Research Article

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Life cycle assessment of animal-based foods and plant-based protein-rich alternatives: an environmental perspective

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Abstract

BACKGROUND: In the European Union proteins for food are largely animal based, consisting of meat and dairy products. Almost all soy but also a larger part of pulses and cereals consumed in the European Union are used for animal nutrition. While livestock is an important source of proteins, it also creates substantial environmental impacts. The food and feed system is closely linked to the planetary and health boundaries and a transformation to healthy diets will require substantial dietary shifts towards healthy foods, such as nuts, fruits, vegetables and legumes.

RESULTS: Extrudated vegetable meat alternatives consisting of protein combined with amaranth or buckwheat flour and a vegetable milk alternative made from lentil proteins were shown to have the potential to generate significantly less environmental impact than their animal-based counterparts in most of the environmental indicators examined, taking into account both functional units (mass and protein content). The underlying field-to-fork life cycle assessment models include several variants for both plant and animal foods. The optimized plant-based foods show a clear potential for improvement in the environmental footprints.

CONCLUSIONS: Development of higher processed and therefore higher performing products is crucial for appealing to potential user groups beyond dedicated vegetarians and vegans and ultimately achieving market expansion. The Protein2Food project showed that prototypes made from European-grown legumes and pseudocereals are a valuable source for high-quality protein foods, and despite being substantially processed they could help reduce the environmental impact of food consumption.

Supporting information may be found in the online version of this article.

Keywords: protein transition; protein-rich food; plant-based meat substitutes; plant-based milk substitutes; life cycle assessment; sustainable food

INTRODUCTION

The world's population could grow to more than 9 billion by 2050, giving rise to a largely increased demand for food in general and protein food and feed in particular.[1] In addition, increased demand for protein globally is driven by socio-economic changes such as rising incomes or increased urbanization, while recognizing the role of protein in a healthy diet.[2] We must also take into account that protein undernourishment exists in some poorer populations in developing countries and an additional need of up to 50% of protein food might occur by 2050.[3] Without changes in current standard diet patterns, this will result in increased demand for animal-based protein and the need to produce more animal feed.[3,4] In fact, in the European Union (EU), proteins for food are largely animal based, consisting of meat and dairy products. At a global level, livestock provides a quarter and, in the EU, even more than 50% of all the protein consumed in food (Table 1).

At the same time, the EU has a 70% deficit in protein-rich grains that is met primarily by imports of GMO soya for concentrate feed

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Table 1. Share of protein intake at EU-28 average[5,6]

	(g per capita per day)	Share (%)
Meat	17.3	29
Dairy	13.4	22
Eggs	2.8	5
Fish, seafood	2.7	4
Cereals	16.3	27
Starchy roots	1.7	3
Pulses	1.5	2
Nuts + oil crops	1.0	4
Vegetables + fruits	3.0	5

Source: Own elaboration based on FAO[5] and Detzel *et al.*[6]

Table 2. Crop use for food and feed in the EU-28[5,6]

	Food (Mt)	Feed (Mt)	Share of feed (%)
Cereals	82.0	167.7	67
Pulses	1.5	2.1	58
Soy	2.2	30.3	93

Source: Own elaboration based on FAO[5] and Detzel *et al.*[6]

from the USA and South America.[7,8] Almost all soy, but also a larger part of pulses and cereals consumed in the EU, is used for animal nutrition (Table 2). While arable land accounts for about 60% of EU-28 total agricultural land, domestic production of protein crops in the EU occupies about 1.5% and that of soy beans about 1% of total arable land.[9,10] In contrast, 68% of the total agricultural land is used for animal production.[11]

Although livestock farming is now an important source of protein, it also causes considerable environmental pollution.[12-14] Agriculture is responsible for about 10% of the EU's greenhouse gas (GHG) emissions and nearly 70% of those come from the animal sector, followed by dairy products.[11,15] This contribution to livestock GHG emissions is due to methane from enteric fermentation. In addition, livestock farming is responsible for, among others, nitrous oxide and ammonia emissions to the air, as well as nitrogen and phosphorus pollution from fertilizer and manure used on pasture and croplands occupied for fodder production and manure management.[12,16,17] Furthermore, intensive livestock farming is estimated to account for 78% of agriculture's negative impact on biodiversity.[1]

The food and feed systems are therefore closely linked to the planetary and health boundaries. Animal-based foods are a major driver of boundary transgressions.[18] The concept of planetary boundaries was first published by Rockström *et al.*[19] and was further developed by Steffen *et al.*[20] It identifies nine processes that regulate the stability and resilience of the Earth's system and it defines quantitative boundaries, the crossing of which increases the risk of generating large-scale abrupt or irreversible environmental changes.

The planetary boundaries framework has recently been applied to set guardrails of diets entailing food consumption patterns that would safeguard both human as well as planetary health boundaries.[21] Three key areas, namely climate change, phosphorus cycling and biodiversity loss, are already exceeded through today's food consumption, while nitrogen cycling is close to the upper tolerance level. Maintaining existing food patterns with a growing world population until 2050 will increase the transgression levels and exceed the boundaries of cropland use.[18] Animal-based foods also contribute to a large transgression of healthy food consumption on a global average and even more when considering an average 'northern' diet.[21] In the 'northern' diet this is caused, in particular, by consumption of red and white meats, dairy and eggs, and by tuberous vegetables with high starch content.[18] Transformation to healthy diets by 2050 will require substantial dietary shifts, including a greater than 50% reduction in global consumption of unhealthy foods, such as red meat and sugar, and a greater than 100% increase in consumption of healthy foods, such as nuts, fruits, vegetables and legumes.[18,21]

The work presented here was carried out within the EU-Horizon 2020 project Protein2Food (AMD-635727). The project aimed at developing prototypes of innovative, nutritious and protein-rich plant-based food as an alternative to conventional animal-based foods such as pig, poultry and beef meat, as well as cow's milk. Studies on the environmental impact of vegetable alternatives and animal-based food show that vegetable proteins perform better than comparable animal products in terms of GHG emissions and other impact categories such as eutrophication or acidification.[22-25]

The prototypes within the Protein2Food project were made from European-grown grain legumes such as lentils, faba beans and lupins, combined with pseudocereals such as buckwheat, quinoa and amaranth. While buckwheat is currently stably domestic, EU quinoa and amaranth production is increasing and is being introduced around Europe.[26] The prototypes developed in the project were vegetable meat and cow's milk replacers to support the protein transition by reducing animal-based protein consumption and dependency on protein import to the EU. These products have high consumer acceptability and are particularly promising for the fulfilment of human dietary requirements due to their well-balanced amino acid profiles.[27]

This article examines the sustainability of an extrudated vegetable meat alternative ('VMA extrudate'), providing an alternative for chicken meat and a vegetable milk as an alternative for cow's milk. The VMA extrudate developed in Protein2Food is a high-moisture meat substitute without soy or wheat, using grain legumes and pseudocereals. It can be produced in the form of nuggets, chunks, strips and burgers and can be flavoured with various aromas to satisfy different tastes. The VMA products are characterized by well-defined fibre formations that closely resemble meat structures and have enhanced taste sensation. The high-protein milk substitute is based on lentil protein isolate and scored as high as commercial beverages (e.g. soy, oat based) in sensory tests conducted as part of the Protein2Food project.[28] Unlike many other plant-based beverages, it contains as much protein as cow's milk and is allergen free. Therefore, it could serve as a high-protein alternative to soymilk.

The Protein2Food prototypes are highly processed foods. One of the guiding questions in the project was whether these innovative plant-based foods are really more environmentally sustainable than the traditional animal-based counterparts. This question was addressed by comparing the environmental footprints of the plant-based protein-rich prototypes against animal-based references.

MATERIALS AND METHODS

Environmental profiles of the selected food products have been calculated through life cycle assessment (LCA) following ISO

Table 3. Product variants examined

Protein2Food prototype	Animal-based reference
VMA with 30% protein content	Chicken breast meat with 21.4% protein content
Variant 1: combination of lupin protein isolate and buckwheat flour	Variant 1: meat from 'high-performance chicken'
Variant 2: combination of lupin protein isolate and amaranth flour	Variant 2: meat from 'conventional chicken'
Variant 3: optimized variant (simulation)	
Vegetable milk substitute with 3.3% protein content	Cow milk with 3.3% protein content
Variant 1: lentil protein-based milk substitute	Variant 1: milk from 'high-performance cow'
Variant 2: optimized variant (simulation)	Variant 2: milk from 'conventional cow'

Table 4. Nutritional composition of product variants examined

		Average nutrition values per 100 g wet mass				
Product	Composition	Total energy (kcal)	Total fat content (g)	Total carbohydrate content (g)	Total protein content (g)	Water content (g)
Chicken breast meat	Chicken meat	119	3.1	0	21.4	76
VMA (variants 1 and 2)	Lupin protein isolate in combination with amaranth or buckwheat flour	136	1.0	5.0	30.0	60
VMA: optimized (variant 3)	Faba bean protein isolate in combination with amaranth flour	136	1.0	5.0	30.0	60
Cow's milk	Cow's milk	67	3.8	4.8	3.3	88
Vegetable milk (variant 1)	Lentil protein isolate, oil, sugar	52	3.3	1.8	3.3	92
Vegetable milk: optimized (variant 2)	Faba bean protein isolate, oil, sugar	52	3.3	1.8	3.3	92

14040 and ISO 14044 standards, as well as taking into account guidance provided by the ILCD methodology[29] and the World Food LCA Database.[30] The product variants presented in this article are VMA extrudates using lupin as protein source and amaranth or buckwheat flour, as well as vegetable milk made from lentil proteins (Table 3). An 'optimized' variant has been included for both plant-based products to further explore improvement potentials. Lupins and particularly lentils are legumes with relatively low yields (see Table 5); the optimized variants simulate a situation that might be achievable if producing the same prototypes with higher yielding protein crops such as faba beans. On top of that, using faba beans instead of lupins would also save a de-oiling step during grain processing. Table 4 shows the nutritional composition of the examined products as well as their water content.The animal-based products were modelled as a 'high-performance' and a 'conventional' variant. 'High-performance' here refers mainly to animal varieties with a high food conversion rate (FCR), which translates into animals with a high output of meat or milk, respectively, per amount of feed. 'Conventional' refers to varieties with a medium food conversion rate. For instance, in the case of chicken FCRs of 1.7 (high performance) and 2.2 (conventional) were assumed. An FCR of 2.2 means that 2.2 kg feed is required per 1 kg chicken live weight. This differentiation was made to benchmark the Protein2Food prototypes against a realistic range of corresponding animal-based products sold on the market.

The LCA was designed as a 'cradle-to-gate' LCA comprising all the life cycle steps from biotic and abiotic raw material sourcing up to the final food products at the factory gate, including all transports as well as all energy and raw material pre-chains. Production and disposal of the infrastructure (machines, transport media, roads, etc.) and their maintenance (spare parts, heating of production halls) as well as packaging material related to the final products were excluded based on Agrifootprint 2.0.[33]

In terms of the geographic scope, the LCA focuses on supplying the European market (EU28). This means that all life cycle steps, with the exception of imported soybeans/soybean meal (Brazil) and palm oil (Malaysia), take place within Europe. For example, an average European dataset for electricity generation was used for crop processing, husbandry and food production.

Figures 1 and 2 provide schematic flow charts illustrating the system boundaries and the main value chain steps using the example of chicken meat and VMA extrudate. These boundaries were considered to reflect the main differences between the life cycle of Protein2Food prototypes and animal-based products.

The functional unit (FU) is a key element of an LCA. It enables comparison between environmental performances of different systems or options (here, protein foods) on an equivalent basis. In Protein2Food, it was decided that protein content would be the adequate FU given the overall objective of developing plant-based food prototypes that are rich in proteins and suitable to replace animal-based proteins also from a nutritional standpoint. In addition, supplying the consumer with proteins is the most recognized function of animal-based products.[25]

On the other hand, many consumers simply buy a portioned food item offered on the shelf or purchase a defined amount at the shop counter. While it does not reflect specific nutritional

Table 5. Main cultivation countries and yield ranges within the EU[31,32]

Crops	Model yield (t ha^{-1})	Main cultivation areas within EU 1	2	3	Yield range (t WM* ha^{-1})
Protein2Food crops					
Amaranth	2.01	n.a.	n.a.	n.a.	n.a.
Buckwheat	1.01	Poland	Lithuania	France	1.3–3.7
(White) Lupin	2.51	Poland	Germany	France	1.6–1.7
Lentil	0.81	Spain	France	Bulgaria	0.6–1.4
Faba bean	3.51	France	UK	Italy	3.2–3.8
Others (EU crops)					
Wheat	7.90	France	Germany	Poland (UK by mass)	6.9–8.0
Maize	9.80	France	Romania	Hungary (Germany by mass)	3.8–8.7
Rapeseed	3.40	France	Germany	Poland	3.0–3.5
Sunflower	3.02	Romania	Bulgaria	Spain (Hungary by mass)	2.0–2.3
Spring pea	3.52	France	UK	Hungary	4.5–7.4
Sugar beet	60.02	France	Germany	Poland	73–87.3
Rye	5.01	Germany	Poland	Denmark	2.9–5.8
Others (overseas crops)					
Soybean (feed)	2.82	n.a.	n.a.	n.a.	n.a.
Oil palm	192	n.a.	n.a.	n.a.	n.a.

*wet mass, this means that all yield data refer to wet mass of the crops
Source: Own elaboration based on FAO[31] and EC.[32]

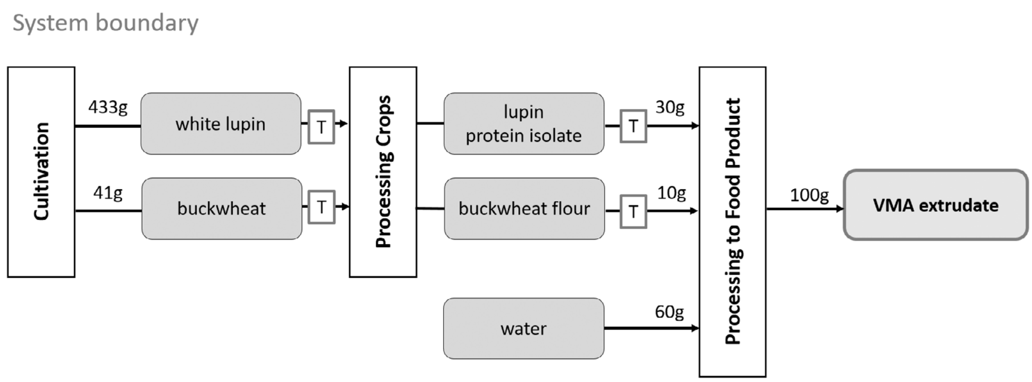

Figure 1. Process flow chart of a Protein2Food meat substitute prototype.

aspects of the food, it could be assumed that nutritional requirements are satisfied within the overall diet.[34,35] Also, mass is the most common FU in LCAs of food products.[25,35] As a sensitivity check, a mass-based and a protein-based FU were applied in the LCA, as well as an energy-based FU in the case of milk.

The core inventory data collected and applied are briefly described in the following. A table overview of key inventory data sources is also provided in the Supporting Information, Table S1.

Crop cultivation data and drying

The agricultural production of protein-rich crops as well as feed crops takes place at many different locations throughout the EU, with main producer countries varying for each crop. In the context of Protein2Food, a crop model was developed in order to reflect as much as possible the condition of major geographic regions with high production volumes of the individual crops. Table 5 shows the crops relevant to Protein2Food and the yields assumed in the LCA calculations ('model yield'). The table, furthermore, shows the three main producer countries within the EU that are taken into account and the yield ranges across Europe as provided by FAO or Eurostat, respectively. Table 6 summarizes the key cultivation parameters for the Protein2Food crops. Main data sources are primary data from field trials (field data) obtained from Protein2Food project partners as well as secondary data sources, such as crop-specific literature (see Table 6). Nitrate leaching is calculated based on the SQCB-model (sustainable quick check for biofuels) from Faist *et al.*,[41] taking into account soil clay content, rooting depth, N fertilization, N uptake by crop/residues and nitrogen in soil organic matter. Emission factors for ammonia emission from fertilizer application have been taken

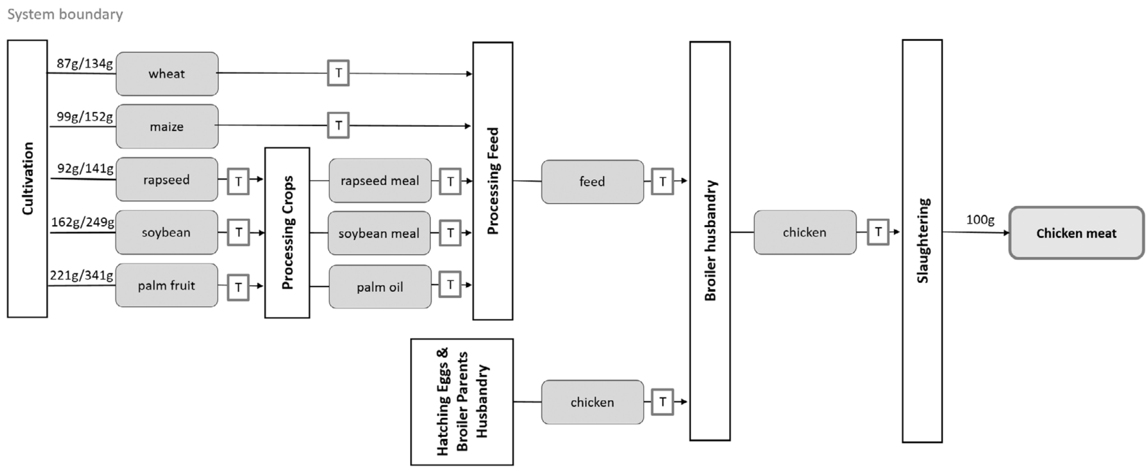

Figure 2. Process flow chart of a traditional fibre meat (chicken) product.

Table 6. Key cultivation parameters of Protein2Food crops[26,36-40]

Key cultivation parameters	Unit	Lentil	White lupin	Faba bean	Amaranth	Buckwheat	Data source
Diesel from sowing up to harvest	L ha^{-1}	12	84	53	75	84	Field data
Nitrogen fertilizer	kg N ha^{-1}	—	—	—	120	20	Field data; Kool *et al.*[36]
Potassium fertilizer	kg K_2O ha^{-1}	19	90	140	20	20	Kool *et al.*[36]; KTBL[37]; Mujica *et al.*[38]
Magnesium fertilizer	kg MgO ha^{-1}	4.8	12.5	17.5	—	—	KTBL[37]
Phosphorus fertilize	kg P_2O_5 ha^{-1}	9.6	32.5	52.5	70	20	Kool *et al.*[36]; KTBL[37]; Mujica *et al.*[38]
Pesticides	kg active ingredient ha^{-1}	1.3	1.3	1.9	0	0	Field data; KTBL[37]; Agrifootprint[33]
Crop yield (refers to water content of crop after drying)	kg ha^{-1}	800	2500	3500	1975	1026	Kool *et al.*[36]; Agrifootprint[33]; Pulvento *et al.*[26]
Water content of crop at harvest	%	20	16	17	12	20	Field data; KTBL[37]; LTZ[39]
Is the crop dried after harvest?	—	Yes	Yes	Yes	No	Yes	—
Water content of crop after drying	%	14	14	14	12	14	KTBL[37]; LTZ[39]
Nitrogen fixation	kg N ha^{-1}	91	160–180	175	—	—	KTBL41; Sulas *et al.*[40]

from Müller-Lindenlauf[42] and nitrous oxide emissions from fertilizer application and crop residues remaining on the field are calculated according to the calculation rules of IPCC.[43] Direct land use change (dLUC) was calculated with a crop-specific approach using the 20-year time horizon as recommended by PAS 2050[44] and based on statistical data published by FAO on land use change from grassland and forest area to agricultural land in the respective import countries. The drying of the crops is assumed to take place relatively close to the cultivation areas.

Crop-processing data

Conventional processing of agricultural products into feed is usually operated under industrial-scale conditions. Inventory data on processing of Protein2Food crops into protein isolates and flours, respectively, were available at laboratory or pilot scale collected by project partners. For the purpose of a 'fair' comparison of those data, they were scaled up to reflect commercial-scale operations by adjustment of process efficiencies regarding protein and flour yields as well as energy efficiency. The processing stages for Protein2Food crops into protein isolates and flours and the respective CED results are listed in the Supporting Information, Table S2. The processing of crops into feed is assumed to take place in the region of the cultivation areas, except for imported crops that are processed partly in the cultivation country and partly in Europe.

Protein foods production data

The inventories of chicken husbandry and slaughterhouse operations were taken from previous studies.[33,45-47] The inventory of milk cow husbandry and milk production were taken from Agrifootprint 2.0.[33] Inventory data on Protein2Food protein-rich extrudate, as well as vegetable milk, were available at laboratory or pilot scale collected by project partners. Those data were also scaled up to reflect commercial-scale operations by improved

Table 7. Selected categories and assigned inventory parameters as well as characterization models used in the LCA[49-53]

	Elementary flow (examples)	Unit	Characterization model
Emission-related categories			
Climate change	To air: CO_2,[a] CH_4,[b] N_2O, $C_2F_2H_4$, CF_4, CCl_4, C_2F_6, R22	kg CO_2-e FU^{-1}	IPCC[49]
Stratospheric ozone depletion	To air: CFC-11, N_2O, HBFC-123, HCFC-22, Halon-1211, methyl bromide, methyl chloride, tetrachloromethane	kg CFC-11-e FU^{-1}	WMO[50]
Photo-oxidant formation	To air: CH_4, NMVOC, benzene, formaldehyde, ethyl acetate, VOC, TOC, ethanol	kg O_3-e FU^{-1}	Carter[51]
Acidification	To air/water/soil: NO_X, NH_3, SO_2, TRS,[c] HCl, H_2S, HF	kg SO_2-e FU^{-1}	Heijungs *et al.*[52]
Terrestrial eutrophication	To air/soil: NO_X, NH_3, SO_X	kg PO_4-e FU^{-1}	Heijungs *et al.*[52]
Aquatic eutrophication	To water: COD, N, NH_{4+}, NO_3−, NO_2−, P	kg PO_4-e FU^{-1}	Heijungs *et al.*[52]
Particulate matter	To air: PM2.5, SO_2, NO_X, NH_3, NMVOC	kg PM2,5-e FU^{-1}	De Leeuw[53]
Resource-related categories at inventory level			
Land footprint	Use of agricultural area	m^2 year FU^{-1}	—
Water footprint	Blue water use	m^3 FU^{-1}	—
Cumulated energy demand (CED, total)	Hard coal, brown coal, crude oil, natural gas, uranium ore, hydro energy, solar energy, wind energy, biomass	MJ FU^{-1}	—
Cumulated energy demand (CED, non-renewable)	Hard coal, brown coal, crude oil, natural gas, uranium ore	MJ FU^{-1}	—
Cumulated energy demand (CED, renewable)	Hydro energy, solar energy, wind energy, biomass	MJ FU^{-1}	—
Use of phosphorus	Phosphorus crude ore	kg FU^{-1}	—

[a] CO_2 fossil and biogenic.
[b] CH_4 fossil and CH_4 biogenic.
[c] Total reduced sulfur.

intermediate product yields and energy efficiencies. The respective CED results are listed in the Supporting Information, Table S2. The food production represents typical European conditions and, therefore, it is located all over Europe. It is assumed that animal husbandry and slaughtering or milk production, as well as various processing steps for the plant products, are located at different production sites. For truck transport to the drying, harvest processing and food production steps, the model assumes a total transport distance of 950, 750 and 850 km for chicken meat, milk and plant products, respectively, with the exception of the imported crops, where the overseas transports are added.

Environmental impact assessment

Environmental footprints were generated by application of a set of environmental categories with related category indicators and characterization models suitable to address areas of environmental concern of the European agriculture and food sector[48] (Table 7). Characterization models were also selected with respect to the avoidance of uncertainty in characterization factors and to the completeness and availability of inventory data. The choice is also based on the German Federal Environmental Agency (UBA) approach 2016, where the available methods have been discussed and evaluated.[54] With regard to the toxicity categories, the UBA study[54] shows that the modification of individual characterization factors by the uncertainty factors documented in Rosenbaum *et al.*[55] would lead to considerable differences in the results. Therefore, the toxicity categories are not used for the derivation of substantiated comparative statements.

RESULTS

The carbon footprints of Protein2Food prototypes and those of their animal-based counterparts are shown in Figs 3 and 4. The carbon footprints of VMA extrudates (Fig. 3) refer to 100 g food product with a protein content of 30 g. Comparisons that were conducted on a mass basis show values of 235 g CO_2 equivalents and 240 g CO_2 equivalents for VMA extrudates from lupin protein combined with amaranth or buckwheat flour, respectively. The carbon footprint of the optimized vegetable VMA made from faba bean protein in combination with amaranth (variant 3) is 130 g CO_2 equivalents per 100 g food product. The corresponding carbon footprints of 100 g chicken meat are 232 g CO_2 equivalents and 342 g CO_2 equivalents for chicken breast obtained from high-performance chicken and from conventional chicken, respectively. Compared to high-performance chicken, the optimized variant has a significantly lower carbon footprint.

Interestingly, the carbon footprint of high-performance chicken is in the range of the VMA extrudates, if compared on a mass basis (left

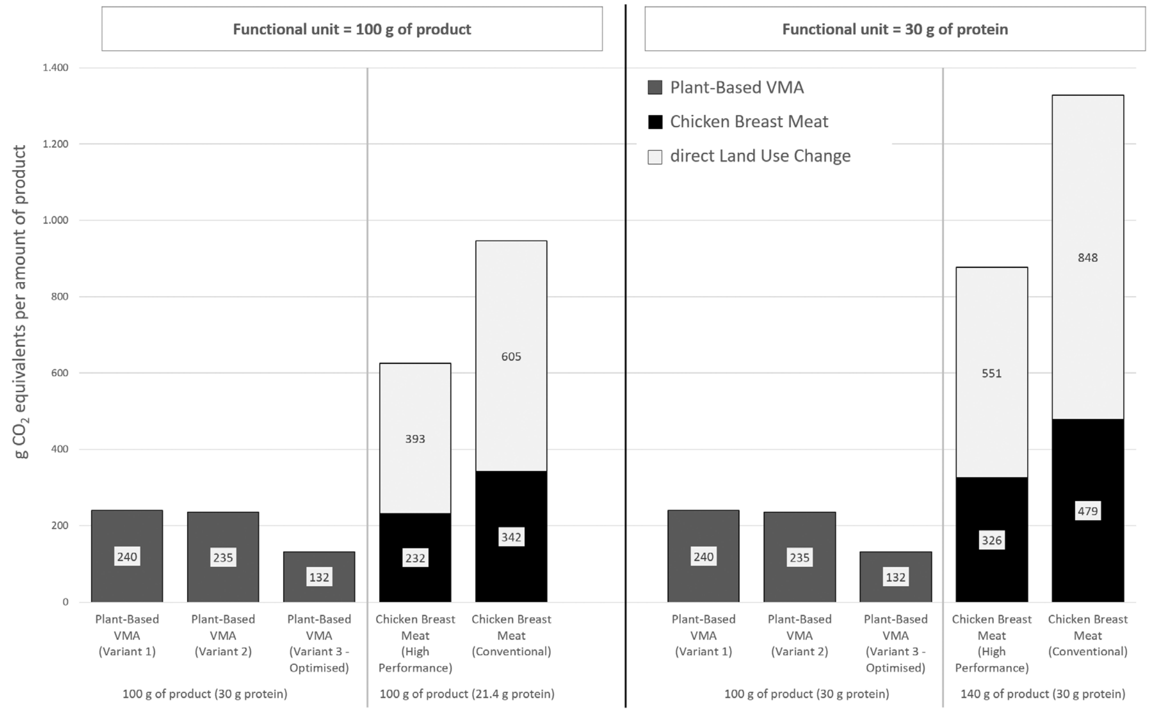

Figure 3. Carbon footprints of VMA extrudate *versus* chicken meat.

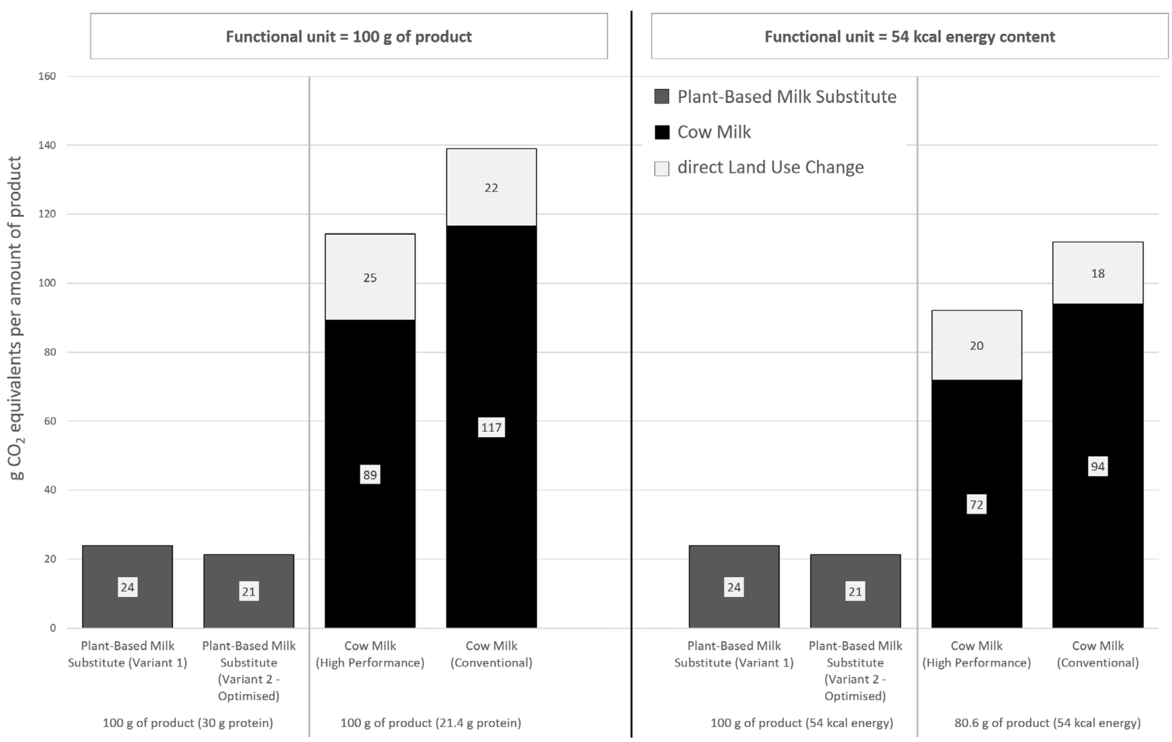

Figure 4. Carbon footprints of vegetable milk substitute *versus* cow's milk.

part of Fig. 3) but becomes somewhat larger if compared on a protein equivalence basis due to the smaller protein content of chicken breast as compared to the VMA extrudates (right part of Fig. 3). 'High-performance chicken' is typically used in highly industrialized broiler husbandry, which often implies highly adverse effects on animal welfare. Yet, when additionally considering the greenhouse gas emissions caused by direct land use change associated with soy feed from overseas (here using the example of Brazil) the carbon footprint of chicken breast is almost double to threefold of that of the VMA extrudates if compared by protein content.

In the case of cow's milk and lentil protein-based milk (Fig. 4), the differences are much more apparent. Even without accounting for

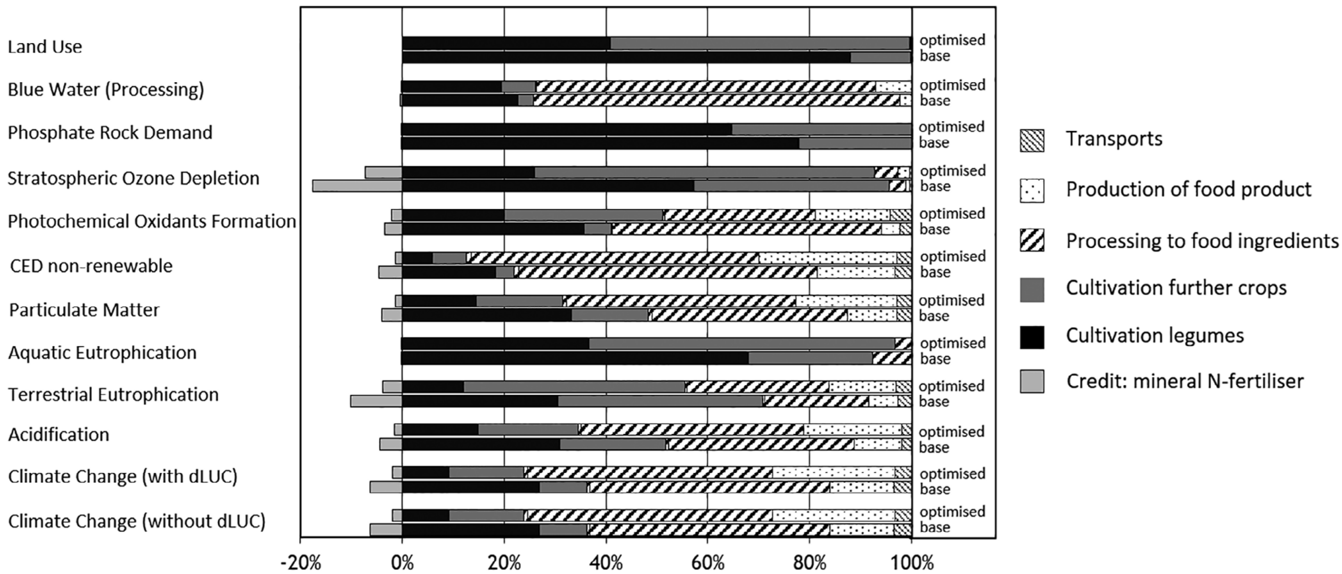

Figure 5. Contribution analysis: VMA extrudate.

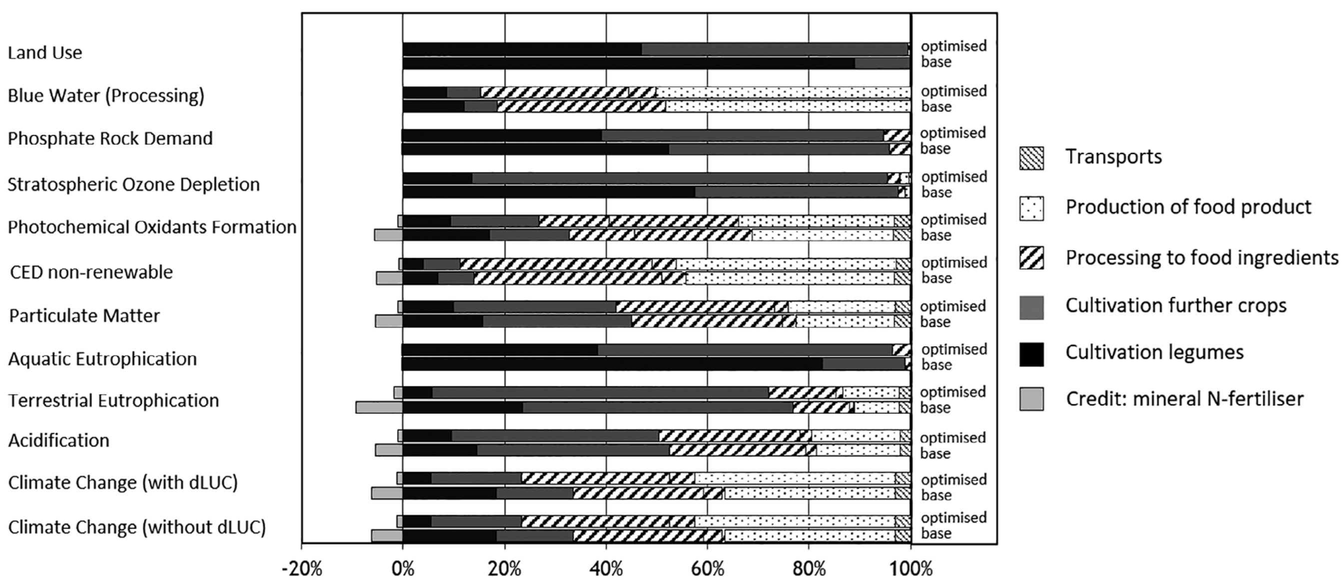

Figure 6. Contribution analysis: vegetable milk substitute.

direct land use change and when considering the energy-based functional unit, the carbon footprint of cow's milk is three times up to almost four times larger than that of the plant-based milk. Soy feed is less relevant in cow's feed as compared to chicken feed and therefore greenhouse gas emissions associated with oversea soy feed has a smaller relative impact on the carbon footprint of cow's milk.

Figures 5 and 6 show contributions of individual life cycle steps to the overall environmental profile of plant-based food products for each of the environmental indicators. Each pair of contribution bars represents the base product as well as its corresponding optimized variant product.

Contributions of processing (including processing of crops to intermediates, e.g. protein isolates, as well as production of food products) are clearly visible in most indicators. Share of processing is up to 75% (base VMA product, for non-renewable primary energy). Also, high shares for processing are observed for most air emission-related indicators with the exception of ozone depletion, where nitrous oxide from farming is of high relevance. The burdens and resources from crop processing, which include, for example, processes of drying and sorting, dehulling and milling of seeds as well as the several stages of protein extraction, are to a great extent related to energy generation. With regard to photochemical ozone formation, the production of chemicals (hydrogen chloride and sodium hydroxide) and, in the case of lupin, hexane emissions from solvent extraction also play a significant role. Further indicators, where farming stage is the

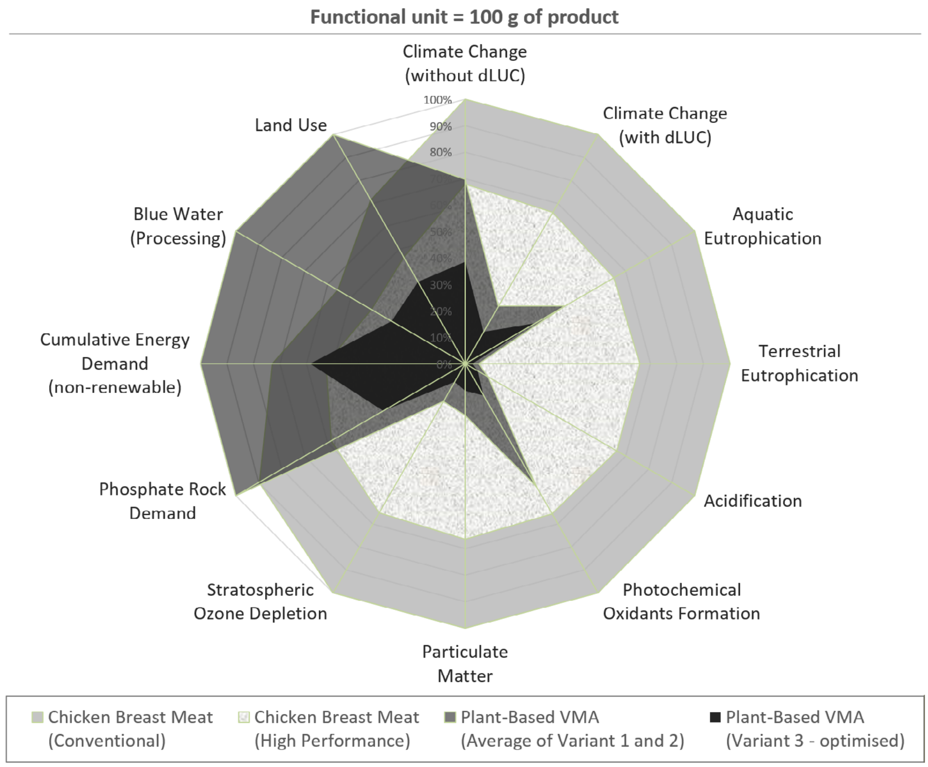

Figure 7. Environmental footprint in comparison: VMA extrudate.

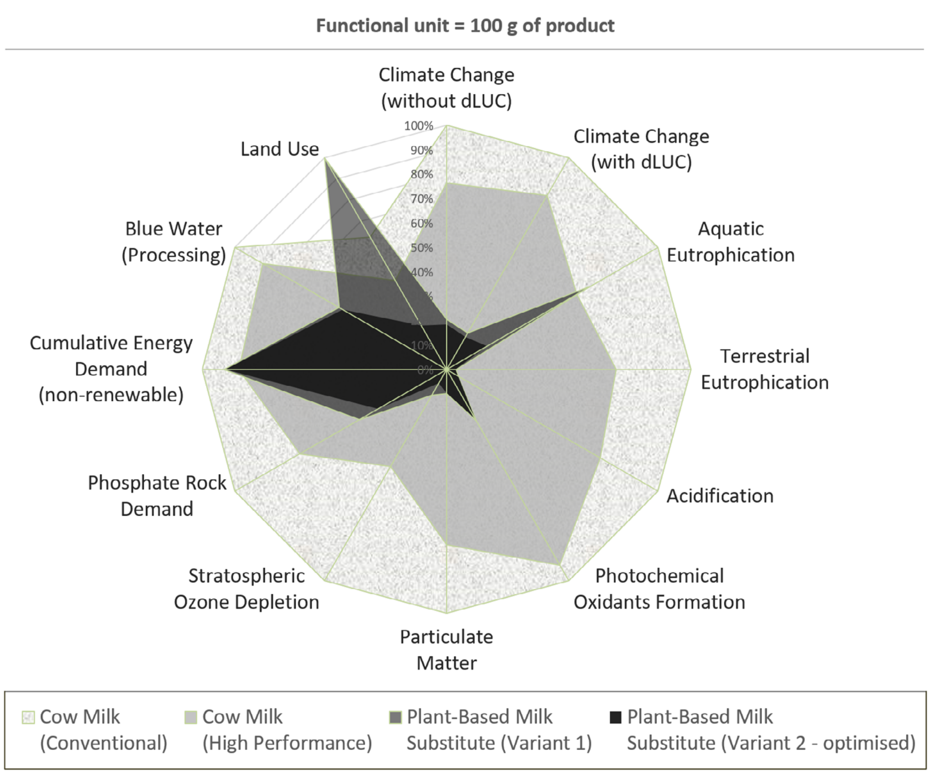

Figure 8. Environmental footprint in comparison: vegetable milk substitute.

predominant contribution, are land use, phosphate rock and aquatic eutrophication (the latter due to nitrate leaching as a result of the nitrogen cycle in the soil and above/below-ground biomass). As protein isolation modelled here is an aqueous process, processing is also the predominant life cycle step regarding blue water demand.Figures 7 and 8 show comparative environmental footprints using spider diagrams entailing 12 environmental indicators. Each diagram displays two plant-based products (base product and optimized variant) along with their reference animal-based product. Net results of all products for each indicator are provided in the Supporting Information, Tables S3 and S4.

In the spider diagrams, the worse result per indicator and variant is set to 100% and the relative better results are shown as percentages of it. The environmental footprint of plant-based VMA (base product) tends to be better than that of chicken meat for most of the indicators, with the exception of cumulative energy and process water demand as well as land use. Strongly reduced nitrogen fertilizer requirements of legume crops relative to classical feed crops are the reason for favourable results of meat substitutes in aquatic eutrophication. On the other hand, both cumulative energy and process water are associated with the several processing steps from crop to protein isolate, whereas land use is closely related to yields of protein crops. The results of the optimized variant of the plant-based VMA indicate that significant improvements in the ecological footprint of the VMA products can be achieved in all categories. As a result, the optimized variant here performs clearly better also regarding land use and process water demand than high-performance chicken.

Similarly, the environmental footprint of lentil-based milk is mostly favourable as compared to cow's milk, with land use being the single indicator showing a clear disadvantage. With regard to aquatic eutrophication, the comparative results of the milk substitute show a more differentiated picture. Lentil-based milk tends to have a lower impact when compared to conventional cow's milk, but provides an ambiguous result when compared to the more efficient cow's milk. This is explained by the relatively low crop yield per hectare for lentils and by the fact that nitrate leaching is a function of agricultural area. Thus the more cropland needed to provide the feed or food ingredients per functional unit, the more nitrate emissions from the soil occur. The optimized variants show a clear advantage due to the higher yield of faba bean, especially in the two categories aquatic eutrophication and land use. The overall advantage of the plant-based prototype is more outstanding in the case of milk. However, both plant-based prototypes still bear a substantial improvement potential that can be seen in the optimized variants.

DISCUSSION

At the time when the Protein2Food project started, most meat replacers available on retail shelves were based on quorn (mycoprotein-based protein), wheat protein (gluten) and soy protein.[56] Recently also, pea protein is increasingly being used in meat alternatives.[57]

Carbon footprints per 100 g meat replacers are reported to be 272 g CO_2 equivalents if soy meal based, 130 g CO_2 equivalents if tofu based and 390 g CO_2 equivalents for minced soy.[25,58,59] 238 g CO_2 equivalents (cradle to factory gate) was reported for 100 g of a meat replacer from isolated pea protein.[57] A meat replacer using potato and soy protein accounted for 347 g CO_2 equivalents per 100 g (cradle to factory gate),[60] while wheat gluten-based meat replacer was calculated to generate 381 g CO_2 equivalents per 100 g.[29]

For the soy-based meat replacers it is unclear from the information provided in the cited literature to what extent they contain highly processed concentrated and/or isolated proteins. It also remains unclear whether direct land use change was considered in the cited carbon footprints of soy products. Overall, the lupin-based meat replacer prototypes developed within Protein2Food are well within the lower range of the carbon footprints reported for meat replacers based on soy (excluding the more mildly processed tofu) and pea proteins.

Plant-based milk alternatives can be made from five plant categories: legume based (e.g. soy, pea, lentils), cereal based (e.g. oat, rice), pseudocereal based (e.g. quinoa, amaranth, buckwheat), nut based (e.g. almonds) and seed based (e.g. hemp, linseed). Of the examples mentioned, only the milk alternatives made from soy, pea and lentil proteins have protein content comparable to that of cow's milk.[61]

Carbon footprints per 100 g milk alternative are reported to range between 22 and 51 g CO_2 equivalents for soy-based drinks[58,62-64] and 61 g CO_2 equivalents for a pea-based drink.[65] The carbon footprint calculated for the lentil-based prototype developed within Protein2Food is at the lower end of the numbers reported for protein-rich milk alternatives.

The LCA results of Protein2Food prototypes rely on assumptions regarding process efficiencies along the value chain and the achievable economic value of by-products from crop processing. Yet the assumptions were backed by expert judgments from participating small and medium-sized enterprises, among others, thereby limiting uncertainty substantially. In fact, the results presented here indicate that Protein2Food meat replacers and milk alternatives made from protein crops other than soy and pea may have similar environmental profiles to those.

It is also worth mentioning that, from a food producer's perspective, lentil proteins are promising raw materials for forming a potential future platform for the production of plant-based dairy alternatives. On the other hand, from a farmer's perspective, beans are preferred because they are easier to grow, and have rather steady, generally higher, yield levels.[26] The use of faba beans as a further crop source is examined in the Protein2Food prototypes in the form of LCA optimization scenarios. The faba bean-based meat replacers thus also provide insight into variability in the agricultural phase, as they represent a high-yield legume crop as protein source. Hence results related to 'variant 1' meat replacers and 'variant 3' replacers do cover agricultural variability in terms of legume yields in a range from 0.8 to 3.5 t ha^{-1} (for lentil and faba bean, respectively, see also Table 6). Similar trends are expected for yield variations within the same crop.

Cultivation of faba beans in those optimized scenarios *versus* lentil and lupin thus here also represents sensitivity analysis regarding the agricultural production phase. With faba bean being a legume crop showing a rather high yield potential (within legume crops), it also reflects a rather 'efficient' legume crop cultivation, e.g. in terms of land required per crop unit, overall fertilizer amount per crop unit. Results indicate that increasing of legume crop yields and use of high-yield legume crops as protein sources for plant-based meat substitutes and vegetable milk alternatives are very promising from an environmental perspective. The optimized meat substitute prototype (variant 3) in particular shows this potential, as it has a significantly lower carbon and further environmental footprint compared to high-performance chickens.

Overall, the optimized product variants indicate that the environmental footprints of Protein2Food prototypes could further benefit from legumes with high field yields.

CONCLUSIONS

Global food production represents the largest pressure caused by humans on Earth and it is clear that the transition to sustainable food systems will not occur without a shift in people's diets.[66] Despite both the health and environmental benefits, changing consumer preferences towards a diet containing low/no animal food is extremely difficult[67,68] and the global average per capita rate of animal product consumption has continued to increase.[69,70]

In western countries, however, vegetarianism and reduced meat diets are increasing, and in recent years plant-based meat substitutes have experienced unprecedented growth.[71,72] New processing techniques have allowed the development of better performing products in terms of taste and texture and the use of a broader range of raw materials.[73]

Plant-based proteins already play an important role in satisfying future protein demand and, overall, cereal proteins account for most of the dietary plant protein intake globally.[15] But food products obtained by using a blend of cereal and pulses can balance the amino acids and may improve the nutritive value of plant-based protein foods.[3]

The Protein2Food project showed that prototypes made from European-grown legumes and pseudocereals are a valuable source for high-quality protein foods and, despite being substantially processed, such food could help reduce the environmental impact of food consumption, especially when replacing cow's milk-based food products. When replacing chicken, the future aim should be to further reduce energy demand of the processing stage (as commercial production matures) as well as optimize legume farming towards higher and stable yields. This confirms that increasing the proportion of vegetable proteins and decreasing those of animal origin in the human diet is a win–win situation from both environmental and nutritional standpoints.[8] Future research should also be directed towards yield variations in legume farming, also depending on the type of crop management (organic *vs*. conventional, tillage practices), the degree of irrigation and regarding its implications for water and energy requirements.

The need for increased consumption of legume-based proteins is challenged by the fact that the area of protein crops in Europe declined almost continuously over the last five decades, from 4.7% of the arable area to about 1.5% of the arable area,[26] despite their agronomic and environmental benefits. A major underlying driver behind the reduction in the proportion of arable land used for protein crops is the increased comparative advantage in the production of starch-rich cereals in Europe over the production of protein-rich grain legumes.[68] Protein crops suffer from yield instability compared to cereals or rapeseeds, and yield fluctuations are one of the main reasons farmers give for not growing these crops.[26] The latter is a major obstacle in further expansion that urgently needs to be overcome and should be a main target for improving protein crop production. It would be important here that a further expansion of the area under protein crops does not lead to direct or indirect land use changes or potential water scarcity[48] but to a diversification of crop rotations.

Development of higher processed and therefore higher performing products is crucial for appealing to potential user groups beyond dedicated vegetarians and vegans and ultimately achieving market expansion.[72] However, due to the high contribution of food processing to the environmental footprint, even with optimized processing, the highly processed plant-based meat and milk replacer foods are expected still to have a higher environmental impact than less processed products. Therefore, mildly processed protein crops such as cooked grain legumes should also be examined regarding their environmental performance in future research in order to identify if those are a suitable permanent component of diets as sources of low-cost dietary proteins for human consumption with a low-impact environmental profile.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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