Research Article

Received: 31 October 2020 Revised: 13 September 2021 Accepted article published: 17 November 2021 Published online in Wiley Online Library: 3 December 2021

(wileyonlinelibrary.com) DOI 10.1002/jsfa.11655

Life cycle assessment of animal-based foods and plant-based protein-rich alternatives: a socio-economic perspective

Consuelo Varela-Ortega,[a,b] Irene Blanco-Gutiérrez,[a,b*] Rhys Manners[c] and Andreas Detzel[d]

Abstract

BACKGROUND: Extensive research shows that replacing animal protein with plant-based protein in the diet would strongly alleviate the environmental impact of the food system. However, much less attention has been given to the socio-economic considerations of dietary transitions. This study analyses the socio-economic performance of innovative legume-based food prototypes, developed in the Protein2Food research project, and conventional animal-based products (chicken meat and dairy milk). We implement a social life cycle assessment (sLCA) to quantify and compare their potential socio-economic impacts along the entire life cycle.

RESULTS: Findings from this analysis show that legume-based prototypes and their respective animal-based counterparts have, overall, a comparable socio-economic performance. Looking at the disaggregated life cycle stages, socio-economic hotspots (points of most negative impacts) were mainly identified at the production stage in legume-based products. Farm-level net margin and profitability are low when compared with their animal equivalents. However, at the processing stage, there are socio-economic gains for plant-based products regarding lower unemployment rates. Finally, at the consumption stage, there are mixed results. Plant-based products show worse protein affordability but better nutritional contents (lower saturated fat and cholesterol) than their animal counterparts.

CONCLUSIONS: To improve socio-economic performance of legume-based foods, greater emphasis should be placed upon developing improved processing technologies and supply chains. This would broaden the supply of sustainable protein-rich food options and make these products more economically attractive. The research illustrates that policies should be targeted to the different stages of the food value chain to optimize the development of innovative plant-based foods.

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

Keywords: protein transition; innovation; plant-based meat substitutes; social life cycle assessment; sustainability

INTRODUCTION

Global consumption and production of animal-based products has increased over recent decades,[1] and further increases are expected in the future.[2,3] These increases have been linked to the degradation of terrestrial, aquatic and climatic systems,[4-6] and to increased prevalence of non-communicable diseases (NCDs) (e.g., coronary heart disease, diabetes and cancer).[7,8] These impacts have led to these dietary trends being described as unsustainable and encouraged an increasingly vocal debate calling for transitions away from these products.[9,10]

The growing body of literature calling for these transitions outlines the potential of replacing animal-based products with plant-based products.[9,11] Research suggests that adoption of diverse and largely plant-based diets could reduce dietary-based emissions, reduce agriculturally driven environmental degradation, supply adequate calories for growing global populations and avert diet-related avoidable deaths.[12-14]

* Correspondence to: I Blanco-Gutiérrez. Department of Agricultural Economics, Statistics and Business Management, ETSIAAB, Universidad Politécnica de Madrid (UPM), Campus Ciudad Universitaria, Av. Puerta de Hierro 2-4, 28040 Madrid, Spain. E-mail: irene.blanco@upm.es

a Department of Agricultural Economics, Statistics and Business Management, ETSIAAB, Universidad Politécnica de Madrid (UPM), Campus Ciudad Universitaria, Madrid, Spain

b CEIGRAM, Universidad Politécnica de Madrid (UPM), Madrid, Spain

c International Institute of Tropical Agriculture (IITA), Kigali, Rwanda

d Institut für Energie- und Umweltforschung Heidelberg (IFEU), Heidelberg, Germany

The benefits generated from plant-based diets are being noted beyond the scientific community, with European consumers shifting towards more plant-based foods.[15] As a consequence, the plant-based food market in the European Union (EU), largely based on legume-based products, is undergoing unprecedented growth,[16] some of which may be associated with increased information reaching consumers about the environmental and health benefits of consuming plant-based products.[17,18]

Extensive environmental research and life cycle assessments have demonstrated the environmental benefits of dietary transitions, with legume-based products being more climate friendly and resource efficient compared to animal-based equivalents (e.g., they generate less greenhouse gas emissions, and require less N fertilizer, land and water resources).[19,20] However, the intense focus on the environmental impacts has been to the detriment of socio-economic considerations of dietary transitions (impacts on farm income, wages and salaries, employment, consumers' affordability, etc.).[21] Although some studies have addressed consumers' perceptions and intentions towards the substitution of animal-based products using legumes and protein-rich crops,[18,22,23] little or no attention has been paid to the direct social and economic impact of such replacements.[24]

The present study addresses this research gap by generating information on the socio-economic impacts of animal-based alternatives based on legumes. We implement a social life cycle assessment (sLCA) to quantify the potential impacts generated by food products during all stages of their life cycles (i.e., from farm to fork). Specifically, we analyse the performance of two new plant-based prototypes (lupin-based meat and lentil-based milk), developed in the EU research project Protein2Food (P2F) ('Development of high-quality food protein through sustainable production and processing', No. 635727-2, Horizon 2020 Framework Programme, EU Commission), and compare them with two conventional animal-based counterparts (chicken meat and dairy milk). This study complements the study of Detzel et al.,[25] in which the same food products are analysed from an environmental perspective using an environmental life cycle assessment (eLCA). Both the sLCA and eLCA analyses focus on the European market (EU 28); i.e., all life cycle steps take place within Europe.

Ultimately, the present study aims to provide relevant information to policymakers, businesses, producers, consumers and other stakeholders about socio-economic hotspots and optimization potential in the development and production of innovative plant-based foods. It therefore helps to provide an integrated evaluation of innovative products of plant origin, facilitating better informed decisions about EU plant-based choices.

METHODOLOGY: SOCIAL LIFE CYCLE ASSESSMENT (SLCA)

The 'social life cycle assessment' (sLCA) methodology evaluates the potential socio-economic impacts of a product during its lifetime.[26] Developed in the 2000s, under the methodological framework of life cycle thinking (LCT), sLCA is considered one of the best tools to complement environmental life cycle assessments (eLCA) – the most popular LCT method.[27] sLCA evaluates the performance of products using social and economic indicators classified across stakeholder categories. Stakeholder categories represent groups of social agents potentially impacted by the production of a specific product, and form the basis of a sLCA.[26]

The sLCA method is constantly being refined and has yet to be developed to parallel the eLCA. The availability of databases and indicators for sLCA analyses is still limited compared to eLCA.[28] Due to the complexity of social issues, diverging sLCA approaches are available.[29] The most recognized approach is the 'sLCA Guidelines', established by the UNEP-SETAC Life Cycle Initiative[30] and recently updated.[31] A standardized methodology (like eLCA) has yet to be developed, limiting widespread implementation.[32] However, sLCA is being increasingly applied and used across sectors, particularly in the food sector (e.g., Chen et al.[33] on milk, Petti et al.[34] on tomato, Kruse et al.[35] on salmon and or Feschet et al.[36] on banana).

The methodology applied in this study follows the rules and processes described in the sLCA guidelines,[30] but adapted to the context of the study. The sLCA has been conducted separately but in parallel with the eLCA performed in P2F,[20,25] to provide a coherent and comprehensive assessment of food products in the project. It follows three consecutive phases: scope definition, inventory analysis and impact assessment.

Scope definition

This phase is critical in any sLCA as it includes the definition of the functional unit and system boundaries.[37]

In the present study, and following the eLCA developed in P2F,[20,25] the functional unit is a mass-based unit that corresponds to 100 g of product. This amount is used as reference to directly compare the social and economic impact of one food product with another.

The system boundaries include the identification of the product's life cycle stages, affected stakeholder groups and impact categories. These boundaries set the limits within which socio-economic indicators are identified and are commonly used to summarize results.

The life cycle of food products has been represented through the three main stages of the agri-food chain, following Martínez-Blanco et al.[32] and Sala et al.:[38] *production* that is related to crop and animal production at farm level; *processing* representing all processes performed by the food industry and distributors; and *consumption*, which extends from the moment of purchase until the product is finally consumed.

The identification of stakeholders was based on the sLCA guidelines[30] and Revéret et al.,[39] taking into account the life cycle stages previously defined. In total, five stakeholder categories have been selected: *agricultural workers*, who are employees that work in farms or holdings engaged in the production of agricultural and livestock products; *processing and retail workers*, who are employees working in the processing and retail sectors; *farmers*, representing owners of agricultural and livestock holdings (mainly family-owned farms); *consumers*, who are the people that buy the products for personal use; and *society*, which refers to the aggregate of people, institutions and interest groups that share customs, laws and acknowledged social values.

Impact categories represent significant social and economic themes to be assessed through the use of indicators.[30] For their selection, we used a combined top-down and bottom-up approach, integrating internationally recognized categories and the perspectives of affected stakeholders.[35,40] We reviewed the impact categories proposed in ISO standards, in particular the sLCA guidelines,[30] with regard to their applicability in the context of the study. We also made use of P2F stakeholder consultation to identify key socio-economic issues directly related to the production of protein-rich food products, as well as potentially affected stakeholder groups. Stakeholders were consulted during the second annual meeting of the P2F project held in Caserta (Italy) in May 2017. This meeting was attended by 38 P2F partners and 12 EU stakeholders, namely representatives of farmers' associations, food processors and distributors, research institutions, non-profit consumers' groups and environmental organizations.[41] The combined top-down and bottom-up approach enabled the identification of 13 impact categories: fair salary, hours of work, equal opportunities/discrimination, health and safety, contribution to farm income, economic security, management attributes, contribution to economic development, contribution to food security, commitment to sustainability issues, choice, product features relevant for consumers and contribution to protein affordability.

Inventory analysis

Inventory analysis refers to the selection of socio-economic indicators and the collection of data and, therefore, is one of the most crucial and complicated steps in an sLCA.

Initially, socio-economic indicators were shortlisted following the combined top-down/bottom-up approach previously defined. The top-down method (revision of sLCA guidelines) was used to obtain 'generic' indicators, while the bottom-up approach (stakeholder consultation) served to identify 'tailored' (context-specific) indicators. Shortlisted indicators were then revised with respect to data availability (known as 'system refinement'),[42] with a final list of indicators selected. In total, 28 socio-economic indicators were evaluated (Table 1). These indicators are aggregated into impact categories, which are further aggregated into stakeholder categories and life cycle stages.

The main source of information used to populate the general indicators is the Social Hotspot Database (SHDB).[43] This database provides models of supply chains by country-specific sectors and compiles information on different social indicators issued by governments and international organizations (e.g., International

Table 1. List of socio-economic indicators applied in sLCA

Stage	Stake holder	Impact category	Indicator
Production	Agricultural workers	Fair salary	Average wage (AW) below non-poverty guideline (NPL)[a] (semi-quantitative score: 1 for NPL > AW by >50%; 2 for NPL > AW by 25–50%; 3 for NPL > AW by <25%; 4 for NPL < AW)
			Average wage (AW) below minimum wage (MW)[a] (semi-quantitative score: 1 for MW > AW by >25%; 2 for MW > AW by 0–25%; 3 for MW < AW by <25%; 4 for MW < AW by >25%)
		Hours of work	Share of employees working more than 48 h/week (%)[a]
		Discrimination	Share of women in the labour force (%)[a]
		Health and safety	Fatal injuries at workplace (no. of cases per 100 000 workers)[a]
			Non-fatal injuries at workplace (no. of cases per 100 000 workers)[a]
		Unemployment	Unemployment rate (€)[a]
		Labour laws	Laws enacted to protect sector specific workers (no.)[a]
	Farmers	Contribution to farm income	Profitability ratio (output/input) (%)[b]
			Net margin (output − input) (€000)[b]
			Share of voluntary coupled support from the direct payment budget of the EU Common Agricultural Policy (%)[b]
		Economic security	Yield variability (relative standard deviation) (%)[b]
			Production price variability (relative standard deviation) (%)[b]
	Society	Contribution to food security	Protein security (kg protein ha^{-1})[b]
Processing	Processing and retail workers	Fair salary	Average wage (AW) below non-poverty guideline (NPL)[a] (semi-quantitative score: 1 for NPL > AW by >50%; 2 for NPL > AW by 25–50%; 3 for NPL > AW by <25%; 4 for NPL < AW)
			Average wage (AW) below minimum wage (MW)[a] (semi-quantitative score: 1 for MW > AW by >25%; 2 for MW > AW by 0–25%; 3 for MW < AW by <25%; 4 for MW < AW by >25%)
		Hours of work	Share of employees working more than 48 h/week (%)[a]
		Equal opportunities	Share of women in the labour force (%)[a]
		Health and safety	Fatal injuries at workplace (no. of cases per 100 000 workers)[a]
			Non-fatal injuries at workplace (no. of cases per 100 000 workers)[a]
		Unemployment	Unemployment rate (€)[a]
		Labour laws	Laws enacted to protect sector specific workers (no.)[a]
Consumption	Consumer	Product features relevant for consumers	Saturated fat content (g 100 g^{-1} of product)[b]
			Fibre content (g 100 g^{-1} of product)[b]
			Vitamin content (g 100 g^{-1} of product)[b]
			Cholesterol content (g 100 g^{-1} of product)[b]
			Protein content (g 100 g^{-1} of product)[b]
	Society	Contribution to food security	Protein affordability (€ kg^{-1} protein)[b]

[a] Generic indicators.
[b] Tailored indicators.

Labour Organization, World Health Organization, World Bank). Regarding tailored indicators, a variety of data sources has been used. Data relating to farms' economic factors (profitability and net margin) were obtained from the European Farm Accountancy Data Network. Information on Common Agricultural Policy (CAP) voluntary coupled support was taken from EU Commission documents.[44,45] Yield and price data (from 2003 to 2016) were obtained from FAOStat to calculate yield and production price variability.[46] FAO Balance Sheets[46] and IFEU (Institut für Energie- und Umweltforschung)[47] were used to calculate protein yields as a proxy of contribution to protein security. Data concerning protein content and other nutritional values (such as vitamin, fibre, saturated fat, and cholesterol content) were obtained from the food composition table of the French Agency for Food, Environmental Health and Safety (ANSES)[48] and P2F reports.[49,50] Finally, prices of vegetable- and animal-based products, used to calculate protein affordability, have been obtained from IVV (Fraunhofer-Institut für Verfahrenstechnik und Verpackung),[49] UCC (University College Cork)[50] and supermarkets' web sites.[51,52]

Impact assessment

The assessment phase is where the sLCA methodology is applied and, consequently, where results are shown for each product.

In the present study, the assessment is done first at the ingredient level. All ingredients of a product are evaluated according to selected indicators (Table 1). Then, by considering the composition of the product and the weight of the ingredients (as a percentage) per functional unit, a weighted average value is derived for each indicator for the product being assessed.

Finally, following UNEP-SETAC,[30] each indicator is classified into four performance categories defined as: good performance (green); medium performance (yellow); upgradeable performance (orange); and bad performance (red). In the case of 'generic' indicators, the performance categories were delimited using the SHDB's thresholds. For 'tailored' indicators, thresholds were established according to the 25% deviation model (i.e., adding, up and down, a 25% deviation from the average), which is widely used in the SHDB. The evaluation scale, with the thresholds chosen for each performance category and each indicator, is shown in Table 2.

Following Carmo et al.,[53] all indicators are assumed to have the same weight. Thus, by simply averaging the performance score of each indicator (good performance indicators were assigned a numerical score of 1; medium performance indicators 2; upgradeable performance indicators 3; and bad performance indicators 4), aggregated results were obtained at the level of stakeholder category and overall food product.

Final scores give an idea of the overall performance of a product but cannot be used to categorically declare some food products as superior to others. In line with UNEP's approach, this study focuses on gaining an understanding of what are the most important differences between products, and at which point in the life cycles these differences are located. It thus helps to identify areas where policy interventions might be worth discussing and thereby may contribute to achieve more effective policies.

RESULTS

The socio-economic performance of selected food products is shown in Figs 1 and 2, according to the evaluation scale described in Table 2 (1: good performance; 2: medium performance; 3: upgradeable performance; and 4: bad performance). Figure 1 displays aggregate results by stakeholder category, life cycle stage and food product, while Fig. 2 shows disaggregate results at indicator level depicted in a radar-type layout. Figure 2(a) compares

Table 2. Evaluation scales by indicator

	Evaluation scale			
Indicator	Bad performance	Upgradeable performance	Medium performance	Good performance
Average wage (AW) being lower than non-poverty guideline (NPL) (No units)	<1.75	1.75–2.5	2.5–3.25	>3.25
Average wage (AW) being lower than minimum wage (MW) (no units)	<1.75	1.75–2.5	2.5–3.25	>3.25
Excessive working time (%)	>50	25–50	10–25	<10
Gender equality (%)	<10	10–20	20–33	>33
Fatal injuries (no.)	>10	5–10	1–5	<1
Non-fatal injuries (no.)	>2000	500–2000	100–500	<100
Unemployment (%)	>1	0.5–1	0.1–0.5	<0.1
Labour laws (no.)	0	1	2	>2
Profitability (%)	<100	100–105	105–110	>110
Net Margin (€000)	0	0–5	5–10	>10
CAP coupled support (%)	>1	1–10	10–20	>20
Yield variability (%)	>13	11–13	8–11	<8
Price variability (%)	>32	25–32	19–25	<19
Protein security (kg ha^{-1})	<244	244–348	348–453	>453
Saturated fat content (g 100 g^{-1})	>1.9	1.5–1.9	1.1–1.5	<1.1
Fibre content (g 100^{-1})	<3.5	3.5–4.5	4.5–6	>6
Vitamin content (g 100^{-1})	<8	8–14	11–14	>14
Cholesterol content (g 100^{-1})	>39	31–39	23–31	<23
Protein content (g 100^{-1})	<5	5–9	9–13	>13
Protein affordability (€ kg^{-1})	>74	59–74	44–59	<44

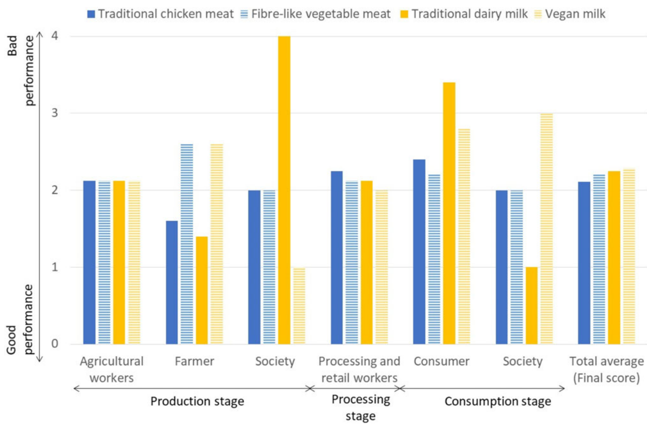

Figure 1. Socio-economic performance of food products by stakeholder category and life cycle stage.

P2F fibre-like vegetable meat (lupin-based meat alternative) with traditional chicken meat, and Fig. 2(b) compares P2F prototype vegan milk (lentil-based milk alternative) with traditional dairy milk. Numerical values for each ingredient are included in the Supporting Information (Tables S1–S4).

Results show that differences over final scores are very subtle, and the four products analysed could all be classified as having a medium-upgradeable socio-economic performance. The aggregate final score for P2F fibre-like vegetable meat is 2.21, for traditional chicken meat 2.1, for P2F prototype vegan milk 2.3 and for traditional dairy milk 2.25 (Fig. 1 and Tables S1–S4 in the Supporting Information). These numbers must be interpreted carefully, considering that they only refer to socio-economic impacts, and that indicators do not necessarily have to have the same weight and importance for society and the economy. Also, the data presented rely on a variety of assumptions, and thus the final score should not be taken as an absolute result but rather as a tool of comparison.

When looking at the more detailed results by stakeholder category and indicator level (Figs 1 and 2), the analysis shows that there are clearly distinct socio-economic differences among products. These differences are more noticeable between vegan and traditional milk products than between vegan and traditional meat products, in part due to the more complex ingredient composition of the P2F prototype vegan milk. Also, they are more evident at the production and consumption stage, where tailored indicators are considered, and therefore a more detailed discrimination between alternatives can be achieved.

At the production stage, the performance of P2F prototypes and traditional counterparts varies greatly at the farmer and society levels (Fig. 1). Farmers face less favourable conditions in the case of vegetable products than in the case of animal-based products, measured by the contribution to farm income and economic security. As seen in Fig. 2, the indicators 'profitability' and 'net margin' have medium and upgradeable performances, respectively, for vegetable products, whereas their performance is good in the case of their traditional counterparts. This can be explained by the profitable margins of intensive and semi-intensive production systems operating in livestock production, particularly in poultry meat. Furthermore, the results for 'yield variability' and, to a lesser extent, 'production price variability' are worse in vegetable products because they have larger production and market risks than their animal-based alternatives. The 'CAP voluntary coupled support' presents contrasting results. Dairy milk products have a good performance because they receive significant coupled support payments (more than 20% of the total coupled aid in the EU). In contrast, chicken meat has null support (it is not an eligible sector), and therefore it presents a bad performance. Vegetable products show an upgradeable performance, due to the limited amount of coupled support payments that protein crops and grain legumes have currently received from the CAP (10.88% of the total coupled aid), justified by their environmental benefits (e.g., nitrogen-fixing capacity). Finally, at society level, differences between products can only be appreciated in the case of milk. 'Protein security' has a good performance in vegetable-based milk, while it shows a bad performance in dairy milk. This is because lentils, sunflower seeds and sugar beet (ingredients of vegetable-based milk) have a higher protein content (kilograms of protein per kilogram of product) than milk and, in the case of sugar beet, very high yields (up to 80 t ha^{-1} and year between 2003 and 2016), which translates into high protein yields.

The processing stage shows a slightly better overall picture for vegetable products regarding fair salary ('average wage being lower than non-poverty guideline'), health and safety ('non-fatal injuries') and 'unemployment' (Figs 1 and 2). The largest differences are found for processing and retail workers in relation to unemployment. In the case of both meat and milk, vegetable products show lower unemployment rates (medium performance) than their traditional counterparts (upgradeable performance). Moreover, regarding fair salary, vegetable meat has a better performance (good) than chicken meat (medium). This is because plant-based products require more processing than traditional meat products and their manufacturing industry is growing rapidly, providing new opportunities and better employment conditions for processing and retail workers. In the case of milk, differences can also be perceived for the indicator of non-fatal injuries. This indicator shows bad performance for dairy milk and upgradeable performance for vegan milk, partly due to recent investments in new and safer food-processing equipment needed to use many different plant-based ingredients. The only indicator in which plant-based products perform worse than animal-based products is labour laws. This can be explained by the fact that animal-based products are more regulated, and therefore show a better performance (medium) than vegetable products (upgradeable) with regard to labour laws.

At the consumption stage, we can observe clear differences between animal-based and plant-based products for consumers and, to a lesser extent, for society (Fig. 1). In general, consumers are positively affected by plant-based products, regarding 'saturated fat', 'fibre', 'cholesterol' and 'protein' content (Fig. 2, and Tables S1–S4 in Supporting Information). The amount of saturated fat and cholesterol in vegetable meat and milk is lower compared to chicken meat and dairy milk. Thus, while the performance of saturated fat and cholesterol is good for vegetable products, it is bad for dairy milk and chicken meat. Differences in fibre and protein content are less noticeable. Fibre content is very low in all products (only slightly so in vegetable meat). Protein content is high in meat, but low in milk, being slightly higher for plant-based products. The only product characteristic relevant for consumers that performs worse in vegetable products than in animal products is 'vitamin content', mainly because buckwheat flour and lupin protein isolate are poor in vitamins. Finally, at society level, vegetable products show worse performance than their traditional counterparts. Protein affordability is assessed as having

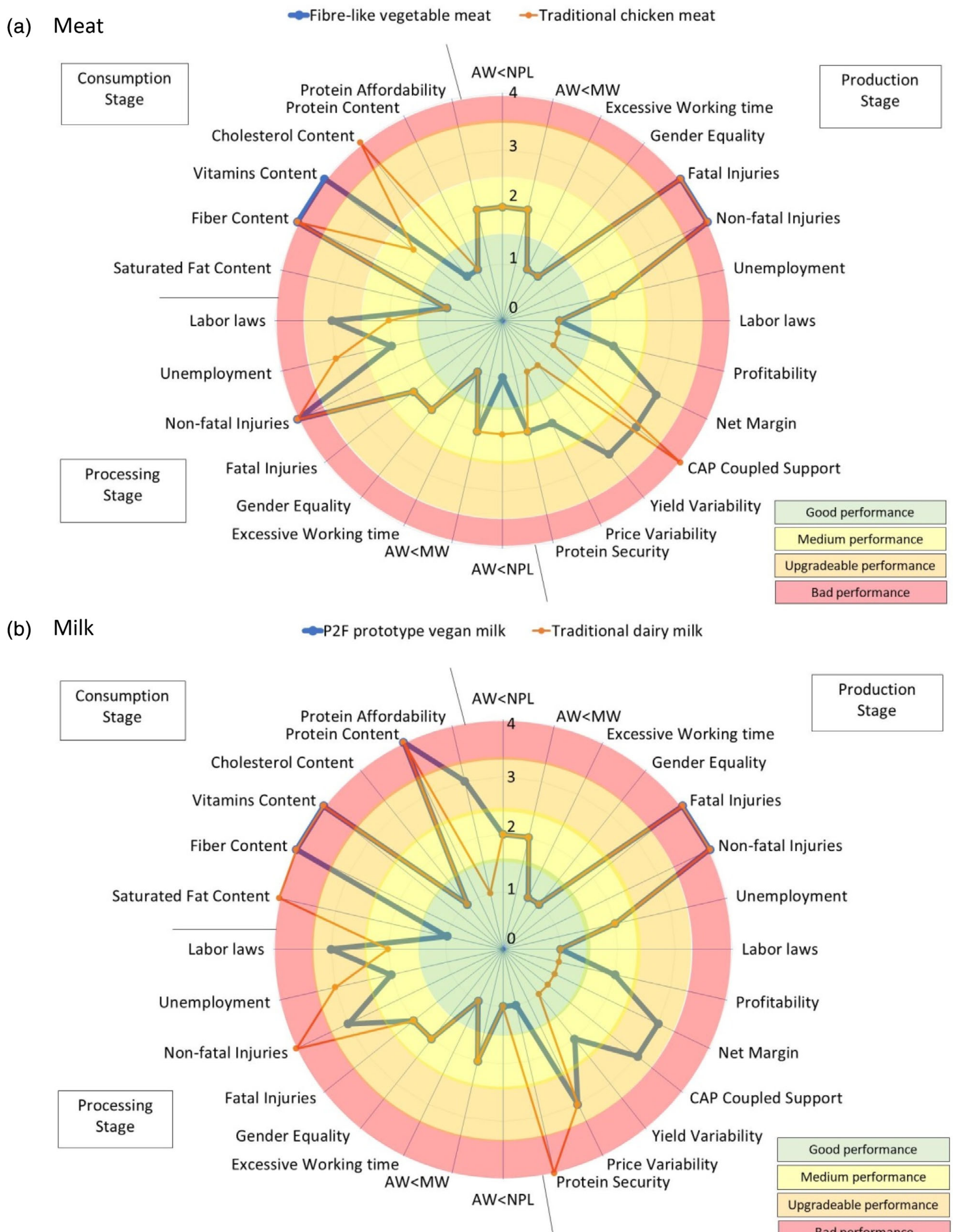

Figure 2. Socio-economic performance of food products specified at indicator level. The centre of the radar, in green, indicates a good indicator performance (scored 1), while the outer circle of the radar, in red, denotes a bad indicator performance (scored 4). Thus, performance gets worse as we move from the inside to the outside of the radar on a scale of 1–4 (i.e., the higher score the worse the performance). AW< MW is average wage being lower than country's minimum wage, and AW< NPL is average wage being lower than non-poverty line.

upgradeable performance for vegan milk, medium performance for meat (vegetable and chicken meat) and good performance for dairy milk. This is because the price of protein is higher in plant-based products (€55.4 and €68.2 € kg^{-1} protein for vegan meat and milk, respectively, *versus* €46.7 and €31.6 kg^{-1} protein, for chicken and dairy milk, respectively), which results in a worse 'protein affordability', especially in the case of milk.

DISCUSSION

We developed an sLCA to analyse the socio-economic impacts related to the life cycle activities of plant-based and animal-based protein-rich products, with the aim of providing a better understanding of the socio-economic advantages and disadvantages of both types of products. Using a set of meaningful indicators, we calculated and displayed the socio-economic profiles of two innovative vegetable products (lupin-based vegetable meat and lentil-based vegetable milk, developed and tested in the course of the P2F project), and compared them with two conventional animal-based counterparts (chicken meat and dairy milk).

In line with other sLCA studies, the main limitation encountered in this study has been the very large amount of time necessary to collect consistent data and information to ensure proper availability, quality and comparability of the data.[29] The analysis has been performed with reliable data, but some uncertainty is assumed.

Our findings reveal that plant-based products and their animal-based counterparts have a comparable socio-economic overall performance (similar final scores). However, the analysis shows distinct socio-economic differences among products and hotspots along the life cycle of products.

Socio-economic hotspots (points of most negative impacts) along the life cycle of plant-based products were mainly identified at the production stage. At this stage, the farm-level net margin and profitability of vegetable meat and milk products are low when compared with their animal-based equivalents. This suggests that without a supportive policy framework the economics of plant-based protein-rich food products are unlikely to be market competitive, especially due to the less favourable conditions for farmers. In line with Manners et al.,[54] our results indicate that low yields and reduced production prices of grain legumes diminish profitability and limit market competitiveness of plant-protein-based products. Siddique et al.[55] and Zander et al.[56] found that the expansion of specialized and intensive production systems and yield increases provided a comparative advantage to cereals and oilseed crops, compared to protein-rich crops. As a result, protein-rich crops are increasingly less profitable than wheat, maize or rice.[57] Preissel et al.[58] and Reckling et al.[59] show that introducing legumes into cropping systems does not always deliver immediate or apparent profits. In spite of the yield-increase effects induced by legumes to other crops (due to their nitrate fixation capacity in the soil), the farm-level gross margin is generally lower where legumes are grown.[60] Magrini et al.,[61] however, argue that if the environmental benefits of growing legumes (e.g., reduction of greenhouse gas emissions) were well reflected in market prices, the 'real' economic value of legumes would increase significantly.

Our results also reveal that factors like crop yield and producer price variability are larger for plant-based meat and milk alternatives, which might increase the risk to farmers growing these crops and, in turn, might decrease confidence in these product lines for both farmers and consumers. Cernay et al.[62] demonstrate that grain legume yields in Europe are more variable than non-legume yields. According to Von Richthofen et al.,[63] this makes their production a risky venture for European farmers, who prefer more stable farm productions (e.g., cultivating cereals or raising livestock). Stagnari et al.[64] propose that observed declines in grain legume production in the EU are explained by their unstable yields, coupled with their susceptibility to biotic and abiotic stress conditions. Zander et al.[56] indicate that changes in agricultural policies have further contributed to these declines. These authors[56] conclude that public support measures (i.e., CAP price supports and subsidies) have been largely responsible for the intermittent increase of legume cultivation in the EU. Legumes are supported in the CAP under greening measures and voluntary coupled support schemes. Our results indicate that, while CAP subsidies for legumes are significant, they are lower than those for some animal products (e.g., milk products), which could diminish the comparative advantage of cultivating legumes for EU farmers. This aspect should be considered in the light of the new CAP 2021–2027, in which the great contribution of legumes to environmental and climate objectives is highly recognized.[16,65]

By looking at the processing and retail stage of the products' life cycle, we note the socio-economic performance of plant-protein-based products improves compared to those sourced from animal-based proteins. Our study reveals that salaries and employment of workers within the plant-based products sector are notably better than that for animal products, especially meat. These findings are in line with previous research suggesting that the added value generated in plant-based product lines through advanced processing of protein extracts, starch and oil contributes to raising profit margins within the processing and retail sectors.[66,67] The manufacturing and selling of processed plant-based products would, however, require entirely new forms of economic coordination and supply chain management, which are not always in place or, in some cases, are in the process of being developed.[17,61] The importance of well-functioning supply chains and regulatory frameworks are seen as crucial for the development of new plant-protein-based products.[16,54] Animal-based food products count with well-established value chains. Also, processing rules and regulations are stricter in the case of meat and milk production for food safety reasons. Since the 1970s, numerous regulations have been developed in the EU in the wake of serious meat crisis, which have significantly eroded meat's healthy image.[68] In line with this, our study reveals that the performance of legislation at the processing stage is better in animal products than in vegetable products. This suggests that more efforts should be made at the legislation level to guarantee food safety in new plant-based products, while at the same time protecting the processing and retail workers.

At the consumer stage, results show that plant-based products perform better than animal-based products. Our work supports the findings of other studies that report that the nutritional composition of vegetable products is more beneficial to consumers than their animal-based counterparts.[66] Cholesterol levels in meat and saturated fat levels in milk were found to be lower in vegetable products than in animal products. Several authors argue that cholesterol and fat consumption – indicators for animal protein-based foods – are highly correlated with health-related problems (e.g., cardiovascular pathologies, diabetes and cancer).[7,8] Other authors (e.g., Leroy and Cofnas[69]), however, question this, and claim that when meat is consumed as part of balanced diets the effects on human health can be positive.[70] Millward and Garnett[71] demonstrate that lowering the consumption of meat and dairy products may pose nutritional challenges for some key nutrients (vitamin B12 and protein intake) in 'at risk' population groups (children and the elderly). Our study reveals that animal-based products have higher vitamin contents than their vegetable alternatives. However, it falls short of determining the type of vitamins and fat, quality of proteins and other mineral nutrients, which is critical in determining the pros and cons of diets.[72]

Previous studies have found that health factors are the key reasons for changing consumption habits, followed by environmental, and socio-cultural reasons (e.g., climate change and concern for animal welfare).[73-75] Economic issues are also highlighted as important for consumers, especially in the case of innovative plant-based foods, in which the final price is often higher than in the case of their animal-based equivalents.[54] Our study indicates that vegetable meat and milk products have lower protein affordability (higher prices of protein) than chicken meat and dairy milk products, which might inhibit consumers from replacing animal-based products by plant-based products. However, Tubb and Seba[76] indicate that rapid technological improvements will make plant-derived proteins cheaper than those from animals by 2030, potentially making novel plant-based products more economically attractive to consumers.

CONCLUSIONS

This study has investigated the socio-economic impacts of novel plant-based products compared to traditional animal-based products. Our application of socio-economic life cycle analysis allowed us to gauge these impacts across three phases in the farm-to-fork pathway. In general, we found that novel plant-based and animal-based products have a similar socio-economic performance. However, important differences can be appreciated along the value chain.

In the production phase, variably yields and producer prices negatively affect the benefits of plant-based products, compared to animal products. The study demonstrates that the economics of innovative legume-based food products are unlikely to be market competitive, especially due to the less favourable conditions for farmers. In contrast, the processing stage indicates that plant-based products compare favourably with the products they are designed to replace. Finally, in the consumption phase we observe a two-sided effect as proteins are less affordable in vegetable foods, whereas these perform better in relation to some food health contents (saturated fat and cholesterol). The study provides relevant information to policymakers, businesses, producers, consumers and other stakeholders about socio-economic hotspots and optimization potential in the development and production of innovative plant-based foods.

This article represents one of the first reviews of these products from a socio-economic perspective and complements more traditional life cycle analyses, which have demonstrated the environmental benefits of these plant-based products. By contributing to the advancement of lifecycle assessments, the study stresses the importance of considering multi-ingredient food products to better understand the social, economic and policy contexts of the food value chain. Greater emphasis should be placed upon developing an environment in Europe that is more conducive to legume production, nurture nascent processing technologies and supply chains, thus reducing prices to consumers. In such an environment, plant-based products could become socio-economically comparable, if not superior to animal-based products in the near future. In a general perspective, this research contributes to understanding how the socio-economic scene evolves hand in hand with nature's resource base to contribute to a more sustainable, resource-efficient, climate-resilient and socially inclusive food supply in Europe and, in turn, to overall food security.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the research project Protein2-Food (Development of high-quality food protein through sustainable production and processing, No. 635727-2, 2015–2020, Horizon 2020 Framework Programme of the EU Commission, https://www.protein2food.eu/) for providing the necessary funds for this research. Emanuele Zannini (University College Cork, Ireland) and Juergen Bez (Fraunhofer-Institut, Freising, Germany) – both colleagues in the Protein2Food project – are greatly acknowledged for providing key information on the plant-based products developed in their laboratories that have been used in this analysis. Sebastián Sangro contributed to data gathering in several parts of the project's development and his work is appreciated by the authors. Lastly, the authors are also indebted to the numerous international stakeholders that have taken active part in this study representing different sectors of the food value chain.

CONFLICT OF INTEREST

This research does not have any conflict of interest.

SUPPORTING INFORMATION

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

REFERENCES

1 Vranken L, Avermaete T, Petalios D, Mathijs E, Curbing global meat consumption: Emerging evidence of a second nutrition transition. *Environmental Science & Policy* **39**:95–106 (2014). https://doi.org/10.1016/j.envsci.2014.02.009
2 Vinnari M and Tapio P, Future images of meat consumption in 2030. *Futures* **41**:269–278 (2009).
3 Odegard IYR and van der Voet E, The future of food: scenarios and the effect on natural resource use in agriculture in 2050. *Ecol Econ* **97**: 51–59 (2014).
4 Tubiello FN, Salvatore M, Rossi S, Ferrara A, Fitton N and Smith P, The FAOSTAT database of greenhouse gas emissions from agriculture. *Environ Res Lett* **8**:1–10 (2013).
5 Aide TM, Clark ML, Grau HR, López-Carr D, Levy MA, Redo D *et al*., Deforestation and reforestation of Latin America and the Caribbean (2001–2010). *Biotropica* **45**:262–271 (2013).
6 Machovina B, Feeley KJ and Ripple WJ, Biodiversity conservation: the key is reducing meat consumption. *Sci Total Environ* **536**:419–431 (2015).
7 Richi EB, Baumer B, Conrad B, Darioli R, Schmid A and Keller U, Health risks associated with meat consumption: a review of epidemiological studies. *Int J Vitam Nutr Res* **85**:70–78 (2015).
8 Wolk A, Potential health hazards of eating red meat. *J Intern Med* **281**: 106–122 (2017).
9 Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S *et al*., Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet* **6736**:3–49 (2019).
10 Gerten D, Heck V, Jägermeyr J, Bodirsky BL, Fetzer I, Jalava M *et al*., Feeding ten billion people is possible within four terrestrial planetary boundaries. *Nat Sustain* **3**:200–208 (2020).
11 Springmann M, Clark M, Mason-D'Croz D, Wiebe K, Bodirsky BL, Lassaletta L *et al*., Options for keeping the food system within environmental limits. *Nature* **562**:519–525 (2018).
12 Tilman D and Clark M, Global diets link environmental sustainability and human health. *Nature* **515**:518–522 (2014).

13 Erb K-H, Lauk C, Kastner T, Mayer A, Theurl MC and Haberl H, Exploring the biophysical option space for feeding the world without deforestation. *Nat Commun* **7**:11382 (2016).
14 Poppe K, Sonnino R, Ahrné L, Brennan L, Jacobs N, Mango C, Menrad K, Moutou K, Schmid O, Tréyer S, and Varela-Ortega, C. Westhoeck H. Recipe for change: an agenda for sustainable food system Report of the FOOD 2030 Expert Group. Brussels; 2018.
15 Derbyshire EJ, Flexitarian diets and health: a review of the evidence-based literature. *Front Nutr* **3**:1–8 (2017).
16 European Commission, Report from the Commission to the Council and the European Parliament on the development of plant proteins in the European Union. *European Comm* **757**:1–15 (2018).
17 Henchion M, Hayes M, Mullen A, Fenelon M and Tiwari B, Future protein supply and demand: strategies and factors influencing a sustainable equilibrium. *Foods* **6**:53 (2017).
18 Possidónio C, Prada M, Graça J and Piazza J, Consumer perceptions of conventional and alternative protein sources: a mixed-methods approach with meal and product framing. *Appetite* **156**:104860 (2021).
19 Harwatt H, Sabaté J, Eshel G, Soret S and Ripple W, Substituting beans for beef as a contribution toward US climate change targets. *Clim Change* **143**:261–270 (2017).
20 Detzel A, Krüger M, Busch M, Drescher A, Wriessnegger CL, and Köppen S. Deliverable 5.3 – Part I: Report on the Life Cycle Assessment Results. Protein 2 Food project report. 2018.
21 Rust NA, Ridding L, Ward C, Clark B, Kehoe L, Dora M *et al*., How to transition to reduced-meat diets that benefit people and the planet. *Sci Total Environ* **718**:137208 (2020).
22 Jallinoja P, Niva M and Latvala T, Future of sustainable eating? Examining the potential for expanding bean eating in a meat-eating culture. *Futures* **83**:4–14 (2016).
23 Lemken D, Spiller A and Schulze-Ehlers B, More room for legume: consumer acceptance of meat substitution with classic, processed and meat-resembling legume products. *Appetite* **143**:104412 (2019).
24 Falcone G, Iofrida N, Stillitano T and De Luca A, Impacts of food and diets' life cycle: a brief review. *Curr Opin Environ Sci Heal* **13**:75–79 (2020).
25 Detzel A, Krüger M, Busch M, Blanco-Gutiérrez I, Varela C, Manners R *et al*., Life cycle assessment of animal-based foods and plant-based protein-rich alternatives: an environmental perspective. *J Sci Food Agric* 1–13 (2021).
26 Benoît C, Norris GA, Valdivia S, Ciroth A, Moberg A, Bos U *et al*., The guidelines for social life cycle assessment of products: Just in time! *Int J Life Cycle Assess* **15**:156–163 (2010).
27 Iofrida N, De LAI, Strano A and Gulisano G, Can social research paradigms justify the diversity of approaches to social life cycle assessment? *Int J Life Cycle Assess* **23**:464–480 (2018).
28 Ramos Huarachi DA, Piekarski CM, Puglieri FN and de Francisco AC, Past and future of social life cycle assessment: historical evolution and research trends. *J Clean Prod* **264**:121506 (2020).
29 Jørgensen A, Social LCA: a way ahead? *Int J Life Cycle Assess* **18**:296–299 (2013).
30 UNEP-SETAC., Guidelines for social life cycle assessment of products, in *United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC)*, ed. by Benoît Catherine and Mazijn Bernard. United Nations Environment Programme (UNEP), Nairobi, Kenya (2009).
31 UNEP, in *Guidelines for Social Life Cycle Assessment of Products and Organizations 2020*, ed. by Benoît Norris C, Traverso M, Neugebauer S, Ekener E, Schaubroeck T, Russo Garrido S *et al*. United Nations Environment Programme (UNEP), Nairobi, Kenya (2020).
32 Martínez-Blanco J, Lehmann A, Muñoz P, Antón A, Traverso M, Rieradevall J *et al*., Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment. *J Clean Prod* **69**:34–48 (2014).
33 Chen W and Holden NM, Social life cycle assessment of average Irish dairy farm. *Int J Life Cycle Assess* **22**:1459–1472 (2017).
34 Petti L, Sanchez Ramirez PK, Traverso M and Ugaya CML, An Italian tomato 'Cuore di Bue' case study: challenges and benefits using subcategory assessment method for social life cycle assessment. *Int J Life Cycle Assess* **23**:569–580 (2018).
35 Kruse SA, Flysjö A, Kasperczyk N and Scholz AJ, Socioeconomic indicators as a complement to life cycle assessment: an application to salmon production systems. *Int J Life Cycle Assess* **14**:8–18 (2009).
36 Feschet P, MacOmbe C, Garrabé M, Loeillet D, Saez AR and Benhmad F, Social impact assessment in LCA using the Preston pathway: the case of banana industry in Cameroon. *Int J Life Cycle Assess* **18**: 490–503 (2013).
37 Lehmann A, Zschieschang E, Traverso M, Finkbeiner M and Schebek L, Social aspects for sustainability assessment of technologies: challenges for social life cycle assessment (SLCA). *Int J Life Cycle Assess* **18**:1581–1592 (2013).
38 Sala S, Vasta A, Mancini L, Dewulf J and Rosenbaum E, *Social Life Cycle Assessment: State of the Art and Challenges for Supporting Product Policies*. European Commission, Luxemburg (2015).
39 Revéret J-P, Couture J-M and Parent J, Socioeconomic LCA of milk production in Canada BT, in *Social Life Cycle Assessment: An Insight*, ed. by Muthu SS. Springer, Singapore, pp. 25–69 (2015).
40 Dreyer LC, Hauschild MZ and Schierbeck J, A framework for social life cycle impact assessment. *Int J Life Cycle Assess* **11**:88–97 (2006).
41 Varela-Ortega C, Blanco I, Manners R, Blas A, and Sangro S. Deliverable 4.3 – Part I. Report on socio-economic assessment of new protein food production: examining stakeholder perspectives. Protein2food project report 2020.
42 Varela-Ortega C, Blanco I, Sangro S, Manners R, and Esteve P. Deliverable 5.3 – Part II. Report on results of socio-economic assessment. Protein2Food project report. 2018.
43 Benoit-Norris C, Cavan DA and Norris G, Identifying social impacts in product supply chains: overview and application of the social hotspot database. *Sustainability* **4**:1946–1965 (2012).
44 EU (European Union), Regulation (EU) No. 1307/2013 of the European Parliament and of the Council establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy. *Off J Eur Union* 1–63 (2013).
45 EC (European Commission). Voluntary coupled support: sectors mostly supported. Notification of the revised decisions taken by Member States by 1 August 2014. Brussels 2015.
46 FAO FAOSTAT. Available: http://www.fao.org/faostat/en/#data [1 October 2018].
47 IFEU (Institut für Energie- und Umweltforschung). Deliverable D5.1. Report on the scenarios. Protein2food project report 2016.
48 ANSES (French Agency for Food, Environmental and Occupational Health and Safety). [Online]. Ciqual: French food composition table. Available: https://ciqual.anses.fr [26 April 2018]
49 IVV (Fraunhofer-Institut für Verfahrenstechnik und Verpackung). Deliverable 3.2. Recipes and optimized processing conditions for meat alternatives. Protein2Food project report 2018.
50 UCC (University College Cork). Deliverable 3.1. Evaluation of commercial reference plant-based protein-rich foods. Protein2Food project report. 2016.
51 REWE (Revisionsverband der Westkauf-Genossenschaften). [Online]. Available: https://www.rewe.de [30 October 2018]
52 MERCADONA. [Online]. Available: https://www.mercadona.es/ [30 October 2018].
53 do Carmo BBT, Margni M and Baptiste P, Social impacts profile of suppliers: a S-LCA approach. *IFAC-PapersOnline* **49**:36–41 (2016).
54 Manners R, Blanco-Gutiérrez I, Varela-Ortega C and Tarquis AM, Transitioning European protein-rich food consumption and production towards more sustainable patterns: strategies and policy suggestions. *Sustainability* **12**:1–20 (2020).
55 Siddique KHM, Johansen C, Turner NC, Jeuffroy M-H, Hashem A, Sakar D *et al*., Innovations in agronomy for food legumes: a review. *Agron Sustain Dev* **32**:45–64 (2012).
56 Zander P, Amjath-Babu TS, Preissel S, Reckling M, Bues A, Schläfke N *et al*., Grain legume decline and potential recovery in European agriculture: a review. *Agron Sustain Dev* **36**:1–20 (2016)
57 Murphy-Bokern Donal, Stoddard Frederick L and Watson Christine A, Legumes in cropping systems. *Legum Crop Syst* CABI, Wallingford, 1–256 (2017).
58 Preissel S, Reckling M, Schläfke N and Zander P, Magnitude and farm-economic value of grain legume pre-crop benefits in Europe: a review. *F Crop Res* **175**:64–79 (2015).
59 Reckling M, Bergkvist G, Watson CA, Stoddard FL, Zander PM, Walker RL *et al*., Trade-offs between economic and environmental impacts of introducing legumes into cropping systems. *Front Plant Sci* **7**:1–15 (2016).

60 Bues A, Preißel S, Reckling M, Zander P, Kuhlman T, Topp K *et al.*, *The Environmental Role of Protein Crops in the New Common Agricultural Policy*. Publications Office of the EU, Brussels (2013).
61 Magrini MB, Anton M, Cholez C, Corre-Hellou G, Duc G, Jeuffroy MH *et al.*, Why are grain–legumes rarely present in cropping systems despite their environmental and nutritional benefits? Analyzing lock-in in the French agrifood system. *Ecol Econ* **126**:152–162 (2016).
62 Cernay C, Ben-Ari T, Pelzer E, Meynard JM and Makowski D, Estimating variability in grain legume yields across Europe and the Americas. *Sci Rep* **5**:1–11 (2015).
63 Von RJS, What do European farmers think about grain legumes. *Grain Legum* **45**:14–15 (2006).
64 Stagnari F, Maggio A, Galieni A and Pisante M, Multiple benefits of legumes for agriculture sustainability: an overview. *Chem Biol Technol Agric* **4**:1–13 (2017).
65 Meredith S and Kollenda E, *CAP Trilogue Briefing: What Green Ambitions of the CAP Reform Can Still be Salvaged?* Institute for European Environmental Policy, Brussels (2021).
66 Curtain F and Grafenauer S, Plant-based meat substitutes in the flexitarian age: an audit of products on supermarket shelves. *Nutrients* **11**:1–14 (2019).
67 Bashi Z, McCullough R, Ong L and Ramirez M, *Alternative Proteins: The Race for Market Share is On*. McKinsey, Chicago, IL (2019).
68 Leroy F, Brengman M, Ryckbosch W and Scholliers P, Meat in the post-truth era: mass media discourses on health and disease in the attention economy. *Appetite* **125**:345–355 (2018).
69 Leroy F and Cofnas N, Should dietary guidelines recommend low red meat intake? *Crit Rev Food Sci Nutr* **60**:2763–2772 (2019).
70 De SS and Vossen E, Meat: The balance between nutrition and health: a review. *Meat Sci* **120**:145–156 (2016).
71 Millward DJ and Garnett T, Plenary lecture 3 – Food and the planet: nutritional dilemmas of greenhouse gas emission reductions through reduced intakes of meat and dairy foods. *Proc Nutr Soc* **69**:103–118 (2010).
72 Campbell TC, A plant-based diet and animal protein: questioning dietary fat and considering animal protein as the main cause of heart disease. *J Geriatr Cardiol* **14**:331–337 (2017).
73 Latvala T, Niva M, Mäkelä J, Pouta E, Heikkilä J, Kotro J *et al.*, Diversifying meat consumption patterns: consumers' self-reported past behaviour and intentions for change. *Meat Sci* **92**:71–77 (2012).
74 Hocquette JF, Is in vitro meat the solution for the future? *Meat Sci* **120**:167–176 (2016).
75 Martínez LMC, Mollá-Bauzá MB and Mora AG, A consumer behaviour approach to analyse the sustainability of food purchasing. *Econ Agrar Recur Nat* **20**:73–93 (2020).
76 Tubb C and Seba T. *RethinkX Dairy*. RethinkX, California (2019).

