Trends in Food Science & Technology 128 (2022) 238–252

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Review

Targeted formulation of plant-based protein-foods: Supporting the food system's transformation in the context of human health, environmental sustainability and consumer trends

Andrea Hoehnel [a], Emanuele Zannini [a], Elke K. Arendt [a,b,*]

[a] University College Cork, School of Food and Nutritional Sciences, College Road, Cork, Ireland
[b] APC Microbiome Ireland, Cork, Ireland

ARTICLE INFO

Keywords:
Plant-based
Diet shift
Environmental sustainability
Human health
Consumer trends
Targeted product formulation

ABSTRACT

Background: With food production being a key contributor to nitrogen and phosphorus cycle disruption, biodiversity loss and climate change, the lacking sustainability of our food systems is a global issue. At the same time, unhealthy diets have been identified as the greatest global burden of disease. Both aspects underline the urgency of food system transformation and call for immediate action.

Scope and Approach: A global shift to predominantly plant-based diets has been described as an effective strategy to make the food system more sustainable. While concerns regarding adequate protein supply from predominantly plant-based diets have been raised, many publications state that adequate protein can be provided when sufficiently diverse plant-based diets are consumed. In particular, a more holistic approach in evaluating food and diet quality (supply of dietary fibre, micronutrients and moderate levels of glycaemic load, salt, saturated fats) has been advocated. This review article provides an overview on current protein intake levels, the diversity of current protein supply and consumer trends and proposes principles for the targeted formulation of plant-based protein-foods that support and accelerate food system transformation.

Key Findings and Conclusions: Vegetal protein intake seems to lack diversity and is mainly covered by cereal foods worldwide. Therefore, an increased inclusion of non-cereal proteins in plant-based protein-foods is desirable.

1. Introduction and environmental perspective

Food production has been identified as one of the strongest drivers for global environmental change and three of the most serious implications are nitrogen and phosphorus cycle disruption, biodiversity loss and climate change (Aiking, 2014; Rockström, et al., 2009; Willett, et al., 2019). Recent estimates associate approx. 30% of anthropogenic greenhouse gas emissions with food production, as well as 70% of freshwater use and the occupation of 37% of ice-free land surface (Searchinger et al., 2019; Willett, et al., 2019). Multiple publications have pointed out that fundamental changes in the food system are needed to preserve environmental health (Aiking, 2014; FAO, 2019; Friel et al., 2020; Garnett, 2014; IPES-Food, 2016; Lee et al., 2019; Norberg-Hodge, 2021; Searchinger et al., 2019; Springmann, et al., 2018; Willett, et al., 2019). Furthermore, our chances to reach the Sustainable Development Goals (SDGs) established by the UN (FAO, 2019) and to meet targets set in the Paris Agreement depend greatly on a transformation of the food system (Lee et al., 2019). The increasing prevalence of diet-related disease risks indicates that also the preservation of human health, in addition to environmental health, requires food system transformation (FAO, 2020; GBD 2017 DALYs and HALE Collaborators, 2018; Global Panel on Agriculture and Food Systems for Nutrition, 2016; Searchinger et al., 2019; United Nations - Department of Economic and Social Affairs, 2019b). According to the 2016 report of the Global Panel on Agriculture and Food Systems for Nutrition (Global Panel on Agriculture and Food Systems for Nutrition, 2016), unhealthy diets represent the greatest global burden of disease. In fact, six out of the top eleven disease risk factors are diet-related and rank amongst other serious risk factors like alcohol and drug use, unsafe sex, air pollution and tobacco smoking (GBD 2017 DALYs and HALE Collaborators, 2018; Global Panel on Agriculture and Food Systems for Nutrition, 2016). Inadequate nourishment, which refers to overnutrition, undernutrition and malnutrition, is on the rise, and so are obesity, diabetes and other diet-related non-communicable diseases (Lartey et al., 2018). For example, the increasing consumption of high glycaemic load (GL) diets based on a large amount of foods high

* Corresponding author.
E-mail address: e.arendt@ucc.ie (E.K. Arendt).

https://doi.org/10.1016/j.tifs.2022.08.007
Received 9 July 2021; Received in revised form 1 June 2022; Accepted 14 August 2022
Available online 19 August 2022

in rapidly digestible starch and sugar has been associated with obesity and increased risk for diabetes, cardiovascular disease and colorectal and breast cancer (Hu et al., 2013; Jenkins, et al., 2021; Ludwig, 2002; Schwingshackl & Hoffmann, 2013).

The growing world population adds further strain to the global food system. In order to feed roughly 10 billion mouths by 2050, an overall rise in food demand is expected if we do not change the way we produce, process, consume and dispose of food (Alexandratos & Bruinsma, 2012; Henchion et al., 2017; Tilman et al., 2011; Tomlinson, 2013). Besides, an adequate distribution of food resources across high-, medium- and low-income countries will become even more challenging. Also, the increasing urbanisation worldwide, but particularly in developing countries, bears difficulties for adequate and sustainable food supply (Abu Hatab et al., 2019). There is a consensus amongst researchers, economists and politicians that all of these aspects are to be accommodated during food system transformation and multiple strategies to achieve this have been proposed (Manners, Blanco-Gutiérrez, et al., 2020; Willett, et al., 2019). The global adoption of primarily plant-based diets (with flexibility to include necessary regional and cultural adjustments) has been mentioned as the most effective strategy and scientists urge for action to promote this diet shift (Marques et al., 2018; Nijdam et al., 2012; Ranganathan, Vennard, Waite, Dumas, Lipinski & Searchinger, 2016; Willett, et al., 2019). In the light of recent events, this approach has become even more attractive since some studies suggest a link between animal-based food systems and emerging zoonoses such as SARS-CoV-2 (Aiking & de Boer, 2020; Jacob et al., 2020; Murray et al., 2016). Two other important strategies to change the food system are a substantial reduction of food waste and a decrease of food losses by improving technologies, particularly agricultural processes (e.g. irrigation systems) (Willett, et al., 2019). However, it has been argued that, in order to ascertain the food system transformation, a combination of various strategies, including those mentioned above, is necessary. Essentially, an international “multi-sector” and “multi-level” approach is needed to change the food we consume as well as the way it is produced (Aiking & de Boer, 2020; Nicol & Taherzadeh, 2020; Röös et al., 2018; Willett, et al., 2019). Moreover, all strategies need to be accompanied by science-based high-level policy interventions (Friel et al., 2020; Garnett, 2014; Manners, Blanco-Gutiérrez, et al., 2020; Neacsu et al., 2017; Nicol & Taherzadeh, 2020; Willett, et al., 2019). Such policies might include the stopping of the expansion of agricultural land, the active reduction of livestock numbers, the introduction of a meat tax and the development of other tax schemes or incentive schemes that support sustainable consumer products (Neacsu et al., 2017; Röös et al., 2018; Säll & Gren, 2015; Tziva et al., 2020).

While collaborative action along the food chain is crucial to achieve food system transformation, a detailed evaluation of the possible contributions of each link of the chain is also needed. This review article provides an overview on consumer product development and aspects related to formulating healthy plant-based protein-foods in support of the food system’s transformation, specifically in support of the shift to predominantly plant-based diets. Plant-based protein-foods have been amongst the top 10 key trends in the food sector for many years and the market is expected to keep growing (Fi Europe, 2020; Mellentin, 2017, 2019). Since food product development represents a link between food industry, food research and consumers, it is bound to play a key role in amalgamating consumer food trends and food system changes required to preserve human and environmental health.

2. The matter of protein adequacy

The advocacy of a shift to predominantly plant-based diets has sparked a debate concerning the macronutrient protein and its “pivotal role” in food system transformation (Aiking & de Boer, 2020). Since animal-based foods provide significant amounts of high-quality protein in many human diets, it has been discussed whether a shift to mainly plant-based diets might lead to inadequate protein intake (Lonnie & Johnstone, 2020; Mariotti, 2017; Wu et al., 2014). But many publications have reported that sufficient, and largely even supersufficient, amounts of protein are being consumed in most world regions and that a reduction of animal-based protein intake would not cause insufficient protein supply (Aiking & de Boer, 2020; Ranganathan, Vennard, Waite, Dumas, Lipinski & Searchinger, 2016; Searchinger et al., 2019). Uncertainties about required and recommended intakes of dietary protein as well as contradicting scientific evidence regarding the effects of high protein intakes (larger than currently recommended intakes Joint FAO/WHO/UNU Expert Consultation, 2007) have additionally fuelled these discussions (Mariotti, 2017).

2.1. Protein quantity

The first step this article takes in reviewing this matter is to look at the current state of protein supply and consumption globally. Fig. 1 displays protein supply (FAOSTAT) and protein consumption (Global Dietary Database; GDD) data for the year 2015 and for seven world regions. The grouping of world regions was based on the classification used by FAO (2011) (FAO, 2011a) with some modifications due to missing data in either FAOSTAT or GDD for the year 2015. An exhaustive list of all included countries for each region is available in the supplementary material to this article. The presented data show that the supply of dietary protein seems more than sufficient in most world regions when compared to the average recommended intake (0.83 g/kg/day and an average bodyweight of 62 kg Joint FAO/WHO/UNU Expert Consultation, 2007; Walpole et al., 2012). However, it has repeatedly been reported that calculated food supply data do not adequately reflect and, in many cases, overestimate food consumption because factors like food waste in households are not considered (Aiking & de Boer, 2020; Del Gobbo et al., 2015; Kearney, 2010; Khatibzadeh et al., 2016; Micha et al., 2015; Schmidhuber et al., 2018). While the presented protein consumption data confirm this trend (for the year 2015), they also suggest that not only protein supply but also protein consumption levels are above average recommended intakes in many countries, but primarily in world regions 1–3, which represent high- and medium-income countries (FAO, 2011a). The same conclusion was drawn in previous articles from the World Resources Institute (WRI) based on consumption data that were obtained by applying the GlobAgri model to FAOSTAT supply data for the year 2009 (three year average 2008–2010) (Ranganathan, Vennard, Waite, Searchinger, Dumas, & Lipinski, 2016; Searchinger et al., 2019). Nevertheless, according to the 2015 data presented in Fig. 1, the population in some countries in regions 4, 5 and 6 seem to consume insufficient amounts of dietary protein. The apparent widespread protein overconsumption should be discussed in the context of widespread overconsumption of dietary energy, which has also been mentioned in the literature (Ranganathan, Vennard, Waite, Searchinger, Dumas, & Lipinski, 2016). This is why recommendations to reduce protein overconsumption are usually preceded by recommendations to reduce energy overconsumption (Aiking & de Boer, 2020). Furthermore, the fact that protein requirements mostly refer to intakes per bodyweight can lead to a flawed interpretation of the data presented in Fig. 1. The recommended intake for adults included in the graph was calculated based on values established by FAO/WHO in 2007 (0.83 g/kg/day) (Joint FAO/WHO/UNU Expert Consultation, 2007) and the global average bodyweight of 62 kg (Walpole et al., 2012) which equals 51.5 g/capita/day. However, the average bodyweight in high-income areas is considerably higher than the global average (e.g. 70.8 kg in Europe, 80.7 kg in Northern America and 74.1 kg in Oceania). Therefore, the recommended protein intake for adults would amount to 58.8 g/capita/day, 67.0 g/capita/day and 61.5 g/capita/day in Europe, Northern America and Oceania, respectively. Additionally, some consumer groups require more dietary protein than adults. This concerns children as well as individuals with higher levels of physical activity (FAO, 2013; Joint FAO/WHO/UNU Expert Consultation, 2007;

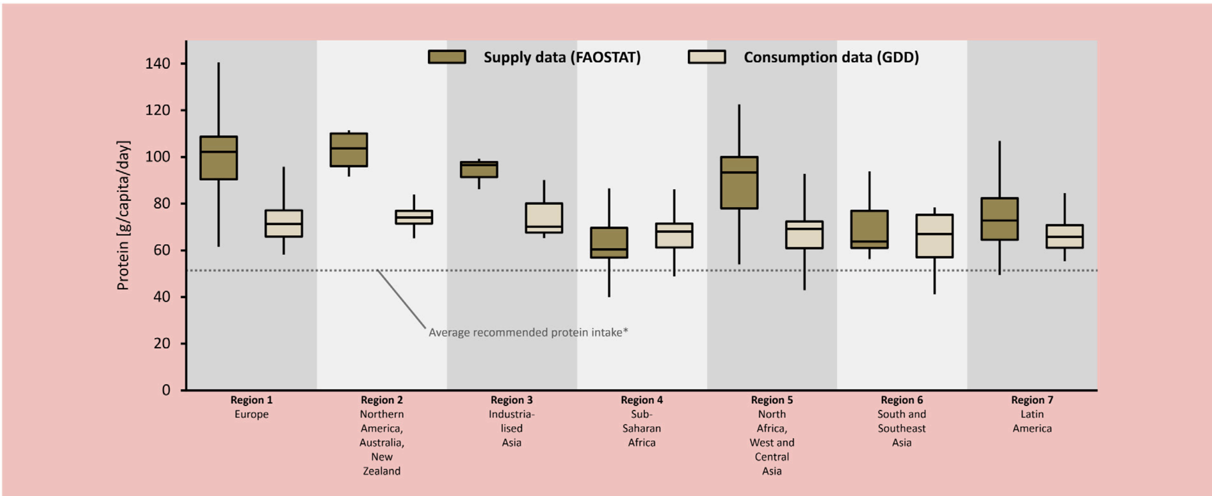

Fig. 1. Protein supply/consumption across seven world regions (displaying range, 1st quartile, median, 3rd quartile): protein **supply** in 2015 according to FAOSTAT data and protein **consumption** in 2015 according to Global Dietary Database (GDD) data. * Average recommended protein intake based on 0.83 g/kg/day and average bodyweight of 62 kg (Joint FAO/WHO/UNU Expert Consultation, 2007; Walpole et al., 2012).

Paul, 1989). Recent research advances have also suggested that the elderly (individuals aged >65) might have higher protein requirements than previously assumed and that elevated levels of dietary protein consumption might help to protect bone health and prevent sarcopenia (Ahnen et al., 2019; Berendsen et al., 2018; Krok-Schoen et al., 2019; Lonnie et al., 2018). This aspect should not be underestimated, especially in the context of the advancing world population ageing (United Nations - Department of Economic and Social Affairs, 2019a). Another important consideration when discussing sufficient protein supply within a sustainable future food system are world population prospects, which project a world population of 9.7 billion in 2050 (United Nations - Department of Economic and Social Affairs, 2019b). Thus, it can be expected that, even if current protein overconsumption is going to be reduced, there will be a growing demand for dietary protein (Aiking, 2014; Henchion et al., 2017; Tilman et al., 2011). In the light of recommended diet shifts, this demand should be covered primarily by plant-based protein, which requires sufficient availability of plant-based protein-foods. Population growth is also expected to further increase the globally uneven distribution of protein resources, which is an issue that needs to be addressed as part of food system transformation (Aiking & de Boer, 2020).

The main purpose of ingesting dietary protein is to provide the human body with sufficient substrate for biosynthesis pathways, specifically for the synthesis of proteins. Dietary protein is a source of nitrogen and indispensable amino acids as well as signal amino acids (e.g. leucine) that regulate metabolism and stimulate anabolism (Millward et al., 2008). When assessing required and recommended dietary protein intake, the majority of methods is based on the maintenance of N balance (Joint FAO/WHO/UNU Expert Consultation, 2007; Lonnie et al., 2018; Millward, 2003). Some articles highlight that this concept does not consider the relevance of protein beyond maintaining *N* balance and that the importance of dietary protein for optimal health is underestimated (Lonnie et al., 2018; Millward, 2003; Millward et al., 2008; Phillips et al., 2016). Many studies have found a positive impact of protein intakes above the average recommended level on overall health, blood pressure, blood lipid levels, weight management, satiety and the prevalence of obesity and diabetes type 2 (Berryman et al., 2016; Markova et al., 2017; Phillips et al., 2016; Santesso et al., 2012). One of the most interesting aspects is the improved satiety reported for high-protein diets, which could contribute to a reduction of energy overconsumption (Klaus et al., 2018). Other publications have reported that a low-protein diet increased life expectancy in mice and was associated with decreased mortality and reduced cancer incidence in humans (Laeger et al., 2014; Levine et al., 2014; Simpson et al., 2015). The presence of this conflicting evidence, which has been referred to as "protein paradox", is likely associated with the fact that the protein level of diets cannot be evaluated in isolation and that study results always also depend on food matrix and other diet components (macro- and micronutrients) (Klaus et al., 2018). Some studies have found that high intakes of plant-derived proteins were associated with either positive effects or less negative effects than high protein intakes from animal sources (Klaus et al., 2018; Sokolowski et al., 2019; Vieira et al., 2017). This is encouraging with regard to a shift to primarily plant-based diets.

2.2. Protein quality

The quality of dietary protein largely depends on the bioavailability of indispensable amino acids (IAAs) from this protein when it is ingested (Herreman et al., 2020; Millward et al., 2008). IAA bioavailability is mainly affected by the protein's amino acid composition (compared to the human amino acid requirement pattern of indispensable amino acids Joint FAO/WHO/UNU Expert Consultation, 2007) and digestibility (Millward et al., 2008). Based on both aspects, protein quality is often described by the protein digestibility corrected amino acid score (PDCAAS) or, more recently, the digestible indispensable amino acid score (DIAAS), which considers the digestibility of each single indispensable amino acid rather than that of the whole protein (used for PDCAAS) (Herreman et al., 2020; Schaafsma, 2005). Many studies report that plant proteins have a lower protein quality than animal proteins (Chardigny & Walrand, 2016; Herreman et al., 2020; Mariotti, 2017; Weindl et al., 2020). This aspect is also known as "protein trade-off" in the context of the shift towards predominantly plant-based diets (Weindl et al., 2020). The lower protein quality of many plant sources is associated with a lack of certain IAAs (Mariotti, 2017). Animal proteins, on the other hand, often possess an amino acid profile that represents a better match with the human requirement pattern (Herreman et al., 2020; Joint FAO/WHO/UNU Expert Consultation, 2007; Klaus et al., 2018; Sá et al., 2020). The lower quality of plant proteins has also been attributed to their often inferior digestibility when compared to animal proteins (Mariotti, 2017). Antinutritional compounds (ANCs), such as phytates and trypsin inhibitors, which naturally occur in many plants, have been found to substantially reduce protein digestibility when present in the ingested food (Mariotti, 2017). However, both ANC contents and protein digestibility greatly depend on food matrix, food structure and applied processing techniques (Hiolle et al., 2020; Sá et al., 2019; Vaz Patto et al., 2015). Fig. 2A shows the proportions of animal and plant protein contributing to the total protein supply across seven world regions. While these are protein supply data which do not accurately reflect consumption, they still provide an indication of the extent to which different protein sources contribute to total protein consumption. In regions 1, 2, 3 and 7, approx. 45%–60% of total protein is provided by animal sources. In regions 4, 5 and 6, less than 40% is covered by animal sources. Considering a substantial reduction of animal food consumption as part of the food system's transformation, the remaining small amount of animal protein together with the current supply of vegetal protein could be insufficient to reach recommended protein intakes. Moreover, it has been argued that, when dietary protein is mainly provided by plant sources, recommended protein intake levels should be raised by approximately 5%–10% to account for lower protein quality (Craig & Mangels, 2009; Mariotti, 2017). While this is a very theoretical approach and it can only provide a limited representation of the real protein adequacy of future predominantly plant-based diets, it suggests the need for an increased plant-based protein supply. Notions that plant-based protein is not fit to satisfy human protein requirements at all have been frequently addressed within the past few years. The WRI "debunk protein myths" in their World Resources Report from 2019 (Searchinger et al., 2019) by stating that a diverse plant-based diet is capable of providing adequate protein as well as micronutrients for human nutrition. Many other publications also mention that this diversity in plant-based protein is crucial for adequate protein supply from predominantly plant-based diets and the key to overcoming the lack of certain IAAs in individual plant proteins (Herreman et al., 2020; Mariotti, 2017; Neacsu et al., 2017; Salomé et al., 2020). Fig. 2B displays the proportions of different plant sources contributing to total vegetal protein supply. These data show that in all seven world regions, the majority of vegetal protein supply is covered by cereals. Furthermore, non-cereal protein supply accounts for as little as 30% in four (including Europe) out of seven regions. The data clearly suggest that plant-based protein supply is lacking diversity in many regions. A predominantly plant-based diet based on these proportions of plant sources could lead to insufficient supply of the IAAs lysine, threonine and tryptophan, which are potentially limiting in cereal protein (Leinonen et al., 2019). Mariotti and Gardner (2019) evaluated the diet composition of different consumer groups in Europe: regular meat-eaters, low meat-eaters, vegetarians and vegans, amongst others. They reported that vegetarians and vegans consume considerably more legumes, vegetarian alternatives and nuts than regular meat-eaters but also slightly more cereal products. They concluded that there was sufficient diversity in plant-based protein intake for vegetarians and vegans and no or very low risk for lysine deficiency. But they also estimated the expected lysine inadequacy of European diets when intake of animal protein is reduced and isocalorically replaced by plant-based foods. Their simulations showed that when animal protein was entirely replaced by the mixture of plant foods that is currently consumed by animal protein consuming individuals, the prevalence of lysine inadequacy could be as high as 80% (at plant protein intake of approximately 85% of total protein intake). This is in agreement with the data presented in Fig. 2, which suggests that this might not only be true for European diets but also for diets in regions 2, 3, 6 and 7. When Mariotti and Gardner (2019) considered a partial replacement of animal protein by a mixture of legumes, seeds and nuts as opposed to the already consumed mixture of plant foods in their simulations, they predicted drastically decreased prevalence of lysine inadequacy.

2.3. *Overall diet quality is paramount*

Another aspect associated with a high proportion of plant-based protein intake coming from cereals is the glycaemic index (GI) and GL of such diets (Jenkins et al., 2004). Cereal products often contain large amounts of rapidly digestible starch (RDS) (Alsaffar, 2011; Martínez et al., 2018; Singh et al., 2010). This is even more pronounced for refined cereal products (as opposed to wholegrain products), which have been increasingly consumed within the last decades (Jenkins et al., 2004; Micha et al., 2015; Willett, et al., 2019). Such diets have been associated with several health risks such as obesity and diabetes (Ludwig, 2002), as mentioned above. Thus, a diet shift should not only target a substantial reduction of the consumption of animal foods and a diversification of plant-based protein supply but also consider a moderation of diet-GL (Jenkins et al., 2004; Ludwig, 2002; Willett, et al., 2019). The EAT-Lancet commission has proposed a reference diet which was established considering both human health and environmental sustainability based on the planetary boundaries concept (Rockström, et al., 2009; Steffen et al., 2015). Table 1 summarises supply and consumption data from 2015 (both expressed as g food/capita/day in contrast to g protein/capita/day as in the two figures above) for two plant-based food groups (cereals and the sum of legumes, beans, nuts and seeds) in comparison to the intakes recommended in the EAT-Lancet reference diet (Willett, et al., 2019). While Del Gobbo et al. (2015) found that food balance data from FAOSTAT (for the years 1980–2009) potentially underestimate legume consumption and overestimate cereal consumption, the data for 2015 provided in Table 1 show that consumption of legumes, beans, nuts and seeds was slightly lower than the supply data suggest. When compared to the EAT-Lancet reference diet, it appears that supply and consumption of legumes, beans, nuts and seeds is much lower than the recommended intake. For cereals, a comparison is more difficult since there were no GDD consumption data available for this food group and the EAT-Lancet reference diet only refers to an intake of wholegrain products (refined cereal products are not part of the reference diet). However, the data suggest that the supply of cereal products (refined and wholegrain) is considerably higher than the recommended intake (wholegrain only). This means that an increased consumption of legumes, beans, nuts and seeds is not only beneficial from a nutritional perspective to diversify plant-based (protein-) food intake but also from an environmental sustainability point of view.

Protein undoubtedly is an important macronutrient, but many scientists urge for a more holistic evaluation of the nutritional value of foods and the whole diet instead of a mere focus on protein quantity and quality (Alcorta et al., 2021; Mariotti & Gardner, 2019; Neacsu et al., 2017). The coingestion of dietary fibre and important micronutrients as well as compounds with potentially adverse health impacts with protein-foods should be taken into account when their nutritional quality is evaluated.

3. Consumer trends

A major diet shift will require changes in consumers' food choices, which depend on many different factors: availability, culture, social status, affordability, sensory attributes, convenience of preparation, consumer beliefs, consumer knowledge, individual perceptions, price, brands and advertising are only a few from a long list of aspects associated with multiple scientific disciplines (de Boer & Aiking, 2019; Köster, 2009; Neacsu et al., 2017). In recent years, consumers' awareness of the impact of food production and diets on the environment and on human health/wellbeing has increased substantially (Kuesten & Hu, 2020; Mellentin, 2019). While this might influence the food choices of some, the majority of consumers still underestimates the environmental impact of meat consumption, for instance (Hartmann & Siegrist, 2017). In a systematic review from 2017, Hartmann and Siegrist (2017) conclude that consumers generally show low willingness to change their behaviour in relation to meat consumption (referring to both reduction as well as substitution by alternative protein-foods). Research has clearly shown that to prevent substantial environmental damage caused by the food system in the future and to protect human health, a global shift to predominantly plant-based diets is a

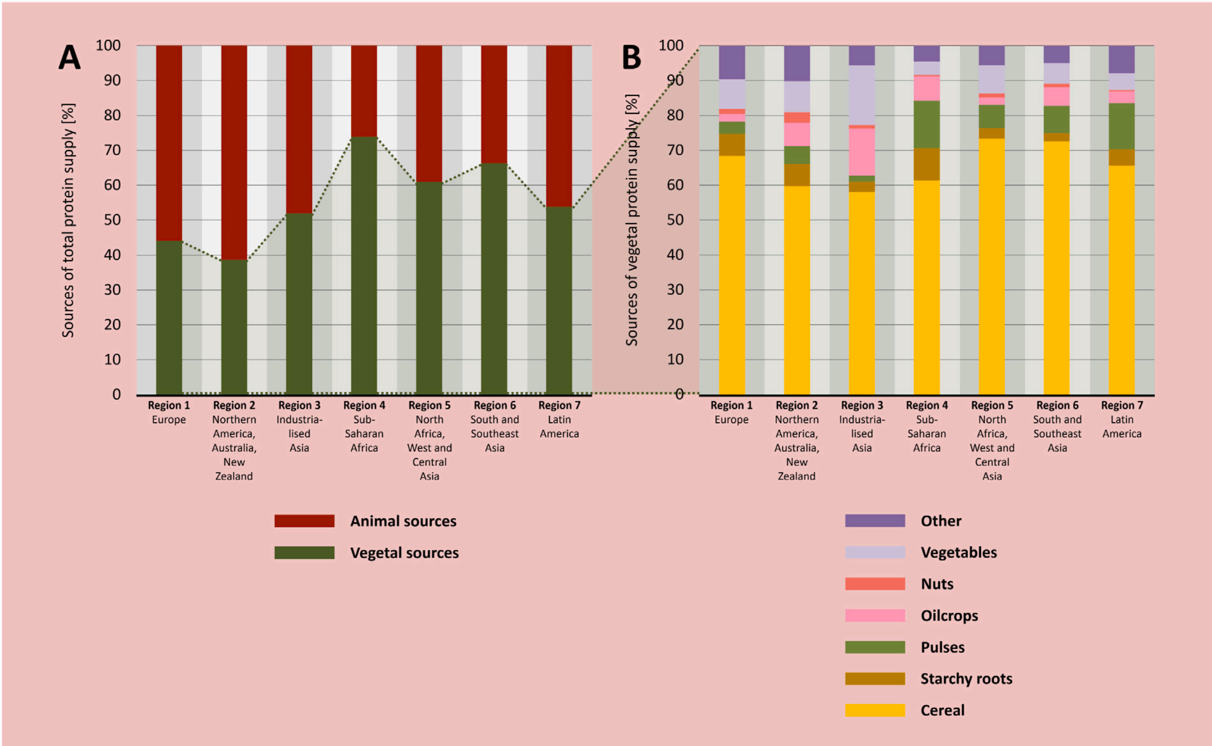

Fig. 2. Sources of protein supply across seven world regions in 2015 according to FAO food balance data (FAOSTAT): (A) Proportions of protein from animal and vegetal sources of total protein supply (based on mean animal and vegetal protein supply across the countries of each region); (B) Proportions of different protein sources of vegetal protein supply (based on mean protein supply from listed vegetal sources across the countries of each region).

Table 1
Supply/consumption of specific food groups across seven world regions.

Supply/consumption [g/capita/day]	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7
Supply cereal	362.2	288.2	479.7	390.3	488.6	588.8	385.1
Consumption cereal	— (no data available)						
EAT-Lancet reference diet	232 (0%–60% of calories) as wholegrain products (rice, wheat, corn and other)						
Supply legumes/oilcrops/nuts	22.1	34.3	34.9	50.0	32.8	58.1	43.2
Consumption legumes/beans/nuts/seeds	18.0	23.1	32.4	26.7	28.7	36.8	27.5
EAT-Lancet reference diet	125 (25–250) legumes, soy foods, peanuts and treenuts						

key strategy (Willett, et al., 2019). But de Boer and Aiking (2017) mentioned that this science-based reasoning seems to be not adequately available to the consumer or is too difficult to comprehend. The gap between consumer behaviour and required change of the food system needs to be addressed at multiple levels (diet, dish, dish ingredients and bites) by the relevant food chain entities (policy-makers, farmers, retailers, food processors, restaurant owners) (Aiking & de Boer, 2020; de Boer & Aiking, 2019; Gravely & Fraser, 2018). For example, the inclusion of environmental health and sustainability considerations in dietary guidelines by policy-makers might not flip a switch and bring about food system transformation on its own, but it could certainly instigate increased acceptance of predominantly plant-based diets and advocate associated health benefits (Aiking & de Boer, 2020; de Boer & Aiking, 2019). Such dietary guidelines have already been established on a national level in several countries, for example, in the UK, the Netherlands, Germany and Sweden (Aiking & de Boer, 2020; Behrens et al., 2017; Gonzalez Fischer & Garnett, 2016). A dietary intervention study published by Micheelsen et al. (2014) in 2014 investigates the acceptability of the "New Nordic Diet", which was established to improve public health in Denmark. This diet is characterised by reduced meat intake (by 35%) and increased intake of plant-based foods (wholegrain foods, fruit, vegetables, nuts) compared to an "Average Danish Diet". Regional and seasonal aspects are also considered to determine the diet's food basket. In an evaluation of the diets environmental impact, it was found that specifically the reduced meat consumption and avoiding long-distance imports contributed to reduced environmental impact of the "New Nordic Diet" in comparison to the "Average Danish Diet" (Saxe, 2014). A key finding of the intervention study was that while it scored high in eating acceptance (tastiness), it lacked practical acceptability (Micheelsen et al., 2014). This seemed to be primarily related to tedious/time-consuming food preparation as well as the perception of high price and limited availability of the required food products. Therefore, practical acceptability was identified as the main barrier to consumers adopting this diet at the time of the intervention study (2010–2011). Macdiarmid et al. (2013) also showed that many consumers seem to have the impression healthy (and environmentally sustainable Aiking & de Boer, 2020) diets are not compatible with their fast-paced lives. This is where other food system sectors like food processing, retail and food service, which have great economic and cultural influence on the food system (Stuckler & Nestle, 2012; Willett, et al., 2019), can help to induce change in consumer food choice and to promote diet shifts. Also, the increasingly important role of innovation and entrepreneurship in the food sector has great potential to drive change in consumer behaviour and the food system in general (Lynde, 2020). What all of these sectors have in common is the need to develop new products. This is why product development should aim to increase diversity of plant-based protein supply and to improve practicability of consuming predominantly plant-based diets by providing healthy plant-based protein-foods in more convenient formats. However, more convenient formats also imply the need for food processing which certainly represents a trade-off regarding the sustainability of these foods; whole legumes, for instance, can be expected to have a lower environmental footprint than processed foods containing legumes. Furthermore, processed foods have an increasingly negative reputation amongst consumers, which is also closely associated with the 'clean-label' trend (Asioli et al., 2017; Román et al., 2017). It is true that diets with high intakes of ultra-processed foods, which are commonly characterised by high fat, sugar and salt contents and low levels of dietary fibre, protein, micronutrients and bioactive compounds, have been associated with an elevated risk of non-communicable diseases and obesity (Fardet, 2018; Jones, 2019; Moubarac, 2015). However, some extent of food processing is indispensable and has assured sufficient and safe food supply for centuries; for example, by increasing shelf life, microbiological quality and digestibility and by reducing ANCs and potentially toxins (Fardet, 2018; Global Panel on Agriculture and Food Systems for Nutrition, 2016; Jones, 2019; Moubarac, 2015). While the consumption of plant-based whole foods is to be encouraged, moderate and targeted processing can help to produce healthy plant-based protein-foods with improved nutritional quality (Fardet, 2018; Magrini et al., 2018). Aschemann-Witzel et al. (2020) conclude in their review from 2020 that consumers' "scepticism toward processing has to be overcome through more plant-based foods meeting both consumer interests": health and 'clean-label'.

4. Targeted product development

Based on the considerations presented above, the development of plant-based protein-foods should follow five key principles, which are summarised in Fig. 3. *(1) Selecting the right protein sources - Principle 1* aims at intentionally choosing those protein sources that, based on scientific evidence, promise both environmental and nutritional benefits. In favour of diversifying plant-based protein supply, mainly non-cereal raw materials should be in the focus (which does not mean that cereal products are not an important and essential part of healthy diets). Also, locally grown crops should be prioritised since the use of local resources is known to considerably lower the environmental footprint of foods (Nijdam et al., 2012; Saxe, 2014; Weindl et al., 2020). *(2) Supporting crop diversity - Principle 2* targets the selection of various different crops as raw materials either in combination for the same product or individually for a range of different products. Crop diversity has been mentioned to be important for soil fertility and in the battle against declining yields and nutritional quality of crops caused by climate change (Gogoi et al., 2018; McGuire & Sperling, 2013; Willett, et al., 2019). Actively choosing various crops for food formulation creates increased demand and could promote their cultivation by farmers, as postulated by Tsolakis et al. (2019) for faba beans. Furthermore, it has been reported that blending different plant-based raw materials is the key to improving nutritional and technological quality of the final food products (Fi Europe, 2020; Salomé et al., 2020). *(3) Using the right ingredients - Principle 3* is directed at choosing the ingredient types (derived from the previously selected protein sources) that are best suited for the application in question. This concerns those ingredients contributing to the protein content (protein ingredients; PIs) of the food as well as other ingredients that are part of the formulation. For PIs, it means choosing the level of protein purification and other types of processing (e.g. heat treatment, enzyme treatment, high-pressure treatment, fermentation, specific chemical modification) that are required. Both protein purification and other processing steps affect physicochemical, techno-functional and nutritional properties of the ingredients (Vogelsang-O'Dwyer, Bez, Petersen, Joehnke, Detzel, et al., 2020; Vogelsang-O'Dwyer, Bez, Petersen, Joehnke, Sørensen, et al., 2020; Vogelsang-O'Dwyer et al., 2021) such as protein content, solubility, dispersibility, protein digestibility, and content of ANCs (Patterson et al., 2017; Sá et al., 2019; Vaz Patto et al., 2015). In support of environmental sustainability, processing should be kept at the necessary level, and raw materials should be used as efficiently as possible. In this context, the use of side-streams from plant-based food production is highly encouraged. Both PIs as well as other ingredients that are often required for the formulation of plant-based protein-foods can be represented by food processing side-streams (Schieber, 2017; Tlais et al., 2020). Especially side-streams high in starch or fibre have been successfully applied as functional ingredients in food product development (Schutyser et al., 2015). *(4) Creating healthy formulations - Principle 4* addresses the need to develop products with adequate nutritional value. The combination of ingredients and further processing steps should be chosen to obtain a final food product with good overall nutritional quality. Protein digestibility is an important factor with impact on nutritional quality and should be considered and monitored in food formulation since it has been shown to greatly depend on food processing and food matrix (Sá et al., 2019). With regard to protein quality, the focus lies on sufficient lysine intake from predominantly plant-based diets (Leinonen et al., 2019). In this regard, also the bioavailability of lysine is crucial and depressed bioavailability due to processing related chemical modification of lysine should be taken into account (Mariotti, 2017; Moughan, 2009). In general, the developed protein-foods should either provide balanced amino acid profiles in accordance with the human requirement pattern (Joint FAO/WHO/UNU Expert Consultation, 2007) or possess an amino acid profile that complements that of cereal proteins in widely consumed staple foods. While protein quality is of great importance in protein-foods, also the presence of other micro- and macronutrients as well as levels of compounds with potentially adverse health effects are to be considered. Specifically, salt, saturated fats and the GL of the foods, which are factors that have been associated with adverse health effects and increased risk of non-communicable diseases, need to be kept at low or moderate levels (Fardet, 2018; Hu et al., 2013; Jenkins, et al., 2021; Jones, 2019; Ludwig, 2002; Moubarac, 2015; Schwingshackl & Hoffmann, 2013). Many plant-based protein sources (e.g. legumes, nuts and seeds) are also known to be rich in dietary fibre, essential minerals like iron and zinc, B vitamins, phenolic compounds and prebiotic oligosaccharides (Vaz Patto et al., 2015), which have been identified as the main contributors to health benefits associated with the consumption of plant foods (Neacsu et al., 2017; Vaz Patto et al., 2015). Therefore, these valuable food constituents should be preserved as much as possible during ingredient and food processing, and adequate levels should remain in the developed plant-based protein-foods. While high levels of these compounds could also be achieved by supplementation with purified food additives, this inevitably requires extensive processing and generally opposes sustainability considerations (Fardet, 2018). Some of the beneficial plant constituents mentioned above (e.g. phenolic compounds, prebiotic oligosaccharides) are also considered as antinutrients (Campos-Vega et al., 2010). Therefore, the contents of these and other ANCs should be monitored during raw material and ingredient selection, but also during food formulation and final processing. *(5) Targeting high consumer acceptance - Principle 5* advocates the combination of the previously discussed principles in a product that, additionally, promises high consumer acceptance. While it would be detrimental for achieving food system transformation to drop any of the principles above in favour of high consumer acceptance, it would be equally disadvantageous to develop expensive products with low sensory quality that decelerate diet shifts by making plant-based protein-foods less appealing to consumers. Research shows that factors like affordability, availability and tastiness still rank above health and sustainability considerations in consumers' food choices (Jones, 2019; Kearney, 2010; Micheelsen et al., 2014; Siró et al., 2008). Providing a wide range of tasty and convenient plant-based protein-foods with a healthy nutritional pattern could help steer consumer food choices towards healthier and more sustainable products. A more detailed view

(1) Selecting the right protein sources

Prioritising crops that promise nutritional and environmental benefit as main raw material

(2) Supporting crop diversity

Choosing blends of various crops for one product or choosing different crops for different products

(3) Selecting the right ingredients

Choosing application-specific ingredients, with the right level of protein purity
→ As processed as necessary, as natural as possible

(4) Creating overall healthy formulations

Focusing on protein quantity/quality but also considering fibre, vitamins, GI, saturated fats and salt

(5) Targeting high consumer acceptance

Combining the principles above with appealing sensory attributes and moderate pricing

Fig. 3. Principles of targeted plant-based protein-food development.

on which protein sources, ingredient types and food applications are the most promising for the development of plant-based protein-foods according to these five principles is given in the following sections.

One question that remains is how plant-based protein-foods will be identified by consumers as what they are, specifically because consumers seem to lack knowledge about good sources of dietary protein and adequate quantities (Banovic et al., 2018; Lonnie & Johnstone, 2020; Tarabella & Burchi, 2015). Nutrition and health related information given as part of food labelling is legally regulated in many countries and attached to specific requirements concerning the food product's composition and nutritional quality. The requirements for protein related statements vary between countries and refer to different variables such as weight-based protein content per serving, energy-based protein content per serving or protein quality determined *in vivo* (Marinangeli et al., 2018). In order to be able to make consumers aware of the nature of plant-based protein-foods, the respective requirements should be considered during product development. For instance, according to European legislation, a food qualifies for the claim 'source of protein' when at least 12% of calories are provided by protein and for the claim 'high in protein' when at least 20% of calories are provided by protein (European Parliament & Council, 2006). The identification of protein-foods based on the percentage of calories that is provided by protein seems desirable in the light of widespread calorie overconsumption. This is particularly important for plant-based substitutes of animal foods since animal foods typically have a high protein-energy/total-energy ratio (Phillips et al., 2016).

4.1. Promising protein sources

Plant-based dietary protein can be obtained from a great variety of sources, including the following: cereals, pseudocereals, legumes, oilseeds, nuts, starchy roots/tubers, vegetables/leaves/shoots, fruit and algae (Loveday, 2020; Petrusán et al., 2016; Sá et al., 2020). The suitability of these plant sources for protein supply in human nutrition, in terms of environmental sustainability and human health, depends on many aspects, including their natural protein content, cost for harvesting, availability of processing techniques, extent of required processing, geographical location and climate (Sá et al., 2020). *Cereals* have been an important food source for centuries. With an annual production of nearly 3000 million tonnes (mt), cereals also are the most cultivated crop category worldwide in comparison to sugar crops with approx. 2200 mt, oilcrops with 1100 mt and pulses with only 88 mt (FAOSTAT 2019). Even though cereals, with an average protein content of 10%–12%, do not count as the plant sources with the highest protein levels, they still represent a substantial source of dietary protein since they are consumed in large quantities (for example, in the form of staple foods bread and pasta). As demonstrated above, the majority of plant-based protein supply is covered by cereals and cereal products in currently consumed diets. Due to a low abundance of IAAs such as lysine and potentially threonine and tryptophan (relative to human AA requirement pattern Joint FAO/WHO/UNU Expert Consultation, 2007) (Huang et al., 2018; Sá et al., 2020; Sosulski & Imafidon, 1990), a diversification of plant-based protein intake has been advocated to ascertain adequate protein supply from predominantly plant-based diets (Mariotti & Gardner, 2019; Neacsu et al., 2017; Salomé et al., 2020). Therefore, cereals are not in the focus as main protein source for formulating new plant-based protein-foods. Besides, from an environmental point of view, it has been argued that an increased cultivation of food crops other than maize, wheat and rice (e.g. less common cereals such as oat, sorghum, millet or non-cereal crops) for food production is desirable for improved crop rotation systems and agricultural biodiversity (Magrini et al., 2018; Willett, et al., 2019). However, cereal proteins possess unique techno-functional characteristics (Boukid & Rosene, 2020) and their utilisation for plant-based protein-foods as functional ingredients or as PIs to complement other protein sources is to be encouraged. *Pseudocereals* such as buckwheat, quinoa and amaranth, which are also referred to as edible seeds or ancient grains, contain with 12%–19% slightly more protein than cereals (Martínez-Villaluenga et al., 2020; Mota et al., 2016). Pseudocereals additionally have a more balanced profile of IAAs than cereals. Especially the lysine level is higher than in most cereal sources (Martínez-Villaluenga et al., 2020; Mota et al., 2016; Sosulski & Imafidon, 1990). Potentially limiting (amino acid scores (AASs) between 0.8 and 1.0) amino acids in comparison to the human requirement pattern (Joint FAO/WHO/UNU Expert Consultation, 2007) are isoleucine, leucine, lysine and valine (Mota et al., 2016). Due to an overall excellent nutritional profile, considering contents of minerals, vitamins and phytochemicals in addition to the balanced amino acid profile, pseudocereals have been mentioned as "the grains of the twenty-first century" (FAO, 2011b; Martínez-Villaluenga et al., 2020).

This statement is further supported by the environmental benefits of these crops. Ancient grains are known as sustainable crops that produce adequate and consistent yields with minimal agricultural inputs (Taylor et al., 2017). Moreover, they are valued with regard to their genetic diversity and their potential to grow under harsh conditions (Taylor et al., 2017). This latter aspect is particularly important with respect to increasingly difficult climatic conditions due to climate change (Willett, et al., 2019). Manners, Varela-Ortega, and van Etten (2020) evaluated the suitability of various protein-rich crops (pseudocereals and legumes) considering the current and future climate in Europe and identified quinoa as the pseudocereal with the most significant potential. But in spite of all their positive traits, crops like quinoa, amaranth and buckwheat remain largely underutilised as food (protein) sources in many parts of the world (Taylor et al., 2017) (global annual production of approx. 1.61 mt for buckwheat and 0.16 mt for quinoa; FAOSTAT 2019). Chia is another type of pseudocereal, which is best-known for its high content of dietary fibre (34.0–53.8%) (Cahill, 2003; Welti-Chanes et al., 2020). But apart from being a valuable source of dietary fibre, chia contains between 18 and 24% protein (Grancieri et al., 2019). However, the relatively low lysine content compared to the other pseudocereals makes it slightly less promising to complement cereal-based protein intake. Furthermore, due to its status as novel food, food applications for chia are more restricted than for other raw materials in the European Union (Kulczyński et al., 2019). A very promising group of plant-based protein sources is the *legume family* with protein contents of 20%–40% (Arntfield & Maskus, 2011; Boye et al., 2010; Sá et al., 2020). This group includes pulses, which are defined as legumes that are harvested exclusively to obtain dry seeds (FAO, 1994; Petrusán et al., 2016). Many legumes possess an amino acid profile that complements that of cereals. Specifically, high lysine contents (higher than in cereals and often even higher than in human requirement pattern Joint FAO/WHO/UNU Expert Consultation, 2007) have been reported (Iqbal et al., 2006; Sá et al., 2020; Sosulski & Imafidon, 1990). This makes legumes and oilseeds the most favourable plant-based protein sources to include in cereal-rich diets from a nutritional point of view (Mariotti & Gardner, 2019). The environmental benefits associated with growing legumes are another reason for their importance in transforming the food system. The disruption of nitrogen cycles, which is mainly caused by the excessive application of synthetically produced fertilisers, is one of the most severe environmental impacts of food production (Willett, et al., 2019). Cropping systems that include legumes require less fertiliser due to their ability to produce nitrogen and improve soil fertility (Gogoi et al., 2018; Magrini et al., 2018). Soy, which belongs to the legume family but is often considered as oilcrop (also the case for peanuts), is one of the most popular plant-based protein sources, and its global production amounts to 333 mt per year (FAOSTAT 2019) (Zhao et al., 2020). However, it has gained increasingly negative reputation during the last decade due to its allergenicity and the cultivation of genetically modified soy (Banovic et al., 2018; Gonera & Milford, 2018). The use of genetically modified organisms (GMOs) is surrounded by concerns regarding human health and environmental implications. While there is very little scientific evidence indicating adverse effects caused by approved GMO food crops and the net environmental impact of GMOs is probably positive (Wesseler et al., 2011), it remains a controversial topic, and no international consensus has been reached in the scientific (and political) community (Ekici & Sancak, 2011; Kramkowska et al., 2013). This review does not cover a detailed discussion of advantages and disadvantages of genetic engineering of food crops. However, the persisting consumer scepticism towards GMO foods needs to be mentioned (Fernbach et al., 2019; Kosseva, 2013). This has led to a growing replacement of soy in food applications by alternative plant-based protein sources like pea and lupin (Islam et al., 2012; Lam et al., 2018). Also, other legumes have moved into the focus for plant-based protein supply, including faba bean, chickpea, lentil and mung bean (Sá et al., 2020). However, more research is needed since cold-weather legumes, such as faba bean, lentil, lupin, pea and chickpea, seem more susceptible to abiotic stresses (compared to warm-weather legumes like soy) and yield instabilities have been observed (Jensen et al., 2010; Manners, Varela-Ortega, & van Etten, 2020). Similar to pseudocereals, legumes continue to be drastically underutilised for human nutrition and plant-based protein supply (Magrini et al., 2018). As mentioned above, according to the EAT-Lancet reference diet (which considers human and environmental health), a much higher consumption of legumes is recommended (Willett, et al., 2019). *Non-legume oilseeds and nuts* represent another group of promising plant-based protein sources (Arrutia et al., 2020; Kotecka-Majchrzak et al., 2020). Interesting members of this group are rapeseed/canola, sunflower seed, flax seed, hempseed, pumpkin seed, sesame seed, sacha inchi seed, almonds and cashew nuts, which contain approx. 16%–36% protein (Kotecka-Majchrzak et al., 2020; Sá et al., 2020; Wang et al., 2018). While the amino acid profiles of these protein sources vary greatly, some examples stand out due to high levels of lysine (e.g. rapeseed/canola, baru almond) (Kotecka-Majchrzak et al., 2020; Sá et al., 2020). Apart from being a source of dietary protein, oilseeds and nuts provide high levels of mono- and polyunsaturated fatty acids, which makes their nutritional profile even more valuable for human diets (Albuquerque et al., 2020). Oilseed proteins can be obtained from oilseed press cakes as a side-stream of vegetable oil production, which suggests oilseeds as a sustainable source of dietary protein with low carbon footprint (Arrutia et al., 2020). Nevertheless, processing oily raw materials continues to be challenging, and further research and technological advances are needed (Arrutia et al., 2020). *Other plants like starchy roots/tubers, vegetables/leaves/shoots and fruits* generally have lower protein contents (exceptions are bamboo leaves and ora-pro-nobis leaves with 13 and 28% protein, respectively) (Petrusán et al., 2016; Sá et al., 2020). Therefore, the relevance of these plants as protein sources (without processing to concentrate protein) strongly depends on the quantities that are consumed. Furthermore, the utilisation of these protein sources for the formulation of plant-based protein-foods would require protein concentration. With respect to environmental sustainability, the value of these protein sources depends on the extent of required processing and whether processing side-streams can be valorised (e.g. potato starch) (Alting et al., 2011). Aquatic plants like *algae* (e.g. seaweed, Chlorella and Spirulina) *and duckweed* also qualify as plant-based protein sources with protein contents as high as 40%–60% (algae) or 20%–35% (duckweed) based on dry matter (Appenroth et al., 2017; Chronakis & Madsen, 2011). Most algae and duckweed species possess relatively balanced amino acid profiles in comparison to the human requirement pattern (Appenroth et al., 2017; Chronakis & Madsen, 2011; Joint FAO/WHO/UNU Expert Consultation, 2007). Some algae, like *Chlorella vulgaris*, have been reported to be particularly rich in lysine (exceeding the lysine content in the human requirement pattern by nearly 100%) (Chronakis & Madsen, 2011). Both algae and duckweed have been mentioned as promising alternative proteins with respect to nutritional and environmental considerations. However, further research is needed with regard to nutritional characteristics, sustainability and yields in large-scale production (Appenroth et al., 2017; Caporgno & Mathys, 2018). This is also the case for *yeast and fungal mycelium* (Matassa et al., 2016). While these protein sources are not plant-based, they represent emerging non-animal protein sources with great potential for the formulation of sustainable protein-foods. Fig. 4 summarises how the principles of targeted product development can be applied at the level of protein sources.

4.2. Promising ingredient types

Raw material processing to produce ingredients is usually associated with at least one (or multiple) of the following objectives: improving techno-functional characteristics (e.g. facilitating application in food formulations), improving nutritional quality (e.g. protein concentration

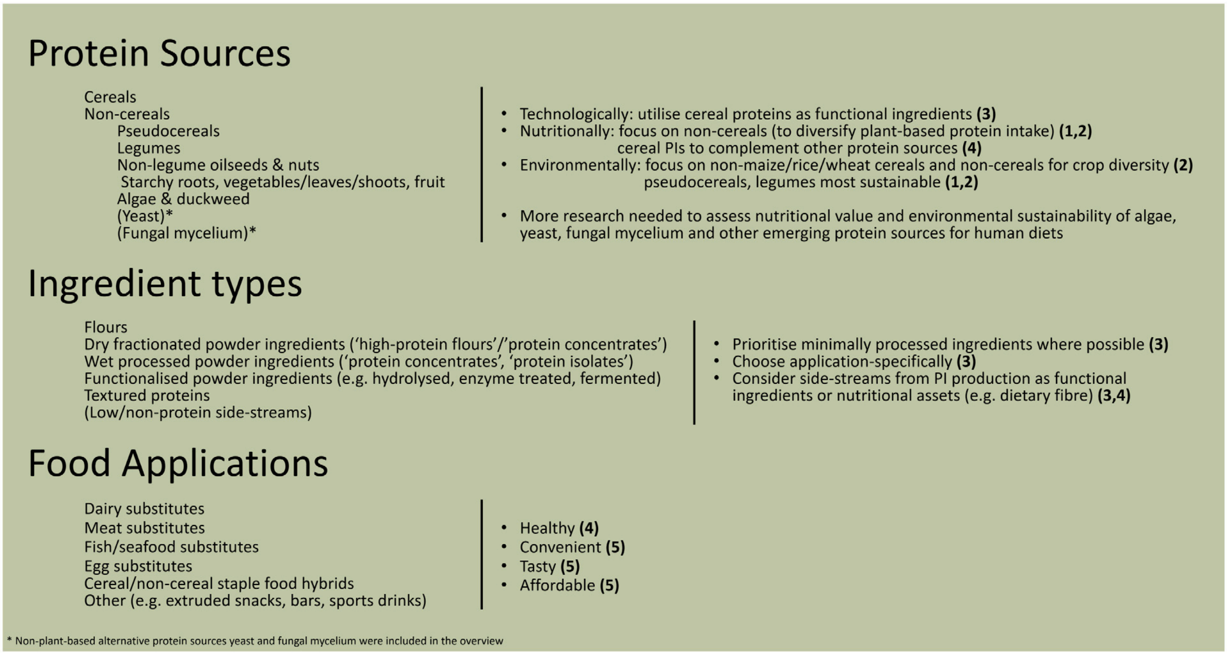

Fig. 4. Overview of plant-based* protein sources, ingredients and food applications relevant for the development of plant-based protein-foods. Bold numbers in brackets refer to the principles of targeted product development introduced above.

and removal of ANCs and allergens), improving food safety (e.g. extending shelf life), improving sensory qualities (e.g. removal of undesirable aroma compounds) (Fardet, 2018). *Flours* are typically obtained by grinding dry raw materials (for raw materials with a high water content potentially preceded by a drying step), in some cases after removal of inedible/undesirable parts (e.g. dehulling) (Fardet, 2018). Flours, especially when derived from raw materials with a naturally high protein content (e.g. pseudocereals, pulses), can represent valuable and sustainable ingredients for the formulation of plant-based protein-foods. However, various food applications (e.g. plant-based beverages such as milk substitutes) require ingredients with a higher degree of protein purification (Vogelsang-O'Dwyer et al., 2021). Protein purification can be achieved with either dry fractionation or wet processing, and the produced ingredients are usually referred to as protein concentrates (in the case of dry fractionation sometimes high-protein flour) or protein isolates (protein content usually > 80% based on dry matter) (Ismail et al., 2020). *Dry fractionation* has been described as sustainable processing option to produce plant-based PIs (especially for pulses) and requires far less energy and water than wet processing (Schutyser et al., 2015; Schutyser & van der Goot, 2011; Vogelsang-O'Dwyer, Bez, Petersen, Joehnke, Sørensen, et al., 2020). Due to the mild processing conditions, proteins can retain their native and sometimes better functionality (Schutyser et al., 2015; Vogelsang-O'Dwyer, Bez, Petersen, Joehnke, Sørensen, et al., 2020; Vogelsang-O'Dwyer et al., 2021). *Wet processing* can be applied to a variety of starting materials, including flours, previously dry fractionated high-protein flours or previously defatted raw materials (e.g. oilseed press cakes) (Arrutia et al., 2020; Vogelsang-O'Dwyer et al., 2021). Commonly used wet processing methods are isoelectric precipitation, ultrafiltration and salt extraction/micellisation (Vogelsang-O'Dwyer et al., 2021). Protein isolates derived from the same raw material but produced with different wet processing methods can vary greatly in their techno-functional and nutritional properties (Alonso-Miravalles et al., 2019; Skejovic Joehnke et al., 2021). While wet processing requires higher energy and water input than dry fractionation, life cycle assessment (LCA) has shown that wet processed plant-based PIs are still a sustainable ingredient option, for example, when compared to milk protein (Alonso-Miravalles et al., 2019; Vogelsang-O'Dwyer, Bez, Petersen, Joehnke, Detzel, et al., 2020; Vogelsang-O'Dwyer, Bez, Petersen, Joehnke, Sørensen, et al., 2020). Additional processing can be applied to either raw materials or ingredients in order to produce functionalised ingredients. Such treatments include (partial) protein hydrolysis, enzymatic treatments (other than hydrolysis), heat treatment or fermentation (Amagliani et al., 2017; Bühler et al., 2020; Hoehnel, Bez, Sahin, et al., 2020; Kårlund et al., 2020; Qamar et al., 2020; Tangyu et al., 2019; Vogelsang-O'Dwyer et al., 2021). Another way of functionalising plant-based protein is the production of texturised vegetable protein (TVP) (Riaz, 2011). Texturisation is commonly achieved by applying a combination of thermal and mechanical energy (extrusion technology), and a large variety of different TVP types can be produced representing either textured PIs (e.g. for application in meat substitute systems) or final food products (e.g. meat substitutes) (Riaz, 2011). Side-streams from the above-mentioned processing techniques or from the production of other plant-based foods can be used in the formulation of plant-based protein foods (Aiking, 2011; Løkra & Strætkvern, 2009; Lynch et al., 2016; Neylon et al., 2020; Schieber, 2017; Tlais et al., 2020). Depending on the nature of the respective side-stream, they may be applied as PIs, as sources of valuable macro- and micronutrients (e.g. dietary fibre and minerals) or as functional ingredients to optimise sensory and nutritional properties of the protein-foods. Fig. 4 summarises how the principles of targeted product development can be applied at the level of ingredient types.

4.3. Promising food applications

This section deals with consumer product options (types of protein-foods) that have high potential to diversify plant-based protein intake. The first product group comprises plant-based substitutes of traditional animal-based foods, which play an essential role in the shift to predominantly plant-based diets due to their increasing consumer acceptance and market share (Alcorta et al., 2021; Blanco-Gutiérrez et al., 2020; ProVeg International, 2020; Smart Protein - ProVeg International, 2021). This group includes *dairy substitutes* (milk, yoghurt, cheese, cream and ice cream), *meat substitutes* (sausages, chicken nuggets, burger patties, meatballs, whole cuts of meat), *fish/seafood substitutes* and *egg substitutes* (Jeske et al., 2016; ProVeg International, 2020; Sha & Xiong, 2020; Tziva et al., 2020; Vogelsang-O'Dwyer et al., 2021).

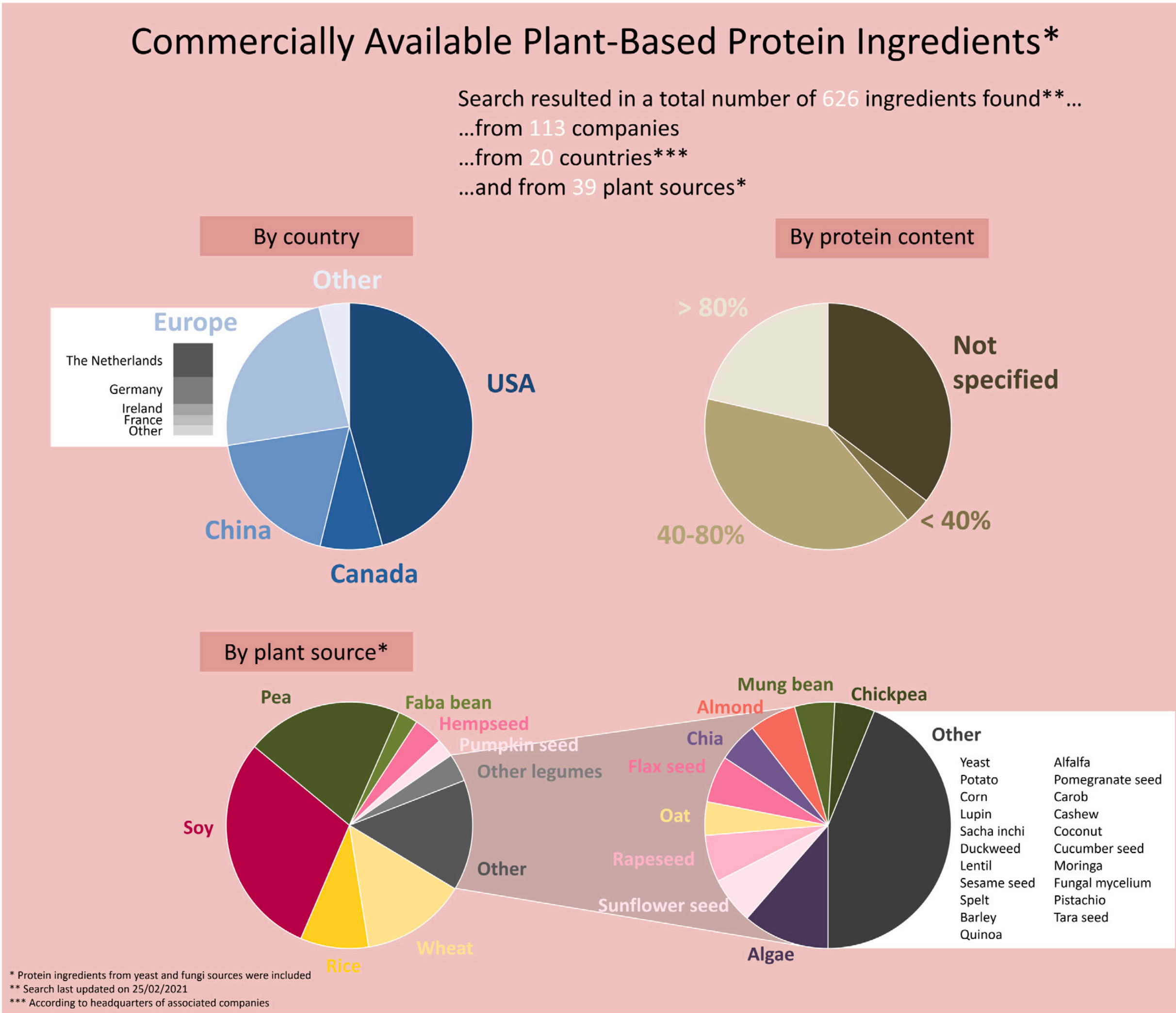

Fig. 5. Overview of commercially available plant-based* protein ingredients (last updated on 25/02/2021), including ingredients from the non-animal protein sources yeast and fungi.

However, the 2020 report on plant-based ingredients and their integration across food and drink categories (by Food Ingredients Europe) states: "Plant-based is about more than meat alternatives. Consumers also are looking for more fruits, vegetables, grains and legumes in convenient formats" (Fi Europe, 2020). Another product group that offers an excellent opportunity to diversify plant-based protein intake is comprised of cereal/non-cereal staple food hybrids, which refers to cereal-based staple foods (e.g. bread and pasta) that contain non-cereal PIs (Boukid et al., 2019; Bresciani & Marti, 2019; Bustos et al., 2015). These cereal/non-cereal staple food hybrids represent a direct diversification of plant-based protein supply within the very product group, which currently contributes to the high proportion of cereal protein in overall vegetal protein supply. The perceived high level of convenience of cereal staple foods amongst consumers further highlights their potential. Moreover, bread and pasta applications require less protein purity than some other protein-foods and allow for the utilisation of minimally processed PIs such as flours and high-protein flours (Hoehnel et al., 2019; Hoehnel, Bez, Amarowicz, et al., 2020; Hoehnel, Bez, Petersen, Amarowicz, Juśkiewicz, Arendt, Zannini, 2020; Hoehnel, Bez, Petersen, Amarowicz, Juśkiewicz, Zannini, Arendt, 2022). It has been shown that the incorporation of legume and pseudocereal PIs also improves the overall nutritional profile of bread and pasta (Hoehnel, Bez, Petersen, Amarowicz, Juśkiewicz, Arendt, Zannini, 2020; Hoehnel, Bez, Petersen, Amarowicz, Juśkiewicz, Zannini, Arendt, 2022). The partial replacement of wheat flour or wheat semolina by non-cereal PIs in the recipes leads to an isocaloric replacement of starch by non-cereal protein in the food matrix (assuming the non-cereal PI contains more protein than wheat flour or wheat semolina). Therefore, a lowered GL and potentially improved satiating effect (due to increased total protein content) of such protein-foods can be expected (Hoehnel, Bez, Petersen, Amarowicz, Juśkiewicz, Arendt, Zannini, 2020; Hoehnel, Bez, Petersen, Amarowicz, Juśkiewicz, Zannini, Arendt, 2022). Other protein-foods, which can contribute to a diversification of plant-based protein supply when produced according to the principles of targeted product development, are the following: extruded snacks, sauces and dressings, bars, smoothies, porridge, sports drinks/sports nutrition products (ProVeg International, 2020). Fig. 4 summarises how the principles of targeted product development can be applied at the level of food applications.

4.4. Currently commercially available plant-based protein ingredients

For the formulation of plant-based protein-foods, product developers rely heavily on the availability of suitable ingredients. This refers to all plant-based ingredients needed for the recipe but primarily to the main ingredients, PIs, that deliver a substantial amount of protein. For the purpose of this review, a web search was performed to obtain an overview of currently commercially available plant-based PIs. The search was focused on plant-based PIs in powder form. However, also textured PIs and non-plant-based alternative protein sources like yeast and fungi were considered. Minimally processed grains and pulses available as simple flours, which can represent promising PIs for certain applications (especially flours of high-protein plant sources), were not the focal point of the search due to their vast abundance (at least for some plant sources). The plant protein market is rapidly growing and constantly changing. The results presented in Fig. 5 on currently commercially available plant-based PIs are based on a web search which was last updated on February 25th, 2021. Seventy-two (11.5%) of the 626 evaluated ingredients were marketed as textured proteins, while the remaining 554 were described as PIs in powder form (labelled "protein", "protein concentrate" or "protein isolate"). The full list of PIs is available in the supplementary material to this article. Fig. 5 provides an overview of the evaluated PIs sorted by country, by protein content and by plant source. The categorisation by country is based on the headquarters of the company associated with each ingredient. A substantial proportion of ingredients is associated with US (45.7%), Chinese (18.7%) or Canadian (8.1%) companies. Also, European companies provide a large number of plant-based PIs, accounting for 23.5% of all evaluated ingredients. Other countries with significant contributions include India (1.4%), Switzerland (1.3%), Japan (0.6%), Thailand (0.6%) and Argentina (0.5%). The ingredients were also classified with regard to their protein contents. For 35.3% of the evaluated ingredients, the protein content was not specified on the suppliers' webpage and only available upon request. Two out five ingredients were advertised with protein contents between 40 and 80%, and for approx. one out of five, a protein content of over 80% was declared. A protein level of less than 40% was only specified for a small proportion of ingredients. This can be attributed to the exclusion of grain and pulse flours from the search, which would be expected to be the main contributors to this protein content category. The 626 evaluated ingredients are derived from 39 different sources: 37 plant sources, yeast and fungi. The four plant sources that stand out are soy, pea, wheat and rice, which account for 29.6%, 20.6%, 13.9% and 8.9% of all ingredients, respectively. One reason for the large proportion of PIs from these well-established plant sources is related to the more extensive (research) knowledge and experience with these raw materials (Zhao et al., 2020). Therefore, these PIs are often available as a range of specialised ingredient types with optimised techno-functional characteristics for specific applications. Other PIs with significant market share are derived from faba bean (2.6%), hemp (3.8%) and pumpkin seed (2.4%). Many promising and emerging plant-based protein sources such as mung bean, chickpea, lentil, quinoa and algae (as well as yeast and fungi) still seem underrepresented amongst commercially available PIs. It is unlikely that the presented data include every plant-based PI on the market. Additionally, overlapping and conflicting information from suppliers and manufacturers can lead to double entries in some cases where product names are not clear. However, the presented data are suitable to identify trends regarding commercially available plant-based PIs. While the plant-based sector is growing and more and more PIs have become available in recent years, the majority (approx. 73.0%) of PIs is derived from only four different plant sources (according to the internet search performed for this review): soy, pea, wheat and rice. In order to improve the diversity of plant-based protein intake by consumers, an improved availability of PIs from a larger range of promising plant sources is required. This will help to provide a diverse range of healthy plant-based protein-foods in convenient formats.

5. Conclusion

There is sufficient evidence to show that protein is consumed in larger amounts than currently recommended in many high-/medium-income countries. However, many uncertainties about adequate protein intake for optimal health remain. Furthermore, between 45 and 60% of the protein supply in high-/medium-income is covered by animal foods, and the majority of vegetal protein supply in diets worldwide is covered by cereal protein. A shift to predominantly plant-based diets to protect human and environmental health should include a diversification of plant-based protein intake as well as a reduction of calorie overconsumption and a moderation of diet GL. Formulating plant-based protein-foods with these targets in mind can help to advance the food system's transformation. However, consumer food choice is a complex process and represents a potentially limiting factor for a shift towards predominantly plant-based diets. Targeted product development of tasty, convenient and healthy plant-based protein-foods has great potential to guide consumers' participation in transforming the food system.

Acknowledgements

The authors want to thank ProVeg International and The Good Food Institute for advice and valuable input regarding commercially available plant-based protein ingredients. The work for this study has been undertaken as part of the project PROTEIN2FOOD. The project has received funding from the European Union's Horizon 2020 research and innovation programme (grant agreement No 635727).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

The following abbreviations are used in this manuscript:

ANC	Antinutritional compound
AAS	Amino acid score
DIAAS	Digestible indispensable amino acid score
FAO	Food and Agriculture Organization of the United Nations
GDD	Global Dietary Database
GI	Glycaemic index
GL	Glycaemic load
GMO	Genetically modified organism
IAA	Indispensable amino acid
PDCAAS	Protein digestibility corrected amino acid score
PI	Protein ingredient
RDS	Rapidly digestible starch
SDG	Sustainable Development Goals
TVP	Texturised vegetable protein
WHO	World Health Organization
WRI	World Resources Institute

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.tifs.2022.08.007.

References

Abu Hatab, A., Cavinato, M. E. R., Lindemer, A., & Lagerkvist, C. J. (2019). Urban sprawl, food security and agricultural systems in developing countries: A systematic review of the literature. *Cities*, *94*, 129–142. http://dx.doi.org/10.1016/j.cities.2019.06.001.

Ahnen, R. T., Jonnalagadda, S. S., & Slavin, J. L. (2019). Role of plant protein in nutrition, wellness, and health. *Nutrition Reviews*, *77*(11), 735–747. http://dx.doi.org/10.1093/nutrit/nuz028.

Aiking, H. (2011). Future protein supply. *Trends in Food Science and Technology*, *22*, 112–120. http://dx.doi.org/10.1016/j.tifs.2010.04.005.

Aiking, H. (2014). Protein production: planet, profit, plus people? *The American Journal of Clinical Nutrition*, *100*(suppl), 483S–489S. http://dx.doi.org/10.3945/ajcn.113.071209.

Aiking, H., & de Boer, J. (2020). The next protein transition. *Trends in Food Science and Technology*, *105*(2018), 515–522. http://dx.doi.org/10.1016/j.tifs.2018.07.008.

Albuquerque, T., Nunes, M. A., Bessada, S., Costa, H., & Oliveira, M. (2020). Biologically active and health promoting food components of nuts, oilseeds, fruits, vegetables, cereals, and legumes. In *Chemical analysis of food* (2nd ed.). (pp. 609–656). Elsevier Inc, http://dx.doi.org/10.1016/B978-0-12-813266-1.00014-0.

Alcorta, A., Porta, A., Tárrega, A., Alvarez, M. D., & Vaquero, M. P. (2021). Foods for plant-based diets: Challenges and innovations. *Foods*, *10*(2), Article 293. http://dx.doi.org/10.3390/foods10020293.

Alexandratos, N., & Bruinsma, J. (2012). *World agriculture towards 2030/2050: the 2012 revision: ESA working paper*, Rome: FAO.

Alonso-Miravalles, L., Jeske, S., Bez, J., Detzel, A., Busch, M., Krueger, M., Wriessnegger, C. L., O'Mahony, J. A., Zannini, E., & Arendt, E. K. (2019). Membrane filtration and isoelectric precipitation technological approaches for the preparation of novel, functional and sustainable protein isolate from lentils. *European Food Research and Technology*, *245*, 1855–1869. http://dx.doi.org/10.1007/s00217-019-03296-y.

Alsaffar, A. A. (2011). Effect of food processing on the resistant starch content of cereals and cereal products - a review. *International Journal of Food Science & Technology*, *46*, 455–462. http://dx.doi.org/10.1111/j.1365-2621.2010.02529.x.

Alting, A. C., Pouvreau, L., Giuseppin, M. L. F., & van Nieuwenhuijzen, N. H. (2011). Potato proteins. In G. O. Phillips, & P. A. Williams (Eds.), *Handbook of food proteins* (pp. 316–334). Cambridge: Woodhead Publishing Limited, http://dx.doi.org/10.1533/9780857093639.316.

Amagliani, L., O'Regan, J., Kelly, A. L., & O'Mahony, J. A. (2017). Composition and protein profile analysis of rice protein ingredients. *Journal of Food Composition and Analysis*, *59*, 18–26. http://dx.doi.org/10.1016/j.jfca.2016.12.026.

Appenroth, K. J., Sree, K. S., Böhm, V., Hammann, S., Vetter, W., Leiterer, M., & Jahreis, G. (2017). Nutritional value of duckweeds (*lemnaceae*) as human food. *Food Chemistry*, *217*, 266–273. http://dx.doi.org/10.1016/j.foodchem.2016.08.116.

Arntfield, S. D., & Maskus, H. D. (2011). Peas and other legume proteins. In G. O. Phillips, & P. A. Williams (Eds.), *Handbook of food proteins* (pp. 233–266). Cambridge: Woodhead Publishing Limited, http://dx.doi.org/10.1533/9780857093639.233.

Arrutia, F., Binner, E., Williams, P., & Waldron, K. W. (2020). Trends in food science & technology oilseeds beyond oil: Press cakes and meals supplying global protein requirements. *Trends in Food Science and Technology*, *100*, 88–102. http://dx.doi.org/10.1016/j.tifs.2020.03.044.

Aschemann-Witzel, J., Gantriis, R. F., Fraga, P., & Perez-Cueto, F. J. (2020). Plant-based food and protein trend from a business perspective: markets, consumers, and the challenges and opportunities in the future. *Critical Reviews in Food Science and Nutrition*, http://dx.doi.org/10.1080/10408398.2020.1793730.

Asioli, D., Aschemann-Witzel, J., Caputo, V., Vecchio, R., Annunziata, A., Næs, T., & Varela, P. (2017). Making sense of the clean label trends: A review of consumer food choice behavior and discussion of industry implications. *Food Research International*, *99*, 58–71. http://dx.doi.org/10.1016/j.foodres.2017.07.022.

Banovic, M., Arvola, A., Pennanen, K., Duta, D. E., Brückner-Gühmann, M., Grunert, K. G., & Lähteenmäki, L. (2018). Foods with increased protein content: A qualitative study on European consumer preferences and perceptions. *Appetite*, *125*, 233–243. http://dx.doi.org/10.1016/j.appet.2018.01.034.

Behrens, P., Kiefte-De Jong, J. C., Bosker, T., Rodrigues, J. F., De Koning, A., & Tukker, A. (2017). Evaluating the environmental impacts of dietary recommendations. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(51), 13412–13417. http://dx.doi.org/10.1073/pnas.1711889114.

Berendsen, A. A., van de Rest, O., Feskens, E. J., Santoro, A., Ostan, R., Pietruszka, B., Brzozowska, A., Stelmaszczyk-Kusz, A., Jennings, A., Gillings, R., Cassidy, A., Caille, A., Caumon, E., Malpuech-Brugere, C., Franceschi, C., & de Groot, L. C. (2018). Changes in dietary intake and adherence to the NU-AGE diet following a one-year dietary intervention among European older adults—Results of the NU-AGE randomized trial. *Nutrients*, *10*(12), Article 1905. http://dx.doi.org/10.3390/nu10121905.

Berryman, C. E., Agarwal, S., Lieberman, H. R., Fulgoni, V. L., & Pasiakos, S. M. (2016). Diets higher in animal and plant protein are associated with lower adiposity and do not impair kidney function in US adults. *The American Journal of Clinical Nutrition*, *104*(3), 743–749. http://dx.doi.org/10.3945/ajcn.116.133819.

Blanco-Gutiérrez, I., Varela-Ortega, C., & Manners, R. (2020). Evaluating animal-based foods and plant-based alternatives using multi-criteria and SWOT analyses. *International Journal of Environmental Research and Public Health*, *17*(21), Article 7969. http://dx.doi.org/10.3390/ijerph17217969.

Boukid, F., & Rosene, S. (2020). Grain proteins : Challenges and solutions in developing consumer-relevant foods. *Cereal Foods World*, *65*(6), http://dx.doi.org/10.1094/CFW-65-6-0062.

Boukid, F., Zannini, E., Carini, E., & Vittadini, E. (2019). Pulses for bread fortification: A necessity or a choice? *Trends in Food Science and Technology*, *88*, 416–428. http://dx.doi.org/10.1016/j.tifs.2019.04.007.

Boye, J. I., Aksay, S., Roufik, S., Ribéreau, S., Mondor, M., Farnworth, E., & Rajamohamed, S. H. (2010). Comparison of the functional properties of pea, chickpea and lentil protein concentrates processed using ultrafiltration and isoelectric precipitation techniques. *Food Research International*, *43*(2), 537–546. http://dx.doi.org/10.1016/j.foodres.2009.07.021.

Bresciani, A., & Marti, A. (2019). Using pulses in baked products: Lights, shadows and potential solutions. *Foods*, *8*(10), Article 451. http://dx.doi.org/10.3390/foods8100451.

Bühler, J. M., Dekkers, B. L., Bruins, M. E., & Van Der Goot, A. J. (2020). Modifying faba bean protein concentrate using dry heat to increase water holding capacity. *Foods*, *9*(8), Article 1077. http://dx.doi.org/10.3390/foods9081077.

Bustos, M., Perez, G., & Leon, A. (2015). Structure and quality of pasta enriched with functional ingredients. *RSC Advances*, *5*, 30780–30792. http://dx.doi.org/10.1039/C4RA11857J.

Cahill, J. P. (2003). Ethnobotany of *Chia, Salvia hispanica* L. (*Lamiaceae*). *Economic Botany*, *57*(4), 604–618. http://dx.doi.org/10.1663/0013-0001(2003)057[0604:EOCSHL]2.0.CO;2.

Campos-Vega, R., Loarca-Piña, G., & Oomah, B. D. (2010). Minor components of pulses and their potential impact on human health. *Food Research International*, *43*(2), 461–482. http://dx.doi.org/10.1016/j.foodres.2009.09.004.

Caporgno, M. P., & Mathys, A. (2018). Trends in microalgae incorporation into innovative food products with potential health benefits. *Frontiers in Nutrition*, *5*(58), http://dx.doi.org/10.3389/fnut.2018.00058.

Chardigny, J. M., & Walrand, S. (2016). Plant protein for food: Opportunities and bottlenecks. OCL - oilseeds fats. *Oilseeds and Fats, Crops and Lipids*, *23*(4), D404. http://dx.doi.org/10.1051/ocl/2016019.

Chronakis, I. S., & Madsen, M. (2011). Algal proteins. In *Handbook of food proteins* (pp. 353–394). Woodhead Publishing Limited, http://dx.doi.org/10.1533/9780857093639.353.

Craig, W. J., & Mangels, A. R. (2009). Position of the American dietetic association: vegetarian diets. *Journal of the American Dietetic Association*, *109*(7), 1266–1282. http://dx.doi.org/10.1016/j.jada.2009.05.027.

de Boer, J., & Aiking, H. (2017). Pursuing a low meat diet to improve both health and sustainability: How can we use the frames that shape our meals? *Ecological Economics*, *142*, 238–248. http://dx.doi.org/10.1016/j.ecolecon.2017.06.037.

de Boer, J., & Aiking, H. (2019). Strategies towards healthy and sustainable protein consumption: A transition framework at the levels of diets, dishes, and dish ingredients. *Food Quality and Preference*, *73*, 171–181. http://dx.doi.org/10.1016/j.foodqual.2018.11.012.

Del Gobbo, L. C., Khatibzadeh, S., Imamura, F., Micha, R., Shi, P., Smith, M., Myers, S. S., & Mozaffarian, D. (2015). Assessing global dietary habits: A comparison of national estimates from the FAO and the global dietary database. *The American Journal of Clinical Nutrition*, *101*(5), 1038–1046. http://dx.doi.org/10.3945/ajcn.114.087403.

Ekici, K., & Sancak, Y. C. (2011). A perspective on genetically modified food crops. *African Journal of Agricultural Research*, *6*(7), 1639–1642. http://dx.doi.org/10.5897/AJAR.9000009.

European Parliament & Council (2006). Regulation (EC) No 1924/2006 of the European parliament and of the council on nutrition and health claims made on foods.

FAO (1994). Definition and classification commodities, 4. Pulses and derived products.

FAO (2011a). *Global food losses and food waste - extent, causes and prevention*. Rome.

FAO (2011b). *Quinoa: an ancient crop to contribute to world food security*. Regional Office for latin America and the Carribean.

FAO (2013). Dietary protein quality evaluation in human nutrition: report of an FAO expert consultation, 31 March-2 April, 2011, Auckland, New Zealand. In *FAO food nutr. pap.*. (92).

FAO (2019). The state of food and agriculture 2019. In *Moving forward on food loss and waste reduction*. Rome: Licence: CC BY-NC-SA 3.0 IGO.

FAO (2020). FAO, IFAD, UNICEF, WFP and WHO. In *Brief to the state of food security and nutrition in the world 2020*. Rome: FAO.

Fardet, A. (2018). Characterization of the degree of food processing in relation with its health potential and effects. In *Advances in food nutrition research. Vol. 85* (1st ed.). (pp. 79–129). Elsevier Inc. http://dx.doi.org/10.1016/bs.afnr.2018.02.002.

Fernbach, P. M., Light, N., Scott, S. E., Inbar, Y., & Rozin, P. (2019). Extreme opponents of genetically modified foods know the least but think they know the most. *Nature Human Behaviour*, *3*, 251–256. http://dx.doi.org/10.1038/s41562-018-0520-3.

Fi Europe (2020). *Plant-based ingredients are here to stay: overview of integration across food and drink categories; innovation at the heart of Europe*. Germany: Frankfurt.

Friel, S., Schram, A., & Townsend, B. (2020). The nexus between international trade, food systems, malnutrition and climate change. *Nature Food*, *1*(1), 51–58. http://dx.doi.org/10.1038/s43016-019-0014-0.

Garnett, T. (2014). Three perspectives on sustainable food security: Efficiency, demand restraint, food system transformation. What role for life cycle assessment? *Journal of Cleaner Production*, *73*, 10–18. http://dx.doi.org/10.1016/j.jclepro.2013.07.045.

GBD 2017 DALYs and HALE Collaborators (2018). Global, regional, and national disability-adjusted life-years (DALYs) for 359 diseases and injuries and healthy life expectancy (HALE) for 195 countries and territories, 1990–2017: A systematic analysis for the global burden of disease study 2017. *Lancet*, *392*, 1859–1922. http://dx.doi.org/10.1016/S0140-6736(18)32335-3.

Global Panel on Agriculture and Food Systems for Nutrition (2016). *Food systems and diets: facing the challenges of the 21st century*. London, UK.

Gogoi, N., Baruah, K. K., & Meena, R. S. (2018). Grain legumes: Impact on soil health and agroecosystem. In *Legumes for soil health and sustainable management* (pp. 511–539). Springer Nature Singapore Pte Ltd. http://dx.doi.org/10.1007/978-981-13-0253-4_16.

Gonera, A., & Milford, A. B. (2018). *The plant protein trend in norway - market overview and future perspectives*. Nofima and NIBIO, http://hdl.handle.net/11250/2564561.

Gonzalez Fischer, C., & Garnett, T. (2016). *Plates, pyramids, planet: Technical report*, The Food Climate Research Network, Environmental Change Institute & The Oxford Martin Programme on the Future of Food, The University of Oxford.

Grancieri, M., Martino, H. S. D., & Gonzalez de Mejia, E. (2019). Chia seed (*Salvia hispanica* L.) as a source of proteins and bioactive peptides with health benefits: A review. *Comprehensive Reviews in Food Science and Food Safety*, *18*, 480–499. http://dx.doi.org/10.1111/1541-4337.12423.

Gravely, E., & Fraser, E. (2018). Transitions on the shopping floor: Investigating the role of Canadian supermarkets in alternative protein consumption. *Appetite*, *130*, 146–156. http://dx.doi.org/10.1016/j.appet.2018.08.018.

Hartmann, C., & Siegrist, M. (2017). Consumer perception and behaviour regarding sustainable protein consumption: A systematic review. *Trends in Food Science and Technology*, *61*, 11–25. http://dx.doi.org/10.1016/j.tifs.2016.12.006.

Henchion, M., Hayes, M., Mullen, A., Fenelon, M., & Tiwari, B. (2017). Future protein supply and demand: Strategies and factors influencing a sustainable equilibrium. *Foods*, *6*(7), 53. http://dx.doi.org/10.3390/foods6070053.

Herreman, L., Nommensen, P., Pennings, B., & Laus, M. C. (2020). Comprehensive overview of the quality of plant- and animal-sourced proteins based on the digestible indispensable amino acid score. *Food Science & Nutrition*, *8*(10), 5379–5391. http://dx.doi.org/10.1002/fsn3.1809.

Hiolle, M., Lechevalier, V., Floury, J., Boulier-Monthéan, N., Prioul, C., Dupont, D., & Nau, F. (2020). *In vitro* digestion of complex foods: How microstructure influences food disintegration and micronutrient bioaccessibility. *Food Research International*, *128*, Article 108817. http://dx.doi.org/10.1016/j.foodres.2019.108817.

Hoehnel, A., Axel, C., Bez, J., Arendt, E. K., & Zannini, E. (2019). Comparative analysis of plant-based high-protein ingredients and their impact on quality of high-protein bread. *Journal of Cereal Science*, *89*, Article 102816. http://dx.doi.org/10.1016/j.jcs.2019.102816.

Hoehnel, A., Bez, J., Amarowicz, R., Arendt, E. K., & Zannini, E. (2020). Combining high-protein ingredients from pseudocereals and legumes for the dedvelopment of high-protein hybrid pasta: Maintained technological quality and adequate sensory attributes. *Journal of the Science of Food and Agriculture*, *102*(12), 4977–4987. http://dx.doi.org/10.1002/jsfa.11015.

Hoehnel, A., Bez, J., Petersen, I. L., Amarowicz, R., Juśkiewicz, J., Arendt, E. K., & Zannini, E. (2020). Enhancing the nutritional profile of regular wheat bread while maintaining technological quality and adequate sensory attributes. *Food & Function*, *11*, 4732–4751. http://dx.doi.org/10.1039/D0FO00671H.

Hoehnel, A., Bez, J., Petersen, I. L., Amarowicz, R., Juśkiewicz, J., Zannini, E., & Arendt, E. K. (2022). Combining high-protein ingredients from pseudocereals and legumes for the development of fresh high-protein hybrid pasta: enhanced nutritional profile. *Journal of the Science of Food and Agriculture*, *102*(12), 5000–5010. http://dx.doi.org/10.1002/jsfa.11015.

Hoehnel, A., Bez, J., Sahin, A. W., Coffey, A., Arendt, E. K., & Zannini, E. (2020). *Leuconostoc citreum* TR116 as a microbial cell factory to functionalise high-protein faba bean ingredients for bakery applications. *Foods*, *9*(11), 1706. http://dx.doi.org/10.3390/foods9111706.

Hu, J., La Vecchia, C., Augustin, L. S., Negri, E., de Groh, M., Morrison, H., Mery, L., & the Canadian Cancer Registries Epidemiology Research Group (2013). Glycemic index, glycemic load and cancer risk. *Annals of Oncology*, *24*(1), 245–251. http://dx.doi.org/10.1093/annonc/mds235.

Huang, S., Wang, L. M., Sivendiran, T., & Bohrer, B. M. (2018). Review: Amino acid concentration of high protein food products and an overview of the current methods used to determine protein quality. *Critical Reviews in Food Science and Nutrition*, *58*(15), http://dx.doi.org/10.1080/10408398.2017.1396202.

IPES-Food (2016). *From uniformity to diversity: a paradigm shift from industrial agriculture to diversified agroecological systems*. International Panel of Experts on Sustainable Food systems.

Iqbal, A., Khalil, I. A., Ateeq, N., & Sayyar Khan, M. (2006). Nutritional quality of important food legumes. *Food Chemistry*, *97*(2), 331–335. http://dx.doi.org/10.1016/j.foodchem.2005.05.011.

Islam, S., Yan, G., Appels, R., & Ma, W. (2012). Comparative proteome analysis of seed storage and allergenic proteins among four narrow-leafed lupin cultivars. *Food Chemistry*, *135*, 1230–1238. http://dx.doi.org/10.1016/j.foodchem.2012.05.081.

Ismail, B. P., Senaratne-lenagala, L., Stube, A., & Brackenridge, A. (2020). Protein demand: review of plant and animal proteins used in alternative protein product development and production. *Animal Frontiers*, *10*(4), http://dx.doi.org/10.1093/af/vfaa040.

Jacob, M. C. M., Feitosa, I. S., & Albuquerque, U. P. (2020). Animal-based food systems are unsafe: Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) fosters the debate on meat consumption. *Public Health Nutrition*, *23*(17), 3250–3255. http://dx.doi.org/10.1017/S1368980020002657.

Jenkins, D. J. A., Dehghan, M., Mente, A., Bangdiwala, S. I., Rangarajan, S., Srichaikul, K., Mohan, V., Avezum, A., Díaz, R., Rosengren, A., Lanas, F., Lopez-Jaramillo, P., Li, W., Oguz, A., Khatib, R., Poirier, P., Mohammadifard, N., Pepe, A., Alhabib, K. F., ... Yusuf, S. (2021). Glycemic index, glycemic load, and cardiovascular disease and mortality. *The New England Journal of Medicine*, *384*(14), 1312–1322. http://dx.doi.org/10.1056/nejmoa2007123.

Jenkins, D. J., Kendall, C. W., Marchie, A., & Augustin, L. S. (2004). Too much sugar, too much carbohydrate, or just too much? *The American Journal of Clinical Nutrition*, *79*, 711–712. http://dx.doi.org/10.1093/ajcn/79.5.711.

Jensen, E. S., Peoples, M. B., & Hauggaard-Nielsen, H. (2010). Faba bean in cropping systems. *Field Crops Research*, *115*(3), 203–216. http://dx.doi.org/10.1016/j.fcr.2009.10.008.

Jeske, S., Zannini, E., & Arendt, E. K. (2016). Past, present and future: The strength of plant-based dairy substitutes based on gluten-free raw materials. *Food Research International*, *110*, 42–51. http://dx.doi.org/10.1016/j.foodres.2017.03.045.

Joint FAO/WHO/UNU Expert Consultation (2007). *Protein and amino acid requirements in human nutrition. Vol. 935: WHO Technical Report Series*, (pp. 1–265).

Jones, J. M. (2019). Food processing: Criteria for dietary guidance and public health? *Proceedings of the Nutrition Society*, *78*(1), 4–18. http://dx.doi.org/10.1017/S0029665118002513.

Kårlund, A., Gómez-Gallego, C., Korhonen, J., Palo-Oja, O. M., El-Nezami, H., & Kolehmainen, M. (2020). Harnessing microbes for sustainable development: Food fermentation as a tool for improving the nutritional quality of alternative protein sources. *Nutrients*, *12*(1020), http://dx.doi.org/10.3390/nu12041020.

Kearney, J. (2010). Food consumption trends and drivers. *Philosophical Transactions of the Royal Society, Series B (Biological Sciences)*, *365*(1554), 2793–2807. http://dx.doi.org/10.1098/rstb.2010.0149.

Khatibzadeh, S., Kashaf, M. S., Micha, R., Fahimi, S., Shi, P., Elmadfa, I., Kalantarian, S., Wirojratana, P., Ezzati, M., Powles, J., & Mozaffarian, D. (2016). A global database of food and nutrient consumption. *Bulletin of the World Health Organization*, *94*(12), 931–934E. http://dx.doi.org/10.2471/BLT.15.156323.

Klaus, S., Pfeiffer, A. F., Boeing, H., Laeger, T., & Grune, T. (2018). The protein paradox – how much dietary protein is good for health? *Ernaehrungs Umschau International*, *65*(2), 42–47. http://dx.doi.org/10.4455/eu.2018.008.

Kosseva, M. R. (2013). Functional food and nutraceuticals derived from food industry wastes. In *Food industry wastes chapter 6* (1st ed.). (pp. 103–120). Elsevier Inc. http://dx.doi.org/10.1016/B978-0-12-391921-2.00006-8.

Köster, E. P. (2009). Diversity in the determinants of food choice: A psychological perspective. *Food Quality and Preference*, *20*(2), 70–82. http://dx.doi.org/10.1016/j.foodqual.2007.11.002.

Kotecka-Majchrzak, K., Sumara, A., Fornal, E., & Montowska, M. (2020). Oilseed proteins – properties and application as a food ingredient. *Trends in Food Science and Technology*, *106*, 160–170. http://dx.doi.org/10.1016/j.tifs.2020.10.004.

Kramkowska, M., Grzelak, T., & Czyzewska, K. (2013). Benefits and risks associated with genetically modified food products. *Annals of Agricultural and Environmental Medicine*, *20*(3), 413–419.

Krok-Schoen, J. L., Archdeacon Price, A., Luo, M., Kelly, O. J., & Taylor, C. A. (2019). Low dietary protein intakes and associated dietary patterns and functional limitations in an aging population: A NHANES analysis. *The Journal of Nutrition, Health and Aging*, *23*(4), 338–347. http://dx.doi.org/10.1007/s12603-019-1174-1.

Kuesten, C., & Hu, C. (2020). Functional foods and protein supplementation. In *Handbook of eating and drinking* (pp. 941–964). Springer Nature Switzerland, http://dx.doi.org/10.1007/978-3-030-14504-0.

Kulczyński, B., Joanna, K.-C., Taczanowski, M., Kmiecik, D., & Gramza-Michałowska, A. (2019). The chemical composition and nutritional value of chia seeds – current state of knowledge. *Nutrients*, *115*(1242), http://dx.doi.org/10.3390/nu11061242.

Laeger, T., Henagan, T. M., Albarado, D. C., Redman, L. M., Bray, G. A., Noland, R. C., Münzberg, H., Hutson, S. M., Gettys, T. W., Schwartz, M. W., & Morrison, C. D. (2014). FGF21 is an endocrine signal of protein restriction. *Journal of Clinical Investigation*, *124*(9), 3913–3922. http://dx.doi.org/10.1172/JCI74915.

Lam, A. C. Y., Karaca, A. C., Tyler, R. T., & Nickerson, M. T. (2018). Pea protein isolates : Structure, extraction, and functionality. *Food Reviews International*, *34*(2), 126–147. http://dx.doi.org/10.1080/87559129.2016.1242135.

Lartey, A., Meerman, J., & Wijesinha-Bettoni, R. (2018). Why food system transformation is essential and how nutrition scientists can contribute. *Annals of Nutrition and Metabolism*, *72*(3), 193–201. http://dx.doi.org/10.1159/000487605.

Lee, H., Brown, C., Seo, B., Holman, I., Audsley, E., Cojocaru, G., & Rounsevell, M. (2019). Implementing land-based mitigation to achieve the Paris agreement in Europe requires food system transformation. *Environmental Research Letters*, *14*, Article 104009. http://dx.doi.org/10.1088/1748-9326/ab3744.

Leinonen, I., Iannetta, P. P., Rees, R. M., Russell, W., Watson, C., & Barnes, A. P. (2019). Lysine supply is a critical factor in achieving sustainable global protein economy. *Frontiers in Sustainable Food Systems*, *3*(27), http://dx.doi.org/10.3389/fsufs.2019.00027.

Levine, M. E., Suarez, J. A., Brandhorst, S., Balasubramanian, P., Cheng, C. W., Madia, F., Fontana, L., Mirisola, M. G., Guevara-Aguirre, J., Wan, J., Passarino, G., Kennedy, B. K., Wei, M., Cohen, P., Crimmins, E. M., & Longo, V. D. (2014). Low protein intake is associated with a major reduction in IGF-1, cancer, and overall mortality in the 65 and Younger but not older population. *Cell Metabolism*, *19*, 407–417. http://dx.doi.org/10.1016/j.cmet.2014.02.006.

Løkra, S., & Strætkvern, K. O. (2009). Industrial proteins from potato juice, a review. *Food*, *3*, 88–95.

Lonnie, M., Hooker, E., Brunstrom, J. M., Corfe, B. M., Green, M. A., Watson, A. W., Williams, E. A., Stevenson, E. J., Penson, S., & Johnstone, A. M. (2018). Protein for life: Review of optimal protein intake, sustainable dietary sources and the effect on appetite in ageing adults. *Nutrients*, *10*(3), 360. http://dx.doi.org/10.3390/nu10030360.

Lonnie, M., & Johnstone, A. M. (2020). The public health rationale for promoting plant protein as an important part of a sustainable and healthy diet. *Nutrition Bulletin*, *45*(3), 281–293. http://dx.doi.org/10.1111/nbu.12453.

Loveday, S. M. (2020). Plant protein ingredients with food functionality potential. *Nutrition Bulletin*, *45*, 321–327. http://dx.doi.org/10.1111/nbu.12450.

Ludwig, D. S. (2002). The glycemic index: Physiological mechanisms relating to obesity, diabetes, and cardiovascular disease. *Journal of the American Medical Association*, *287*(18), 2414–2423, https://jamanetwork.com/journals/jama/fullarticle/194907.

Lynch, K. M., Steffen, E. J., & Arendt, E. K. (2016). Brewers' spent grain: a review with an emphasis on food and health. *Journal of the Institute of Brewing*, *122*(4), 553–568. http://dx.doi.org/10.1002/jib.363.

Lynde, R. (2020). Innovation & entrepreneurship driving food system transformation. *Physiology & Behavio*, *220*, Article 112866. http://dx.doi.org/10.1016/j.physbeh.2020.112866.

Macdiarmid, J. I., Loe, J., Kyle, J., & McNeill, G. (2013). It was an education in portion size. Experience of eating a healthy diet and barriers to long term dietary change. *Appetite*, *71*, 411–419. http://dx.doi.org/10.1016/j.appet.2013.09.012.

Magrini, M. B., Anton, M., Chardigny, J. M., Duc, G., Duru, M., Jeuffroy, M. H., Meynard, J. M., Micard, V., & Walrand, S. (2018). Pulses for sustainability: Breaking agriculture and food sectors out of lock-in. *Frontiers in Sustainable Food Systems*, *2*(64), http://dx.doi.org/10.3389/fsufs.2018.00064.

Manners, R., Blanco-Gutiérrez, I., Varela-Ortega, C., & Tarquis, A. M. (2020). Transitioning European protein-rich food consumption and production towards more sustainable patterns-strategies and policy suggestions. *Sustainability*, *12*(1962), http://dx.doi.org/10.3390/su12051962.

Manners, R., Varela-Ortega, C., & van Etten, J. (2020). Protein-rich legume and pseudo-cereal crop suitability under present and future European climates. *European Journal of Agronomy*, *113*, Article 125974. http://dx.doi.org/10.1016/j.eja.2019.125974.

Marinangeli, C. P. F., Mansilla, W. D., & Shoveller, A.-K. (2018). Navigating protein claim regulations in north america for foods containing plant-based proteins. *Cereal Foods World*, *63*(5), 207–216. http://dx.doi.org/10.1094/CFW-63-5-0207.

Mariotti, F. (2017). Plant protein, animal protein, and protein quality. In *Vegetarian and plant-based diets in health and disease prevention* (pp. 621–642). Elsevier Inc. http://dx.doi.org/10.1016/B978-0-12-803968-7.00035-6.

Mariotti, F., & Gardner, C. D. (2019). Dietary protein and amino acids in vegetarian diets—A review. *Nutrients*, *11*(11), 2661. http://dx.doi.org/10.3390/nu11112661.

Markova, M., Pivovarova, O., Hornemann, S., Sucher, S., Frahnow, T., Wegner, K., Machann, J., Petzke, K. J., Hierholzer, J., Lichtinghagen, R., Herder, C., Carstensen-Kirberg, M., Roden, M., Rudovich, N., Klaus, S., Thomann, R., Schneeweiss, R., Rohn, S., & Pfeiffer, A. F. (2017). Isocaloric diets high in animal or plant protein reduce liver fat and inflammation in individuals with type 2 diabetes. *Gastroenterology*, *152*, 571–585.e8. http://dx.doi.org/10.1053/j.gastro.2016.10.007.

Marques, A. C., Fuinhas, J. A., & Pais, D. (2018). Economic growth, sustainable development and food consumption: Evidence across different income groups of countries. *Journal of Cleaner Production*, 245–258. http://dx.doi.org/10.1016/j.jclepro.2018.06.011.

Martínez, M. M., Román, L., & Gómez, M. (2018). Implications of hydration depletion in the *in vitro* starch digestibility of white bread crumb and crust. *Food Chemistry*, *239*, 295–303. http://dx.doi.org/10.1016/j.foodchem.2017.06.122.

Martínez-Villaluenga, C., Peñas, E., & Hernández-Ledesma, B. (2020). Pseudocereal grains: Nutritional value, health benefits and current applications for the development of gluten-free foods. *Food and Chemical Toxicology*, *137*, 1–26. http://dx.doi.org/10.1016/j.fct.2020.111178.

Matassa, S., Boon, N., Pikaar, I., & Verstraete, W. (2016). Microbial protein: future sustainable food supply route with low environmental footprint. *Microbial Biotechnology*, *9*(5), 568–575. http://dx.doi.org/10.1111/1751-7915.12369.

McGuire, S., & Sperling, L. (2013). Making seed systems more resilient to stress. *Global Environmental Change*, *23*, 644–653. http://dx.doi.org/10.1016/j.gloenvcha.2013.02.001.

Mellentin, J. (2017). 10 Key trends in food, nutrition and health 2018.

Mellentin, J. (2019). 10 Key trends in food, nutrition and health 2020.

Micha, R., Khatibzadeh, S., Shi, P., Andrews, K. G., Engell, R. E., & Mozaffarian, D. (2015). Global, regional and national consumption of major food groups in 1990 and 2010: A systematic analysis including 266 country-specific nutrition surveys worldwide. *BMJ Open*, *5*, Article e008705. http://dx.doi.org/10.1136/bmjopen-2015-008705.

Micheelsen, A., Havn, L., Poulsen, S. K., Larsen, T. M., & Holm, L. (2014). The acceptability of the new nordic diet by participants in a controlled six-month dietary intervention. *Food Quality and Preference*, *36*, 20–26. http://dx.doi.org/10.1016/j.foodqual.2014.02.003.

Millward, D. J. (2003). An adaptive metabolic demand model for protein and amino acid requirements. *British Journal of Nutrition*, *90*(2), 249–260. http://dx.doi.org/10.1079/bjn2003924.

Millward, D. J., Layman, D. K., Tomé, D., & Schaafsma, G. (2008). Protein quality assessment: Impact of expanding understanding of protein and amino acid needs for optimal health. *The American Journal of Clinical Nutrition*, *87*(5), 1576S–1581S. http://dx.doi.org/10.1093/ajcn/87.5.1576s, (suppl).

Mota, C., Santos, M., Mauro, R., Samman, N., Matos, A. S., Torres, D., & Castanheira, I. (2016). Protein content and amino acids profile of pseudocereals. *Food Chemistry*, *193*, 55–61. http://dx.doi.org/10.1016/j.foodchem.2014.11.043.

Moubarac, J.-C. (2015). *Ultra-processed food and drink products in latin america: trends, impact on obesity, policy implications*. Washington, DC: Pan American Health Organization World Health Organization, PAHO.

Moughan, P. J. (2009). Digestion and absorption of proteins and peptides. In *Designing functional foods: measuring and controlling food structure breakdown and nutrient absorption* (pp. 148–170). Woodhead Publishing Limited, http://dx.doi.org/10.1533/9781845696603.1.148.

Murray, K. A., Allen, T., Loh, E., Machalaba, C., & Daszak, P. (2016). Emerging viral zoonoses from wildlife associated with animal-based food systems: Risks and opportunities. In *Food safety risks from wildlife*. http://dx.doi.org/10.1007/978-3-319-24442-6.

Neacsu, M., McBey, D., & Johnstone, A. M. (2017). Meat reduction and plant-based food: Replacement of meat: Nutritional, health, and social aspects. In *Sustain. protein sources* (pp. 359–375). Elsevier Inc. http://dx.doi.org/10.1016/B978-0-12-802778-3.00022-6.

Neylon, E., Arendt, E. K., Lynch, K. M., Zannini, E., Bazzoli, P., Monin, T., & Sahin, A. W. (2020). Rootlets, a malting by-product with great potential. *Fermentation*, *6*(4), 117. http://dx.doi.org/10.3390/fermentation6040117.

Nicol, P., & Taherzadeh, A. (2020). Working co-operatively for sustainable and just food system transformation. *Sustainability*, *12*(7), 2816. http://dx.doi.org/10.3390/su12072816.

Nijdam, D., Rood, T., & Westhoek, H. (2012). The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. *Food Policy*, *37*(6), 760–770. http://dx.doi.org/10.1016/j.foodpol.2012.08.002.

Norberg-Hodge, H. (2021). Alternatives to the global food regime: Steps toward system transformation. In *Rethinking food and agriculture* (pp. 399–412). Elsevier Inc. http://dx.doi.org/10.1016/B978-0-12-816410-5.00018-9.

Patterson, C. A., Curran, J., & Der, T. (2017). Effect of processing on antinutrient compounds in pulses. *Cereal Chemistry*, *94*(1), 2–10. http://dx.doi.org/10.1094/CCHEM-05-16-0144-FI.

Paul, G. L. (1989). Dietary protein requirements of physically active individuals. *Sports Medicine*, *8*(3), 154–176. http://dx.doi.org/10.2165/00007256-198908030-00003.

Petrusán, J. I., Rawel, H., & Huschek, G. (2016). Protein-rich vegetal sources and trends in human nutrition: A review. *Current Topics in Peptide & Protein Research*, *17*, 1–19.

Phillips, S. M., Chevalier, S., & Leidy, H. J. (2016). Protein requirements beyond the RDA: implications for optimizing health. *Applied Physiology, Nutrition, and Metabolism*, *41*, 565–572. http://dx.doi.org/10.1139/apnm-2015-0550.

ProVeg International (2020). *European consumer survey on plant-based foods: describing the product landscape and uncovering priorities for product development and improvement: Plant-Based Food Sector Report*.

Qamar, S., Manrique, Y. J., Parekh, H., & Falconer, J. R. (2020). Nuts, cereals, seeds and legumes proteins derived emulsifiers as a source of plant protein beverages: A review. *Critical Reviews in Food Science and Nutrition*, *60*, http://dx.doi.org/10.1080/10408398.2019.1657062.

Ranganathan, J., Vennard, D., Waite, R., Dumas, P., Lipinski, B., & Searchinger, T. (2016). *Shifting diets for a sustainable food future. Vol. 11* (pp. 1–90). World Resources Institute.

Ranganathan, J., Vennard, D., Waite, R., Searchinger, T., Dumas, P., & Lipinski, B. (2016). Toward a sustainable food future. In *Shifting diets. Vol. 11, Chapter 8*. Washington, D.C.: International Food Policy Research Institute (IFPRI).

Riaz, M. N. (2011). Texturized vegetable proteins. In *Handbook of food proteins* (pp. 395–418). Woodhead Publishing Limited, http://dx.doi.org/10.1533/9780857093639.395.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., Nykvist, B., de Wit, C. A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P. K., Costanza, R., Svedin, U., ... Foley, J. A. (2009). A safe operation space for humanity. *Nature*, *461*(September), 472–475. http://dx.doi.org/10.1038/461472a.

Román, S., Sánchez-Siles, L. M., & Siegrist, M. (2017). The importance of food naturalness for consumers: Results of a systematic review. *Trends in Food Science and Technology*, *67*, 44–57. http://dx.doi.org/10.1016/j.tifs.2017.06.010.

Röös, E., Carlsson, G., Ferawati, F., Hefni, M., Stephan, A., Tidåker, P., & Witthöft, C. (2018). Less meat, more legumes: Prospects and challenges in the transition toward sustainable diets in Sweden. *Renewable Agriculture and Food Systems*, *35*, 192–205. http://dx.doi.org/10.1017/S1742170518000443.

Sá, A. G. A., Moreno, Y. M. F., & Carciofi, B. A. M. (2019). Food processing for the improvement of plant proteins digestibility. *Critical Reviews in Food Science and Nutrition*, *60*(20), http://dx.doi.org/10.1080/10408398.2019.1688249.

Sá, A. G. A., Moreno, Y. M. F., & Carciofi, B. A. M. (2020). Plant proteins as high-quality nutritional source for human diet. *Trends in Food Science and Technology*, *97*, 170–184. http://dx.doi.org/10.1016/j.tifs.2020.01.011.

Säll, S., & Gren, I. M. (2015). Effects of an environmental tax on meat and dairy consumption in Sweden. *Food Policy*, *55*, 41–53. http://dx.doi.org/10.1016/j.foodpol.2015.05.008.

Salomé, M., de Gavelle, E., Dufour, A., Dubuisson, C., Volatier, J. L., Fouillet, H., Huneau, J. F., & Mariotti, F. (2020). Plant-protein diversity is critical to ensuring the nutritional adequacy of diets when replacing animal with plant protein: Observed and modeled diets of french adults (INCA3). *Journal of Nutrition*, *150*, 536–545. http://dx.doi.org/10.1093/jn/nxz252.

Santesso, N., Akl, E. A., Bianchi, M., Mente, A., Mustafa, R., Heels-Ansdell, D., & Schünemann, H. J. (2012). Effects of higher-versus lower-protein diets on health outcomes: A systematic review and meta-analysis. *European Journal of Clinical Nutrition*, *66*, 780–788. http://dx.doi.org/10.1038/ejcn.2012.37.

Saxe, H. (2014). The new nordic diet is an effective tool in environmental protection: It reduces the associated socioeconomic cost of diets. *The American Journal of Clinical Nutrition*, *99*, 1117–1125. http://dx.doi.org/10.3945/ajcn.113.066746.

Schaafsma, G. (2005). The protein digestibility-corrected amino acid score (PDCAAS) - a concept for describing protein quality in foods and food ingredients: A critical review. *Journal of AOAC International*, *88*(3), 988–994. http://dx.doi.org/10.1093/jaoac/88.3.988.

Schieber, A. (2017). Side streams of plant food processing as a source of valuable compounds: Selected examples. *Annual Review of Food Science and Technology*, *8*, http://dx.doi.org/10.1146/annurev-food-030216-030135, 5.1–5.16.

Schmidhuber, J., Sur, P., Fay, K., Huntley, B., Salama, J., Lee, A., Cornaby, L., Horino, M., Murray, C., & Afshin, A. (2018). The global nutrient database: availability of macronutrients and micronutrients in 195 countries from 1980 to 2013. *The Lancet Planetary Health*, *2*(8), http://dx.doi.org/10.1016/S2542-5196(18)30170-0, e353–e368.

Schutyser, M. A., Pelgrom, P. J., van der Goot, A. J., & Boom, R. M. (2015). Dry fractionation for sustainable production of functional legume protein concentrates. *Trends in Food Science and Technology*, *45*(2), 327–335. http://dx.doi.org/10.1016/j.tifs.2015.04.013.

Schutyser, M. A., & van der Goot, A. J. (2011). The potential of dry fractionation processes for sustainable plant protein production. *Trends in Food Science and Technology*, *22*, 154–164. http://dx.doi.org/10.1016/j.tifs.2010.11.006.

Schwingshackl, L., & Hoffmann, G. (2013). Long-term effects of low glycemic index/load vs. high glycemic index/load diets on parameters of obesity and obesity-associated risks: A systematic review and meta-analysis. *Nutrition, Metabolism & Cardiovascular Diseases*, *23*(8), 699–706. http://dx.doi.org/10.1016/j.numecd.2013.04.008.

Searchinger, T., Waite, R., Hanson, C., & Ranganathan, J. (2019). *Creating a sustainable food future: a menu of solutions to feed nearly 10 billion people by 2050: World Resources Report.*

Sha, L., & Xiong, Y. L. (2020). Plant protein-based alternatives of reconstructed meat: Science, technology, and challenges. *Trends in Food Science and Technology*, *102*, 51–61. http://dx.doi.org/10.1016/j.tifs.2020.05.022.

Simpson, S. J., Le Couteur, D. G., & Raubenheimer, D. (2015). Putting the balance back in diet. *Cell*, *161*, 18–23. http://dx.doi.org/10.1016/j.cell.2015.02.033.

Singh, J., Dartois, A., & Kaur, L. (2010). Starch digestibility in food matrix: A review. *Trends in Food Science and Technology*, *21*, 168–180. http://dx.doi.org/10.1016/j.tifs.2009.12.001.

Siró, . I., Kápolna, E., Kápolna, B., & Lugasi, A. (2008). Functional food, product development, marketing and consumer acceptance-a review. *Appetite*, *51*, 456–467. http://dx.doi.org/10.1016/j.appet.2008.05.060.

Skejovic Joehnke, M., Jeske, S., Ispiryan, L., Zannini, E., Arendt, E. K., Bez, J., Christian Sørensen, J., & Petersen, I. L. (2021). Nutritional and anti-nutritional properties of lentil (*lens culinaris*) protein isolates prepared by pilot-scale processing. *Food Chemistry X*, *9*, Article 100112. http://dx.doi.org/10.1016/j.fochx.2020.100112.

Smart Protein - ProVeg International (2021). *Plant-based foods in Europe : how big is the market? Plant-Based Food Sector Report.*

Sokolowski, C. M., Higgins, S., Vishwanathan, M., & Evans, E. M. (2019). The relationship between animal and plant protein intake and overall diet quality in young adults. *Clinical Nutrition*, *39*(8), 2609–2616. http://dx.doi.org/10.1016/j.clnu.2019.11.035.

Sosulski, F. W., & Imafidon, G. I. (1990). Amino acid composition and nitrogen-to-protein conversion factors for animal and plant foods. *Journal of Agricultural and Food Chemistry*, *38*(6), 1351–1356. http://dx.doi.org/10.1021/jf00096a011.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., de Vries, W., Vermeulen, S. J., Herrero, M., Carlson, K. M., Jonell, M., Troell, M., DeClerck, F., Gordon, L. J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., ... Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature*, *562*, 519–525. http://dx.doi.org/10.1038/s41586-018-0594-0.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science (80)*, *347*(6223), http://dx.doi.org/10.1126/science.1259855.

Stuckler, D., & Nestle, M. (2012). Big food, food systems, and global health. *PloS Medicine*, *9*(6), http://dx.doi.org/10.1371/journal.pmed.1001242.

Tangyu, M., Muller, J., Bolten, C. J., & Wittmann, C. (2019). Fermentation of plant-based milk alternatives for improved flavour and nutritional value. *Applied Microbiology and Biotechnology*, *103*, 9263–9275. http://dx.doi.org/10.1007/s00253-019-10175-9.

Tarabella, A., & Burchi, B. (2015). *Aware food choices: bridging the gap between consumer knowledge about nutritional requirements and nutritional information*. Springer, https://link.springer.com/book/10.1007%2F978-3-319-23856-2.

Taylor, J. P., Jacob, F., Zannini, E., & Arendt, E. K. (2017). Reduction of hordein content in beer by applying prolyl endoprotease to the malting process. *Journal of the American Society of Brewing Chemists*, http://dx.doi.org/10.1094/ASBCJ-2017-3072-01.

Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(50), 20260–20264. http://dx.doi.org/10.1073/pnas.1116437108.

Tlais, A. Z. A., Fiorino, G. M., Polo, A., Filannino, P., & Di Cagno, R. (2020). High-value compounds in fruit, vegetable and cereal byproducts: An overview of potential sustainable reuse and exploitation. *Molecules*, *25*(13), 2987. http://dx.doi.org/10.3390/molecules25132987.

Tomlinson, I. (2013). Doubling food production to feed the 9 billion: A critical perspective on a key discourse of food security in the UK. *Journal of Rural Studies*, *29*, 81–90. http://dx.doi.org/10.1016/j.jrurstud.2011.09.001.

Tsolakis, N., Wood, T., Privat, I., Terrier, B., Roturier, J.-M., Singh Srai, J., & Griffiths, H. (2019). Developing fava beans as a sustainable source of high-quality protein for food supply chains through optimised genetics, farming and processing. In *23rd Cambridge international manufacturing symposium*. University of Cambridge.

Tziva, M., Negro, S. O., Kalfagianni, A., & Hekkert, M. P. (2020). Understanding the protein transition: The rise of plant-based meat substitutes. *Environmental Innovation and Societal Transitions*, *35*(2019), 217–231. http://dx.doi.org/10.1016/j.eist.2019.09.004.

United Nations - Department of Economic and Social Affairs (2019). World population ageing 2019.

United Nations - Department of Economic and Social Affairs, P. D. (2019). World population propspects 2019, volume I: Comprehensive tables (ST/ESA/SER.A/426).

Vaz Patto, M. C., Amarowicz, R., Aryee, A. N., Boye, J. I., Chung, H. J., Martín-Cabrejas, M. A., & Domoney, C. (2015). Achievements and challenges in improving the nutritional quality of food legumes. *Critical Reviews in Plant Sciences*, *34*, 105–143. http://dx.doi.org/10.1080/07352689.2014.897907.

Vieira, A. R., Abar, L., Chan, D. S., Vingeliene, S., Polemiti, E., Stevens, C., Greenwood, D., & Norat, T. (2017). Foods and beverages and colorectal cancer risk: A systematic review and meta-analysis of cohort studies, an update of the evidence of the WCRF-AICR continuous update project. *Annals of Oncology*, *28*, 1788–1802. http://dx.doi.org/10.1093/annonc/mdx171.

Vogelsang-O'Dwyer, M., Bez, J., Petersen, I. L., Joehnke, M. S., Detzel, A., Busch, M., Krueger, M., Ispiryan, L., Mahony, J. A. O., Arendt, E. K., & Zannini, E. (2020). Techno-functional, nutritional and environmental performance of protein isolates from blue lupin and white Lupin. *Foods*, *9*(230), 230. http://dx.doi.org/10.3390/foods9020230.

Vogelsang-O'Dwyer, M., Bez, J., Petersen, I. L., Joehnke, M. S., Sørensen, J. C., Detzel, A., Busch, M., Krueger, M., O'Mahony, J. A., Arendt, E. K., & Zannini, E. (2020). Comparison of faba bean protein ingredients produced using dry fractionation and isoelectric precipitation: Techno-functional, nutritional and environmental performance. *Foods*, *9*(3), 322. http://dx.doi.org/10.3390/foods9030322.

Vogelsang-O'Dwyer, M., Zannini, E., & Arendt, E. K. (2021). Production of pulse protein ingredients and their application in plant-based milk alternatives. *Trends in Food Science and Technology*, *110*, 364–374. http://dx.doi.org/10.1016/j.tifs.2021.01.090.

Walpole, S. C., Prieto-Merino, D., Edwards, P., Cleland, J., Stevens, G., & Roberts, I. (2012). The weight of nations: An estimation of adult human biomass. *BMC Public Health*, *12*, http://dx.doi.org/10.1186/1471-2458-12-439.

Wang, S., Zhu, F., & Kakuda, Y. (2018). Sacha inchi (*Plukenetia volubilis* L.): Nutritional composition, biological activity, and uses seed kernels. *Food Chemistry*, *265*, 316–328. http://dx.doi.org/10.1016/j.foodchem.2018.05.055.

Weindl, I., Ost, M., Wiedmer, P., Schreiner, M., Neugart, S., Klopsch, R., Kühnhold, H., Kloas, W., Henkel, I. M., Schlüter, O., Bußler, S., Bellingrath-Kimura, S. D., Ma, H., Grune, T., Rolinski, S., & Klaus, S. (2020). Sustainable food protein supply reconciling human and ecosystem health: A Leibniz position. *Global Food Security*, *25*, Article 100367. http://dx.doi.org/10.1016/j.gfs.2020.100367.

Welti-Chanes, J., Serna-Saldívar, S. O., Campanella, O. H., & Tejeda-Ortigoza, V. (2020). *Science and technology of fibers in food systems*. (April), Springer Nature Switzerland, https://link.springer.com/book/10.1007%2F978-3-030-38654-2.

Wesseler, J., Scatasta, S., & Fall, E. H. (2011). The environmental benefits and costs of genetically modified (GM) crops. *Frontiers of Economics and Globalization*, *10*, 173–199. http://dx.doi.org/10.1108/S1574-8715(2011)0000010012.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., Vries, W. D., Sibanda, L., ... Murray, C. F. (2019). Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. *The Lancet Commisions*, *18*, 1–47. http://dx.doi.org/10.1016/S0140-6736(18)31788-4.

Wu, G., Fanzo, J., Miller, D. D., Pingali, P., Post, M., Steiner, J. L., & Thalacker-Mercer, A. E. (2014). Production and supply of high-quality food protein for human consumption: Sustainability, challenges, and innovations. *Annals of the New York Academy of Sciences*, *1321*, 1–19. http://dx.doi.org/10.1111/nyas.12500.

Zhao, H., Shen, C., Wu, Z., Zhang, Z., & Xu, C. (2020). Comparison of wheat, soybean, rice, and pea protein properties for effective applications in food products. *Journal of Food Biochemistry*, *44*(4), 1–12. http://dx.doi.org/10.1111/jfbc.13157.