nutrient n.

Functional unit: The PHC Index is designed as a ratio without a unit, thus ensuring that the environmental and nutritional performance of a product is independent of portion size and energy density. However, according to the FIC (Food Information to Consumers) regulation [32], the calculations in this study were performed for 100 g of product. First, for each nutrient included, the quotient of the environmental impact of the product (P_{envi}) and the nutrient content of the product ($P_{nutrient}$) was calculated. The ratio obtained was then divided by the quotient of the recommended daily planetary allowance for the corresponding environmental impact (RDA_{envi}) and the recommended daily allowance for each nutrient ($RDA_{nutrient}$). Finally, the aggregated PHC was obtained by calculating the arithmetic mean $\bar{x}$ or median $\tilde{x}$ of the single PHC Index factors.

Weighting: Two of the presented PHC Index variations (versions (b) and (d)) were subject to weighting, whereby the weighting factors reflect the ratio of actual and target nutrient intake for the average adult in Germany. The specific weighting factors for each nutrient are presented in Table 2.

Table 2. Nutrients included in the PHC Index and corresponding weighting factors.

Nutrients Included in PHC Index	Weighting Factor	Source
Protein	1.06	[26,28]
Saturated fat	1.00	[26,28]
MPUFAs	1.00	[26,28]
Dietary fiber	1.12	[26,28]

Table 2. *Cont.*

Nutrients Included in PHC Index	Weighting Factor	Source
Vitamin B1	0.67	[26,28]
Vitamin B2	0.64	[26,28]
Vitamin B6	0.62	[26,28]
Vitamin B9	0.89	[26,28]
Vitamin B12	0.62	[26,28]
Vitamin C	0.72	[26,28]
Vitamin D	1.32	[26,28]
Vitamin E	0.88	[26,28]
Salt (NaCl)	1.67	[26,28]
Calcium	0.87	[26,28]
Magnesium	0.77	[26,28]
Iron	0.79	[26,28]
Zinc	1.14	[26,28]
Iodine	1.59	[26,28]

Concerning the formula's algorithm design, two different mathematical instruments were tested. The PHC Index for an environmental impact is composed of the sum of the single PHC factors for each nutrient n. In this step, the arithmetic mean (PHC versions (a) and (b)) or the median (PHC versions (c) and (d)) of the single factors were calculated. This enables a comparison with the daily allowance per person to preserve the planetary boundary for an environmental impact factor.

Capping was applied at two points in the PHC formula, with the first capping being mandatory. Specifically, in single-ingredient products (monoproducts), it is unlikely that all 18 considered micro- and macronutrients are contained. For example, vitamin B12 rarely occurs in plant-based products. As a result, the first part of the PHC formula would include a division by zero, making it unsolvable. To avoid this, in this case, the quotient of the impact factor per nutrient was set to 99,999 (for example, 99,999 g $CO_{2e}/\mu g$ vitamin B12 in 100 g banana).

The second capping was optional and was applied to the single PHC factors, and, again, is mostly due to the absence of certain nutrients in monoproducts. A PHC factor of 1 or lower ensures that the planetary boundary of an environmental impact factor is preserved when consuming a product P while meeting the recommended daily requirements RDA of a nutrient n. The worst rating for the PHC expresses an exceedance of the planetary boundary by more than fourfold. Consequently, capping was introduced at this point and set to a value of four, with the objective of preventing single planetary boundary factors from reaching exceedingly high levels due to the absence of a nutrient in a given product.

The selection of analyzed food products comprised monoproducts in the food categories cereals, starchy products, sugar products, nuts and seeds, vegetable oils, vegetables, fruits, stimulants, meat products, milk, eggs and dairy products.

Regarding the production countries of the analyzed products, relevant countries concerning the German market were considered. The target population for which the recommended daily nutrient intakes were selected were healthy German adults. The dietary context is reflected by the selection and weighting of the nutrients included in the PHC Index.

2.3. Comparison with Further Indices

In the process of evaluating the combined functional unit, a comparison with existing nutritional scores was conducted. For this purpose, the observed food products were calculated using the Nutrient Rich Food Index 9.3 (NRF9.3) [30] and the Nutrient Rich Diet Index 9.3 (NRD9.3) [31]. The calculations of these indices are given in Equations (5) and (6). For the recommended daily nutrient intakes, values provided by the German Nutrition Society (DGE) were used to ensure a common basis for comparison [27].

$$NRF9.3 = \sum_{i=1}^{n=9} \frac{P_{nutrient}}{RDA_{nutrient}} / ED \times 100 - \sum_{i=1}^{n=3} \frac{P_{nutrient}}{MRV_{nutrient}} / ED \times 100 \tag{5}$$

$$NRD9.3 = \sum_{i=1}^{n=9} \frac{P_{nutrient}}{RDA_{nutrient}} \times 100 - \sum_{i=1}^{i=3} \frac{P_{nutrient}}{MRV_{nutrient}} \times 100 \tag{6}$$

Here, the following hold true:
$P_{nutrient}$: content of nutrient n in 100 g of product P;
$RDA_{nutrient}$: recommended daily allowance of nutrient n per person;
ED: energy density of 100 g product;
$MRV_{nutrient}$: maximum recommended daily value of nutrient n per person.

As the NRF family solely covers different varieties of nutritional aspects of food products, the environmental dimension was added by forming the quotient of an environmental impact and NRF9.3 [12]. Therefore, the same environmental impacts used in the PHC Index were applied. As the NRF9.3 is standardized to 100 kcal, the environmental impacts of a product were also converted to 100 kcal and then divided by NRF9.3, as given in Equation (7). Thus, a direct comparison of two-dimensional indices was enabled, serving as a secondary evaluation of the PHC Index.

$$\frac{\frac{P_{envi}}{ED} \times 100}{NRF\ 9.3} \tag{7}$$

Here, the following hold true:
P_{envi}: environmental impact per 100 g of product P;
ED: energy density of 100 g product.

2.4. Data Sources and Data Computation

The LCI data used to model the 125 foods were compiled in SimaPro© (version 9.3.0.3) and extracted from the databases Ecoinvent (version 3.8), Agri-footprint (version 5.0) and Agribalyse (version 3.1.1). The calculation of the PHC Index, NRF9.3 and NRD9.3 was conducted using Microsoft Excel©.

3. Results

Taking into account the Nutrient-related Planetary Boundaries (NuPlaBos) (Table 3 for Global Warming Potential), the calculation of the single PHC factors and the final PHC Index are first shown and explained for the example product "bananas from Ecuador" (bananas EC). Second, the application of the PHC Index on a broader set of products is demonstrated. Third, the corresponding results are compared with the NRF9.3. The NuPlaBos were derived in accordance with the environmental goals defined by Willett et al. (2019) [25] and the recommended nutrient intakes for a healthy average adult (Table 1), expressed as environmental impact per nutrient ($NuPlaBo = \frac{RDA_{envi}}{RDA_{nutrient}}$, Table 3). Five benchmarks were defined to allow for a meaningful differentiation between products, with the B label defined as lower than the planetary boundary (<1), the A label within half of B (<0.5), C between 1 and <2, D between 2 and <4 and E more than four times the corresponding NuPlaBo transgression.

Table 3. Nutrient-related planetary boundaries (NuPlaBos) for Global Warming Potential (GWP) *: g CO_{2e} per nutrient (LB = lower bound; UB = upper bound).

Boundary Transgression		**<0.5**			**1**			**2**			**4**			**>4**		
Label		**A**	LB	UB	**B**	LB	UB	**C**	LB	UB	**D**	LB	UB	**E**	LB	UB
Protein	per g	10	10	11	21	20	22	42	39	45	83	78	90	83	78	90
SFAs	per g	35	33	38	71	67	76	142	133	153	283	266	306	283	266	306
MPUFAs	per g	18	17	19	35	33	38	71	67	76	142	133	153	142	133	153
Fiber	per g	25	24	27	51	48	55	101	95	110	203	191	219	203	191	219
Vitamin B1	per mg	634	596	685	1268	1192	1370	2537	2385	2740	5074	4769	5479	5074	4769	5479
Vitamin B2	per mg	544	511	587	1087	1022	1174	2174	2044	2348	4349	4088	4697	4349	4088	4697
Vitamin B6	per mg	507	477	548	1015	954	1096	2029	1908	2192	4059	3815	4384	4059	3815	4384
Vitamin B9	per g	2.5	2.3	2.7	5.0	4.7	5.4	10.7	9.5	10.9	20.2	19.0	21.9	20.2	19.0	21.9
Vitamin B12	per µg	190	179	205	381	358	411	761	715	822	1522	1431	1644	1522	1431	1644
Vitamin C	per mg	7	7	7	14	13	15	28	26	30	55	52	60	55	52	60
Vitamin D	per µg	152	143	164	304	286	329	609	572	658	1218	1145	1315	1218	1145	1315
Vitamin E	per mg	54	51	59	109	102	117	217	204	235	435	409	470	435	409	470
NaCl	per g	203	191	219	406	382	438	812	763	877	1624	1526	1753	1624	1526	1753
Calcium	per mg	0.8	0.7	0.8	1.5	1.4	1.6	3.0	2.9	3.3	6.1	5.7	6.6	6.1	5.7	6.6
Magnesium	per mg	2.2	2.0	2.3	4.3	4.1	4.7	8.7	8.2	9.4	17.4	16.4	18.8	17.4	16.4	18.8
Iron	per mg	51	48	55	101	95	110	203	191	219	406	382	438	406	382	438
Zinc	per mg	76	72	82	152	143	164	304	286	329	609	572	658	609	572	658
Iodine	per µg	3.8	3.6	4.1	7.6	7.2	8.2	15.2	14.3	16.4	30.4	28.6	32.9	30.4	28.6	32.9

* For land use, blue water use, N-min and P-min, see Supporting Information 1.

3.1. PHC Index Derivation Example: Bananas, Ecuador

In this chapter, as an example, the steps to calculate the PHC Index are explained for bananas from Ecuador from conventional production. The results of calculating the *Product Factors* by dividing the environmental impact of a product (P_{envi}) by the corresponding nutrient content ($P_{nutrient}$) and corresponding NuPlaBos are illustrated in Table 4. The *Product Factors* $\frac{P_{envi}}{P_{nutrient}}$ show how much CO_{2e} is emitted by the consumption of a certain amount of nutrient supplied by bananas from Ecuador.

Table 4. Example: Product Factors $\frac{P_{envi}}{P_{nutrient}}$ for bananas from Ecuador and NuPlaBos.

Nutrient	$\frac{P_{envi}}{P_{nutrient}}$ of Banana, Conv. EC	$\frac{RDA_{envi}}{RDA_{nutrient}}$ = NuPlaBos
Protein (PROT)	14.6 g CO_{2e}/g	20.8 g CO_{2e}/g
Saturated fat (SFAs)	294.4 g CO_{2e}/g	70.8 g CO_{2e}/g
Unsaturated fat (MPUFAs)	215.1 g CO_{2e}/g	35.4 g CO_{2e}/g
Dietary fiber (FIBER)	8.4 g CO_{2e}/g	50.7 g CO_{2e}/g
Vitamin B1 (VB1)	381.4 g CO_{2e}/mg	1268.4 g CO_{2e}/mg
Vitamin B2 (VB2)	294.4 g CO_{2e}/mg	1087.2 g CO_{2e}/mg
Vitamin B6 (VB6)	46.2 g CO_{2e}/mg	1014.7 g CO_{2e}/mg
Vitamin B9 (VB9)	1198.6 g CO_{2e}/mg	5073.6 g CO_{2e}/mg
Vitamin B12 (VB12)	99,999 g CO_{2e}/µg	380.5 g CO_{2e}/µg
Vitamin C (VC)	1.5 g CO_{2e}/mg	13.8 g CO_{2e}/mg
Vitamin D (VD)	99,999 g CO_{2e}/µg	304.4 g CO_{2e}/µg
Vitamin E (VE)	62.1 g CO_{2e}/mg	108.7 g CO_{2e}/mg
Salt (NaCl)	5593.4 g CO_{2e}/g	405.9 g CO_{2e}/g
Calcium (Ca)	2.4 g CO_{2e}/mg	1.5 g CO_{2e}/mg
Magnesium (Mg)	0.6 g CO_{2e}/mg	4.3 g CO_{2e}/mg
Iron (Fe)	47.7 g CO_{2e}/mg	101.5 g CO_{2e}/mg
Zinc (Zn)	103.6 g CO_{2e}/mg	152.2 g CO_{2e}/mg
Iodine (I)	8.4 g CO_{2e}/µg	7.6 g CO_{2e}/µg

The resulting ratios $\frac{P_{envi}}{P_{nutrient}}$ (Product Factors) were then divided by the corresponding NuPlaBos to generate the nutrient-specific single PHC factors (Table 5), which indicate whether nutrients (from bananas from Ecuador) can be consumed in an amount that meets the daily recommended intake for that nutrient while remaining within the planetary boundary. The planetary boundary is preserved for all values equal to 1 or lower.

This step is further illustrated in Figure 1 for the Global Warming Potential (GWP). A green filling indicates that the planetary boundary is preserved, while a yellow filling implies a twofold overshoot of the planetary boundary, an orange filling implies a fourfold overshoot and a red filling an overshoot greater than fourfold of the planetary boundary. As a result, bananas from Ecuador exceed the GWP planetary boundary for SFAs, MPUFAs, vitamin B12, vitamin D, NaCl and iodine.

Concerning capping, the mandatory first capping step sets the Product Factor to 99,999, as otherwise, a division by zero would be mathematically implied. For bananas, this applies, for example, to vitamin B12, resulting in an impact factor per nutrient of 99,999 g CO_{2e}/µg vitamin B12 (as vitamin B12 does not occur naturally in bananas). The second capping step is optional and affects the single PHC factors. For bananas, the PHC factor for vitamin B12 reaches 263 (a 263-fold transgression of the NuPlaBo) due to the absence of vitamin B12. As this is an extremely high value that would distort the PHC

Index, it was set to 4 (the reachable maximum exceedance at the label level) when capping was applied.

Table 5. Example: single PHC factors per nutrient for bananas from Ecuador (GWP).

Nutrient	Single PHC Factors per Nutrient	Interpretation
Protein	0.70	For the provision of protein, only 70% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
SFAs	4.16	For the provision of the physiological amounts of SFAs, the planetary boundary is 4.16-fold transgressed. With regard to this nutrient, the consumption of bananas leads to the safety zone being exceeded.
MPUFAs	6.08	For the provision of the physiological amounts of MUFAs + PUFAs, the planetary boundary is 6.08-fold transgressed. With regard to this nutrient, the consumption of bananas leads to the safety zone being exceeded.
Fiber	0.17	For the provision of fiber, only 17% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
Vitamin B1	0.30	For the provision of vitamin B1, only 30% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
Vitamin B2	0.27	For the provision of vitamin B2, only 27% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
Vitamin B6	0.05	For the provision of vitamin B6, only 5% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
Vitamin B9	0.24	For the provision of vitamin B9, only 24% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
Vitamin B12	262.80	For the provision of vitamin B12, the planetary boundary is 262-fold transgressed. With regard to this nutrient, the consumption of bananas leads to the safety zone being exceeded.
Vitamin C	0.11	For the provision of vitamin C, only 11% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
Vitamin D	328.50	For the provision of vitamin D, the planetary boundary is 328-fold transgressed. With regard to this nutrient, the consumption of bananas leads to the safety zone being exceeded.
Vitamin E	0.57	For the provision of vitamin E, only 57% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
Salt (NaCl)	13.78	For the provision of the physiological amounts of salt, the planetary boundary is 13.78-fold transgressed. With regard to this nutrient, the consumption of bananas leads to the safety zone being exceeded.
Calcium	1.57	For the provision of Ca, the planetary boundary is 1.57-fold transgressed. With regard to this nutrient, the consumption of bananas leads to the safety zone being exceeded.
Magnesium	0.13	For the provision of Mg, only 13% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
Iron	0.47	For the provision of Fe, only 47% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
Zinc	0.68	For the provision of Zn, only 68% of the planetary boundary is used. In terms of this nutrient, the consumption of bananas is within the safety zone.
Iodine	1.10	For the provision of iodine, the planetary boundary is 1.1-fold transgressed. With regard to this nutrient, the consumption of bananas leads to the safety zone being exceeded.

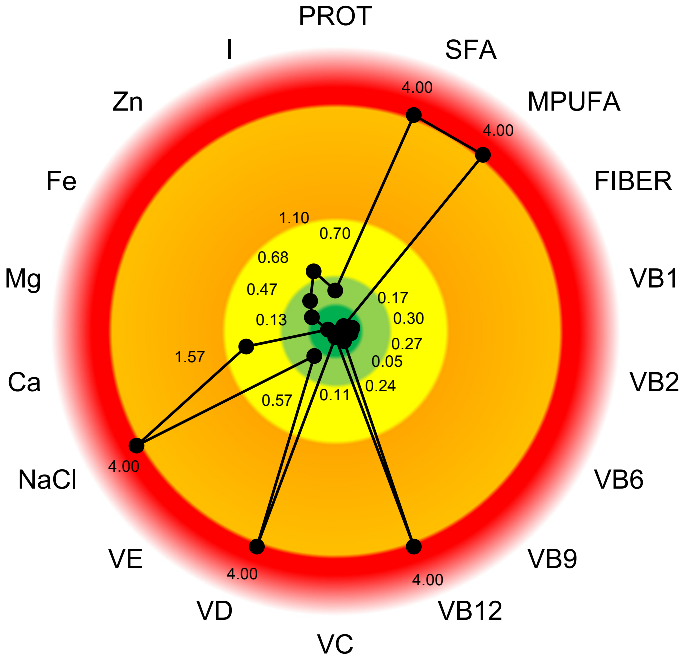

Figure 1. Single PHC factors for CO_{2e} (GWP) per nutrient for bananas from Ecuador (conventional production).

The aggregation of the single PHC factors to generate the final PHC Index was carried out in a number of ways, as shown in Table 6. It can be seen that the use of the arithmetic mean without capping significantly distorts the final PHC Index. In the case of bananas, the high value of 34.54 was mainly due to the lack of vitamin D and vitamin B12. The application of the optional capping step dramatically altered the final score, resulting in a 1.46-fold exceedance of the planetary boundary, respectively, and 1.61-fold when nutritional weighting was applied additionally. By aggregating with the median, a more equitable way of uniting the single PHC factors was obtained, taking into account the lack of single nutrients in monoproducts. Thus, a PHC score of 0.63 was generated, leading to a B label, indicating that the nutrient supply from bananas is within the planetary boundary for climate change. Applying the optional capping step and weighting only marginally affected the median.

Table 6. Aggregation models tested for the PHC Index and corresponding labels for bananas from Ecuador (GWP)

Product	Arithmetic Mean (Uncapped)	PHC Label	Arithmetic Mean (Capped at PHC Factor 4 (D < E))	PHC Label	Arithmetic Mean (Capped at PHC Factor 4 (D < E)) Weighted	PHC Label	Median (Uncapped)	PHC Label	Median (Capped at PHC Factor 4 (D < E))	PHC Label	Median (Capped at PHC Factor 4 (D < E)) Weighted	PHC Label
Banana, conv. EC	34.54	E	1.46	C	1.47	C	0.63	B	0.63	B	0.62	B

3.2. PHC Index of Further Plant- and Animal-Based Products

Figure 2 illustrates the single PHC factors for further selected plant-based foods, comparing wheat from different production countries, tomato from different production countries, cultivation scenarios (heated greenhouse and unheated greenhouse) and cultivation practices (conventional, organic) and peach from different production countries and cultivation practices. From left to right, the diagrams represent the environmental categories of greenhouse gas emissions, land use, blue water use, mineral nitrogen fertilizer application and mineral phosphorus fertilizer application. Each radar diagram accounts for the 18 single PHC factors, each representing the specific planetary boundaries for 18 nutrients for the given environmental category.

The cross-country comparison of wheat shows only minor differences in the single PHC factors. Wheat production remains within the planetary boundary for the majority of nutrients observed. It is mostly surpassed for all environmental categories regarding vitamins B12, C, D and E. Moreover, the planetary boundary is crossed for saturated fat (except blue water use), unsaturated fat (except GHGs and blue water use), vitamin E (except GHGs and blue water use), NaCl (except land use and blue water use), calcium (except GHGs and blue water use) and iodine (except GHGs and blue water use). Mineral phosphorus fertilizer application resulted in most planetary boundary transgressions, particularly for wheat from Poland, where only fiber and vitamin B1 could be supplied within the planetary boundary. Concerning tomato, the planetary boundaries for GHGs, blue water use and mineral nitrogen and phosphorus fertilizer application were always surpassed for vitamins B12 and D. The worst performance for GHGs was shown for tomatoes grown in heated greenhouses in the Netherlands, which could only supply vitamins B6, B9 and C within the planetary boundary. Tomatoes grown in unheated greenhouses in Spain and France (with the tomato cultivated in France being organic) were able to preserve the planetary boundary for GHGs of the supply of fiber, vitamins B1, B2, B6, B9, C, and E and magnesium, while the organic variety also preserved the boundary regarding the supply of iron. Similar to wheat, the cross-country comparison of peach production (with the peach from France being organic) showed comparable results. It is remarkable that the organic peach from France performed worse concerning the planetary boundary for blue water use. However, the conventionally produced varieties, too, crossed the boundary for blue water use for almost all analyzed nutrients. Overall, all planetary boundaries were crossed for the supply of SFAs, MPUFAs and vitamin B12.

Figure 3 depicts the single PHC factors for the selected animal-based foods produced in Germany: eggs, milk and meat from pigs. For each product, conventional and organic production was analyzed.

In terms of the planetary boundary for GHG emissions (GWP) for eggs, conventionally produced eggs were mostly half as high as organically produced eggs, which means that conventional production respects the boundary for providing more nutrients than organic eggs. Similarly, organic egg production showed higher PHC factors regarding land use and blue water use. In terms of mineral N and P application, only conventional eggs showed a transgression of several nutrients (vitamins B1, B6, C and E; minerals NaCl, Ca, Mg and I), whereas the transgression for mineral P application was more strongly pronounced than for N. Due to the absence of mineral N and P application in organic production systems, here, the corresponding single N-min and P-min PHC Indices are within the safety zone.

Milk production was mostly capable of providing all nutrients within the planetary boundaries for blue water use (excluding fiber) and mineral nitrogen and phosphorus fertilizer application. However, both conventional and organic milk production failed to provide almost any nutrients within the planetary boundaries for GHGs and land use. Overall, organic milk production resulted in higher PHC factors when it came to land use, while conventional milk production showed higher PHC factors concerning GHGs. The organic production of pork meat exceeded the planetary boundaries for GHGs and land use for most nutrients, while conventional production succeeded in providing protein, saturated fat and unsaturated fat within these boundaries in addition to vitamin B1 for GHGs and vitamins B1, B2 and B9, magnesium, iron and zinc for blue water use, which could be provided within the boundaries by both production methods. Regarding mineral fertilizer application, conventional meat production mostly surpassed the planetary boundaries for all nutrients. Due to the absence of mineral N and P application in organic production systems, here, the corresponding single N-min and P-min PHC Indices are within the safety zone.

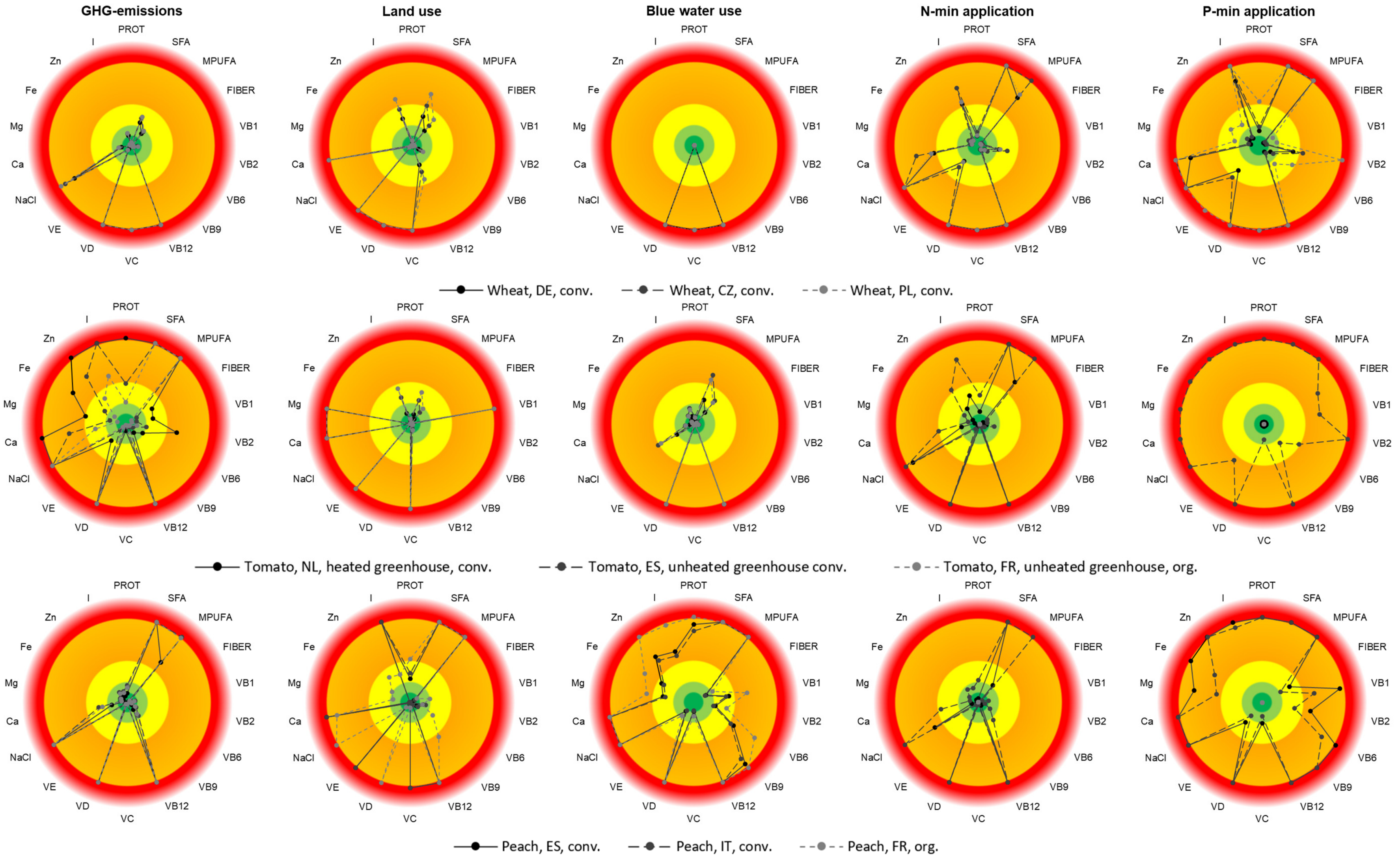

Figure 2. Single PHC factors for selected plant-based foods in terms of GHG emissions, land use, blue water use, N-min application and P-min application.

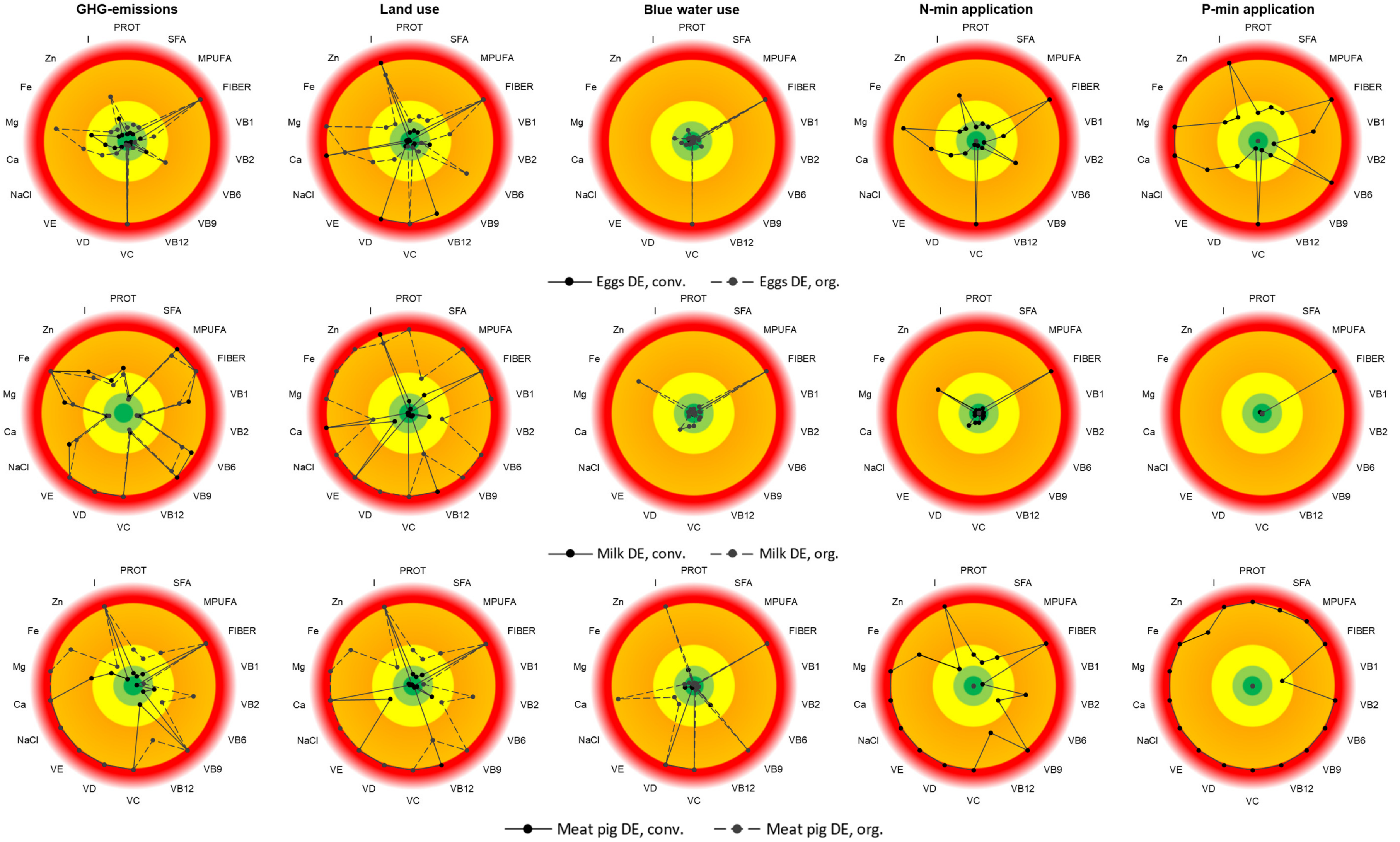

Figure 3. Single PHC factors for selected animal-based foods in terms of GHG emissions, land use, blue water use, N-min application and P-min application.

3.3. PHC Index: Aggregation, Capping and Weighting

As already illustrated for the example of bananas in Table 6, Table 7 summarizes the aggregation, capping and weighting steps applied to the products presented in Figures 2 and 3 and additional selected products. The full set of analyzed products and analyzed environmental indicators can be found in Supporting Information 2.

In Table 7, the carbon footprint of the products (both mass and energy based) is presented on the left side, while the nutriRECIPE is displayed on the right. For example, sugar has a carbon footprint rating of A but a nutriRECIPE rating of E, whereas cattle meat is the opposite, showing a carbon label of E but a nutriRECIPE rating of A. To come to the final aggregate PHC Index, first, the arithmetic mean was tested against the median. The results for the median showed more reasonable results, as the arithmetic mean led to a boundary transgression higher than 4 in all products. As a consequence, all products would receive a PHC label of E. The median showed a stronger discriminatory effect. Second, the capping of the single PHC factors was applied at the transgression factor of 4, with the lowest possible "bad" value resulting in a label of E. Thus, both aggregation methods—the mean and the median—produced reasonable results, although the arithmetic mean hindered the full utilization of the label range from A to E. Finally, weighting was applied based on the public health relevance of the nutrients, leading to slightly more pronounced results compared to non-weighted values (see, for example, apples, grapes, onions and sheep meat).

3.4. Comparison with the Environmentally Adjusted NRF9.3

Figure 4 illustrates the comparison of the capped and weighted median PHC Index for GWP against the GWP-adjusted NRF9.3. While the values for the PHC Index are set on the upper axis of the diagram, the lower axis represents kg CO_{2e}/NRF9.3. For products indicated with an asterisk, the environment-adjusted NRF9.3 could not be calculated, as the NRF9.3 here yielded a negative value due to the poor nutritional quality. Consequently, these products would show negative GHG emissions per NRF9.3. This was the case for sugar, coconuts, soybean oil, palm kernel oil, palm oil, coconut oil, dates and grapes, which all had a rather unfavorable nutritional profile, being high in sugar and/or saturated fat.

Products with a favorable PHC Index below 1 (classified as A and B) also tended to show the lowest values for GHGs per NRF9.3. Therefore, cereals (except rice), potatoes, legumes, nuts and seeds (excluding cashew nuts), cabbage, carrots, pumpkin, lettuce, spinach, oranges, bananas and eggs all were rated by the PHC Index as nutritious while still staying within the planetary boundary for GHGs. These products also emitted less than 0.12 kg CO_{2e}/NRF 9.3. On the other end of the spectrum, products that could not meet nutritional demands without significantly exceeding the planetary boundary for climate change showed considerably higher GHG emissions per NRF9.3, too. This was the case for cashew nuts, vegetable oils, tomatoes, cucumbers, coffee, cocoa, wine, meat from cattle and sheep as well as cow milk, which ranged from 0.3 to 6.2 kg CO_{2e}/NRF9.3. Additionally, the products excluded from the comparison due to their negative NRF9.3 values mostly had a PHC Index above 2.5 (with the exception of coconut and grapes).

Overall, Figure 4 shows that there is a correlation between the PHC Index and the environment-adjusted NRF9.3, which is reflected by a correlation coefficient of 0.65. However, while the PHC Index explicitly indicates whether a food product can satisfy nutritional requirements while simultaneously remaining within the planetary boundary, this conclusion cannot be drawn from the environment-adjusted NRF9.3.

Table 7. GWP, corresponding PHC Indices and labels, GWP/NRF9.3 and nutriRECIPE Index of selected products (see Supporting Information 2 for all products and the other environmental indicators).

Product	Origin, Prod. Method	GWP * (Mass Based) g CO_{2e}/100 g	PC-L	GWP * (kcal Based) g CO_{2e}/100 kcal	PC-L	Arithmetic Mean (Uncapped)	PHC-L	Arithmetic Mean (Capped at PC Factor 4 (D < E))	PHC-L	Arithmetic Mean (Capped at PC Factor 4 (D < E)) Weighted	PHC-L	Median (Uncapped)	PHC-L	Median (Capped at PC Factor 4 (D < E))	PHC-L	Median (Capped at PC Factor 4 (D < E)) Weighted	PHC-L	kg CO_{2e} (100 kcal Based)/NRF9.3	nutri-RECIPE	nutriRECIPE-L
Wheat	DE conv.	25.4	A	7.7	A	434.7	E	1.06	C	1.11	C	0.24	A	0.24	A	0.18	A	0.02	88%	A
Wheat	CZ conv.	29.6	A	9.0	A	434.8	E	1.12	C	1.14	C	0.28	A	0.28	A	0.21	A	0.02	88%	A
Wheat	PL conv.	31.4	A	9.5	A	434.8	E	1.15	C	1.16	C	0.30	A	0.30	A	0.23	A	0.02	88%	A
Rice	IT conv.	174.7	C	49.1	B	437.3	E	2.37	D	2.30	D	2.22	D	2.22	D	2.05	D	0.20	57%	C
Potato	DE conv.	8.2	A	10.8	A	37.0	E	1.25	C	1.31	C	0.26	A	0.26	A	0.36	A	0.02	89%	A
Sugar from beet	DE conv.	18.8	A	4.6	A	3135.8	E	3.81	D	3.81	D	295.65	E	4.00	E	4.00	E	n.a.	−12%	E
Beans	CA OF conv.	121.7	C	43.9	B	99.2	E	1.89	C	1.81	C	0.67	B	0.67	B	0.51	B	0.07	115%	A
Peas	UA OF conv.	54.4	A	17.7	A	33.6	E	1.22	C	1.24	C	0.48	A	0.48	A	0.45	A	0.03	109%	A
Almonds	US conv.	168.1	C	27.5	A	440.8	E	1.67	C	1.62	C	0.67	B	0.67	B	0.59	B	0.05	80%	B
Cashew nuts	RoW conv.	786.8	E	131.6	C	452.3	E	2.63	D	2.48	D	3.15	D	3.14	D	2.30	D	0.59	75%	B
Walnuts	FR conv.	125.6	C	17.4	A	448.7	E	1.43	C	1.39	C	0.49	A	0.49	A	0.48	A	0.14	57%	C
Soybeans	BR conv.	417.9	D	114.5	C	207.7	E	1.84	C	1.79	C	0.80	B	0.80	B	0.79	B	0.16	132%	A
Groundnuts	AR conv.	518.0	E	86.5	C	441.8	E	2.08	D	1.95	C	1.18	C	1.18	C	1.17	C	0.29	87%	A
Sunflower oil	MM conv.	88.8	B	10.0	A	2845.1	E	3.34	D	3.34	D	95.26	E	4.00	E	4.00	E	0.02	38%	D
Palm oil	MM conv.	511.6	E	57.9	B	1663.9	E	3.39	D	3.39	D	295.65	E	4.00	E	4.00	E	n.a.	21%	D
Olive oil	MM conv.	57.8	B	6.5	A	4484.6	E	3.34	D	3.31	D	77.39	E	4.00	E	4.00	E	0.40	33%	D
Tomato	NL HGH conv.	92.2	B	460.8	E	39.8	E	2.71	D	2.55	D	3.77	D	3.44	D	3.14	D	0.30	115%	A
Tomato	FR UGH org.	19.9	A	99.4	C	34.3	E	1.62	C	1.67	C	0.81	B	0.81	B	0.78	B	0.06	115%	A
Tomato	ES UGH conv.	37.1	A	185.7	D	35.7	E	2.03	D	1.98	C	1.52	C	1.52	C	1.45	C	0.12	115%	A
Onion	RoW OF conv.	23.9	A	79.5	C	34.4	E	1.75	C	1.73	C	1.02	C	1.02	C	0.91	B	0.23	89%	A
Spinach	NL OF conv.	28.5	A	129.7	C	33.9	E	1.07	C	1.10	C	0.25	A	0.25	A	0.23	A	0.01	174%	A
Orange	ES conv.	11.4	A	24.3	A	34.1	E	1.34	C	1.39	C	0.44	A	0.44	A	0.38	A	0.02	77%	B
Peach	ES conv.	6.8	A	15.4	A	34.0	E	1.21	C	1.20	C	0.31	A	0.31	A	0.38	A	0.04	62%	B
Peach	IT conv.	12.4	A	28.3	A	35.0	E	1.46	C	1.44	C	0.57	B	0.57	B	0.71	B	0.07	62%	B
Peach	FR org.	10.5	A	24.0	A	34.7	E	1.39	C	1.38	C	0.49	A	0.49	A	0.60	B	0.06	62%	B
Banana	EC conv.	12.8	A	18.0	A	34.5	E	1.46	C	1.47	C	0.63	B	0.63	B	0.62	B	0.20	41%	C
Apple	IT conv.	6.5	A	9.4	A	33.5	E	1.05	C	1.06	C	0.52	B	0.52	B	0.42	A	0.08	50%	C
Grapes	RoW conv.	12.2	A	16.9	A	34.1	E	1.32	C	1.36	C	0.56	B	0.56	B	0.44	A	n.a.	41%	C
Coffee	VN conv.	987.7	E	264.1	D	486.3	E	3.14	D	3.02	D	5.67	E	4.00	E	3.74	D	0.15	82%	A
Wine	RoW conv.	18.1	A	24.8	A	836.0	E	2.60	D	2.55	D	7.37	E	4.00	E	4.00	E	0.27	36%	D
Beer	DE conv.	3.9	A	10.1	A	830.9	E	2.03	D	2.02	D	1.08	C	1.08	C	1.44	C	0.09	43%	C
Meat, cattle	DE conv.	2821.3	E	2027.7	E	4033.3	E	3.87	D	3.84	D	33.10	E	4.00	E	4.00	E	6.20	88%	A
Meat, dairy cow	DE conv.	763.7	E	583.9	E	578.8	E	3.52	D	3.37	D	9.53	E	4.00	E	4.00	E	1.78	88%	A
Meat, sheep	DE conv.	718.6	E	339.7	E	4005.5	E	3.30	D	3.16	D	6.42	E	4.00	E	3.90	D	4.34	76%	B
Meat, pig	DE conv.	171.7	C	100.7	C	1162.2	E	2.23	D	2.14	D	1.60	C	1.60	C	1.25	C	0.71	82%	A
Meat, pig	DE org.	624.1	E	287.6	E	3319.9	E	2.97	D	2.78	D	4.58	E	3.71	D	3.35	D	2.03	82%	A
Meat, chicken	DE conv.	89.1	B	65.3	B	122.0	E	1.61	C	1.58	C	1.37	C	1.37	C	1.08	C	0.23	80%	A
Butter	DE conv.	1177.4	E	179.2	D	2480.7	E	3.63	D	3.66	D	98.54	E	4.00	E	4.00	E	n.a.	15%	E
Eggs	DE conv.	66.6	B	59.4	B	416.0	E	0.96	B	0.95	B	0.43	A	0.43	A	0.43	A	0.12	131%	A
Eggs	DE org.	150.5	C	109.9	C	770.0	E	1.39	C	1.37	C	0.80	B	0.80	B	0.79	B	0.22	131%	A
Cow milk	DE conv.	132.1	C	222.2	D	167.9	E	2.81	D	2.72	D	3.09	D	3.09	D	2.80	D	2.76	69%	B
Cow milk	DE org.	125.8	C	187.8	D	141.8	E	2.56	D	2.50	D	2.61	D	2.61	D	2.36	D	2.34	69%	B

* Including GHG emissions from direct agriculture and land use as well as agricultural upstream processes (production of mineral fertilizer, pesticides and dLUC).

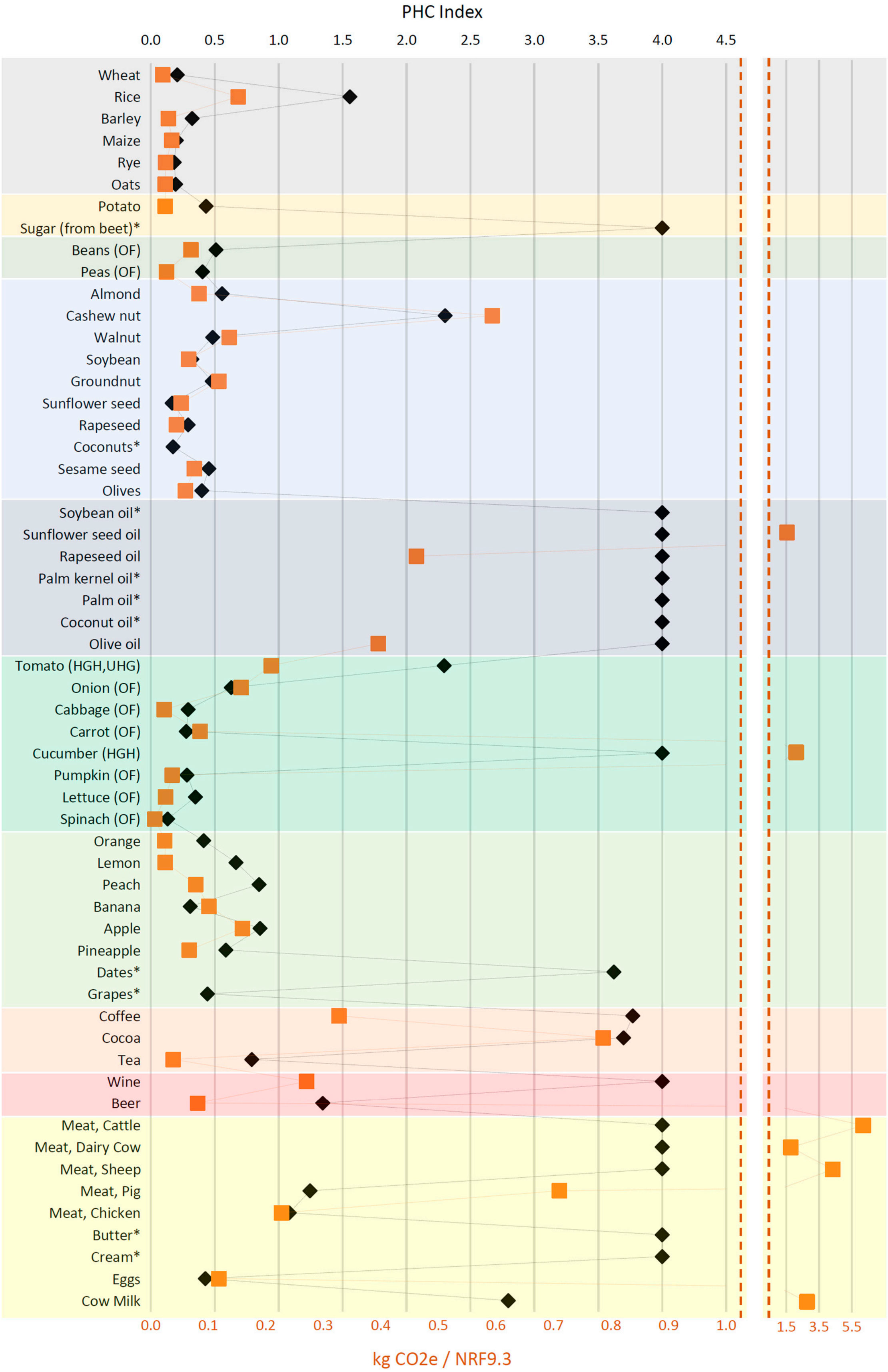

Figure 4. GWP: PHC Index (median capped, black dots) and kg CO_{2e}/NRF9.3 (capped, orange dots) (for the other environmental indicators, see Supporting Information 1). * For these products, the environmentally adjusted NRF9.3 (orange dots) is not calculable.

4. Discussion

In line with the goals of the study and following the framework proposed by Green et al. (2023) [10], a new environmental nFU—expressed as Nutrient-related Planetary Boundaries (NuPlaBos)—and, subsequently, the Planet Health Conformity (PHC) Index were developed. To derive the corresponding environmental pressures, the benchmarks proposed by Willet et al. (2019) [25], which also served as baseline for the Planetary Health Diet (PHD), were used. In this study, the new approach was applied to 125 basic foods and five environmental indicators. Furthermore, the results were compared to the environmentally adjusted NRF9.3 [12]. It was found that a considerable amount of food products were rated as preserving the planetary boundaries when a mass- or energy-based unit was applied. Including nutrients in the calculation significantly changed the results, with many of these products actually exceeding the planetary boundaries when nutrients were accounted for in the analysis.

Compared to other nFU approaches, the new PHC Index is equipped with the following innovative features (see also SWOT analysis in SI): First, to highlight the nutritional strengths and weaknesses of food products from an environmental planetary boundary-based perspective, the new index breaks down the mass-based recommendations of the PHD into corresponding specifications on a nutrient level. For the development of the PHC Index, nutrients with a high public health relevance were selected.

Second, due to its two-factorial design (environmental impact divided by nutrient = Product Factor AND environmental RDA divided by nutritional RDA = NuPlaBo) and the division of these two factors by each other, all units are truncated. Consequently, the new index is applicable to a broad range of nutritional–environmental questions, at level of single products, composed recipes, whole dishes, menus, entire diets and/or whole consumption patterns.

Third, due to its nutrient-based approach, the new index can be easily adapted to the nutritional needs of specific individuals or population groups to evaluate the ecological compatibility and comparability of foods, recipes, diets, etc., in a context-specific manner.

However, the application of the new index is also subject to some limitations. First, when the index is applied at the food level, the aggregation procedure of the single environmental nutrient factors is debatable, as single foods (especially monoproducts) almost always have unbalanced nutrient profiles. To substantiate this critical step in the calculation setup, different aggregation options were tested (as arithmetic mean, as median, with and without capping and with and without weighting). As the nutrient profiles of recipes, dishes and diets are likely to be more balanced (due to the mixture of monoproducts and, therefore, nutrients), the question of aggregation is much less important, allowing a better suitability of the index at these levels. However, for consistency, it is advisable to use the same PHC methodology at each level of consideration.

Second, in order to overcome the fact that monoproducts always lack some critical nutrients, which means a division by zero when factorizing and, therefore, a non-solvability of the equation system, an if-function has been programmed, leading to a ratio of 99,999, reflecting a very low nutrient content or the absence of nutrient correspondingly.

Third, the PHC portrays a ratio without units, which, on the one hand, makes it independent of portion size and energy density. On the other hand, these aspects are important parameters to be considered within a diet. Consequently, consumers should additionally follow portion size recommendations for foods regardless of the PHC label.

Fourth, it has to be noted that when the new PHC Index is applied to composed foods (convenience foods/polyproducts like a pizza) that are processed or even ultra-processed, the influence of processing should be considered. More importantly, the nutrient composition (recipe) must be known. Currently, there are only a few practical approaches addressing this issue [33].

Fifth, the current version of the PHC Index is not fully implementable in the market because it only includes the agricultural phase (cradle to farmgate) of the food value chain (missing: processing, transport, packaging, disposal, etc.), due to constraints made by Willet et al. (2019) [25].

Comparison with environmentally adjusted NRF9.3: Although a correlation between the PHC Index and the environmentally adjusted NRF9.3 [12] was observed (correlation coefficient of 0.65), the PHC performs better because its results are normatively embedded in the concept of the planetary boundaries. Moreover, in cases of negative NRF9.3 results (which occur with nutrient-deficient foods such as sugar, palm oil, butter, etc.), the environmentally adjusted NRF9.3 cannot be calculated, limiting its broader application. For a further discussion of the strengths and limitations of the PHC Index in the context of other nFU approaches, see the SWOT analysis in the Supplementary Materials.

5. Conclusions and Recommendations

Future Life Cycle Assessments (LCAs) of food products aiming to compare various foods should prioritize a nutritional functional unit (nFU) as the basis for the assessment, given that nourishment is the primary function of food. Traditional approaches that disregard nutritional quality may lead to biased comparisons. Research has shown that results based on nFUs can vary substantially from those using mass- or energy-based functional units. Multi-nutrient FUs provide a more comprehensive view of the environmental impact of foods, capturing both ecological and health-related dimensions. For nFUs to be effective in guiding consumers and contributing to more sustainable food systems, they should be aligned with dietary recommendations and contextualized within the nutritional needs and health status of the target population.

We propose the following recommendations to further develop this approach:

- **Incorporate Multi-Nutritional Life Cycle Assessment (nLCA):** Food producers, wholesalers and policy makers are encouraged to integrate multi-nutritional LCA methods, such as the PHC Index, into food profiling for sustainable labeling, addressing both environmental and nutritional impacts.
- **Implement the PHC Index in consumer labels:** Incorporating the PHC Index into labeling systems could help consumers make choices that are both health conscious and environmentally sound, overcoming the limitations of current one-dimensional labels.
- **Adapt the PHC Index for specific population needs:** Tailoring the index to specific demographic groups may improve its accuracy and relevance in different dietary contexts.
- **Future research to expand the PHC Index to additional phases of the food value chain:** We recommend that future studies extend the PHC Index framework beyond the agricultural phase to include processing, packaging and transportation. This will allow for a more comprehensive evaluation of the total environmental and nutritional impact of food products throughout their life cycle.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su162310658/s1: Supporting Information 1 (pdf document) and Supporting Information 2 (Excel document).

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References

1. Eberle, U.; Teufel, J.; Quack, D.; Antoni-Komar, I.; Langen, N.; Hirschnitz-Garbers, M. Ernährungssysteme nachhaltig umbauen: Vier Handlungsfelder für die Politik. *GAIA Ecol. Perspect. Sci. Soc.* **2018**, *27*, 394–395. [CrossRef]
2. He, P.; Liu, Z.; Baiocchi, G.; Guan, D.; Bai, Y.; Hubacek, K. Health–environment efficiency of diets shows nonlinear trends over 1990–2011. *Nat. Food* **2024**, *5*, 116–124. [CrossRef] [PubMed]
3. Chatzimpiros, P.; Harchaoui, S. Sevenfold variation in global feeding capacity depends on diets, land use and nitrogen management. *Nat. Food* **2023**, *4*, 372–383. [CrossRef]
4. Ivanovich, C.C.; Sun, T.; Gordon, D.R.; Ocko, I.B. Future warming from global food consumption. *Nat. Clim. Change* **2023**, *13*, 297–302. [CrossRef]
5. Crippa, M.; Solazzo, E.; Guizzardi, D.; Monforti-Ferrario, F.; Tubiello, F.N.; Leip, A. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* **2021**, *2*, 198–209. [CrossRef]
6. Hofman-Bergholm, M. A transition towards a food and agricultural system that includes both food security and planetary health. *Foods* **2022**, *12*, 12. [CrossRef]
7. Richardson, K.; Steffen, W.; Lucht, W.; Bendtsen, J.; Cornell, S.E.; Donges, J.F.; Drüke, M.; Fetzer, I.; Bala, G.; von Bloh, W.; et al. Earth beyond six of nine planetary boundaries. *Sci. Adv.* **2023**, *9*, eadh2458. [CrossRef]
8. Campbell, B.M.; Beare, D.J.; Bennett, E.M.; Hall-Spencer, J.M.; Ingram, J.S.I.; Jaramillo, F.; Ortiz, R.; Ramankutty, N.; Sayer, J.A.; Shindell, D. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol. Soc.* **2017**, *22*, 8. [CrossRef]
9. Reguant-Closa, A.; Pedolin, D.; Herrmann, M.; Nemecek, T. Review of Diet Quality Indices that can be Applied to the Environmental Assessment of Foods and Diets. *Curr. Nutr. Rep.* **2024**, *13*, 351–362. [CrossRef]
10. Green, A.; Nemecek, T.; Mathys, A. A proposed framework to develop nutrient profiling algorithms for assessments of sustainable food: The metrics and their assumptions matter. *Int. J. Life Cycle Assess.* **2023**, *28*, 1326–1347. [CrossRef]
11. Grigoriadis, V.; Nugent, A.; Brereton, P. Working towards a combined measure for describing environmental impact and nutritive value of foods: A review. *Trends Food Sci. Technol.* **2021**, *112*, 298–311. [CrossRef]
12. McLaren, S.; Berardy, A.; Henderson, A.; Holden, N.; Huppertz, T.; Jolliet, O.; De Camillis, C.; Renouf, M.; Rugani, B. *Integration of Environment and Nutrition in Life Cycle Assessment of Food Items: Opportunities and Challenges*; FAO: Rome, Italy, 2021.
13. Batlle-Bayer, L.; Bala, A.; Lemaire, E.; Albertí, J.; García-Herrero, I.; Aldaco, R.; Fullana-I-Palmer, P. An energy-and nutrient-corrected functional unit to compare LCAs of diets. *Sci. Total Environ.* **2019**, *671*, 175–179. [CrossRef] [PubMed]
14. McAuliffe, G.A.; Takahashi, T.; Beal, T.; Huppertz, T.; Leroy, F.; Buttriss, J.; Collins, A.L.; Drewnowski, A.; McLaren, S.J.; Ortenzi, F.; et al. Protein quality as a complementary functional unit in life cycle assessment (LCA). *Int. J. Life Cycle Assess.* **2023**, *28*, 146–155. [CrossRef] [PubMed]
15. Saarinen, M.; Fogelholm, M.; Tahvonen, R.; Kurppa, S. Taking nutrition into account within the life cycle assessment of food products. *J. Clean. Prod.* **2017**, *149*, 828–844. [CrossRef]
16. Sonesson, U.; Davis, J.; Hallström, E.; Woodhouse, A. Dietary-dependent nutrient quality indexes as a complementary functional unit in LCA: A feasible option? *J. Clean. Prod.* **2019**, *211*, 620–627. [CrossRef]
17. Bunge, A.C.; Wickramasinghe, K.; Renzella, J.; Clark, M.; Rayner, M.; Rippin, H.; Halloran, A.; Roberts, N.; Breda, J. Sustainable food profiling models to inform the development of food labels that account for nutrition and the environment: A systematic review. *Lancet Planet. Health* **2021**, *5*, e818–e826. [CrossRef]
18. Oehler, A.; Wendt, S. Good Consumer Information: The Information Paradigm at its (Dead) End? *J. Consum. Policy* **2017**, *40*, 179–191. [CrossRef]
19. WBAE. Politik für eine Nachhaltigere Ernährung: Eine Integrierte Ernährungspolitik Entwickeln und Faire Ernährungsumgebungen Gestalten [Gutachten]. Wissenschaftlicher Beirat für Agrarpolitik, Ernährung und Gesundheitlichen Verbraucherschutz beim BMEL. 2020. Available online: https://www.bmel.de/SharedDocs/Downloads/DE/_Ministerium/Beiraete/agrarpolitik/wbae-gutachten-nachhaltige-ernaehrung.html (accessed on 14 November 2024).
20. Dréano-Trécant, L.; Egnell, M.; Hercberg, S.; Galan, P.; Soudon, J.; Fialon, M.; Touvier, M.; Kesse-Guyot, E.; Julia, C. Performance of the front-of-pack nutrition label Nutri-Score to discriminate the nutritional quality of foods products: A comparative study across 8 European countries. *Nutrients* **2020**, *12*, 1303. [CrossRef]
21. Hafner, E.; Pravst, I. Evaluation of the ability of nutri-score to discriminate the nutritional quality of prepacked foods using a sale-weighting approach. *Foods* **2021**, *10*, 1689. [CrossRef]
22. Eberle, U.; Rödder, M.; Zühlsdorf, A.; Spiller, A.; Rehaag, R. *Klimalabel vs. Eco-Score. Ergebnisberichte des Vorhabens "Klimaschutz und Ernährung: Klimalabel versus Eco-Score—Optionen zur Klima- und Umweltkennzeichnung von Lebensmitteln" im Auftrag des Bundesministeriums für Umwelt, Naturschutz und nukleare Sicherheit*; Corsus-corporate sustainability GmbH, Zühlsdorf & Parnter, Katalyse-Institut: Berlin, Germany, 2021.
23. EUC. *Commission Recommendation of 16.12.2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations*; European Commission: Brussels, Belgium, 2021.
24. Buerke, A. *Nachhaltigkeit und Consumer Confusion am Point of Sale, Schriftenreihe der HHL Leipzig Graduate School of Management*; Springer Fachmedien: Wiesbaden, Germany, 2016. [CrossRef]

25. Willett, W.; Rockström, J.; Loken, B.; Springmann, M.; Lang, T.; Vermeulen, S.; Garnett, T.; Tilman, D.; DeClerck, F.; Wood, A.; et al. Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **2019**, *393*, 447–492. [CrossRef]
26. Forner, F.; Volkhardt, I.; Meier, T.; Christen, O.; Stangl, G.I. The nutriRECIPE-Index–development and validation of a nutrient-weighted index for the evaluation of recipes. *BMC Nutr.* **2021**, *7*, 74. [CrossRef] [PubMed]
27. Deutsche Gesellschaft für Ernährung DGE. Available online: https://www.dge.de/wissenschaft/referenzwerte/ (accessed on 8 September 2024).
28. Deutsche Gesellschaft für Ernährung DGE (Ed.) *12. Ernährungsbericht 2012*; DGE: Bonn, Germany, 2012.
29. Schlarbaum, L.; Forner, F.; Bohn, K.; Amberg, M.; Mäder, P.; Lorkowski, S.; Meier, T. Nutritional Assessment of Ready-to-Eat Salads in German Supermarkets: Comparison of the nutriRECIPE-Index and the Nutri-Score. *Foods* **2022**, *11*, 4011. [CrossRef] [PubMed]
30. Drewnowski, A.; Fulgoni, V., III. Nutrient profiling of foods: Creating a nutrient-rich food index. *Nutr. Rev.* **2008**, *66*, 23–39. [CrossRef] [PubMed]
31. Van Kernebeek, H.R.J.; Oosting, S.J.; Feskens, E.J.M.; Gerber, P.J.; De Boer, I.J.M. The effect of nutritional quality on comparing environmental impacts of human diets. *J. Clean. Prod.* **2014**, *73*, 88–99. [CrossRef]
32. European Commission. *REGULATION (EU) No 1169/2011 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 25 October 2011 on the Provision of Food Information to Consumers, Amending Regulations (EC) No 1924/2006 and (EC) No 1925/2006 of the European Parliament and of the Council, and Repealing Commission Directive 87/250/EEC, Council Directive 90/496/EEC, Commission Directive 1999/10/EC, Directive 2000/13/EC of the European Parliament and of the Council, Commission Directives 2002/67/EC and 2008/5/EC and Commission Regulation (EC) No 608/2004*; European Commission: Brussels, Belgium, 2011.
33. Bohn, K.; Amberg, M.; Meier, T.; Forner, F.; Stangl, G.I.; Mäder, P. Estimating food ingredient compositions based on mandatory product labeling. *J. Food Compos. Anal.* **2022**, *110*, 104508. [CrossRef]