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by Munialo, Claire. D.

DOI link to the version of record on the publisher's site

Harper Adams University

Munialo, Claire. D. (2023). A review of alternative plant protein sources, their extraction, functional characterisation, application, nutritional value and pinch points to being the solution to sustainable food production. *International journal of food science & technology*.

19 April 2023

International Journal of Food Science + Technology

Review

A review of alternative plant protein sources, their extraction, functional characterisation, application, nutritional value and pinch points to being the solution to sustainable food production

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(Received 17 January 2023; Accepted in revised form 14 April 2023)

Summary Proteins from animal sources have for many centuries been used as the conventional food proteins in the food industry to produce a variety of food products. This is mainly attributed to their functional properties that range from foaming ability and stability to emulsification and gelation. However, animal husbandry has a greater impact on the environment compared to crop production. Thus, research on the potential use of plant-based proteins, which could be more sustainable, cheaper and environmentally friendly has continued to be the focus of many academics and the food industry. Even though studies have been carried out to investigate the functional properties of plant-based protein sources, there is still a need to understand the challenges that exist in the extraction and the functional characteristics of proteins from plant sources, which could be used as a more feasible exchange for animal-based proteins. Therefore, this review aims to contribute to the existing knowledge on the extraction, characterisation and functional properties of plant-based proteins. To this end, relevant literature was searched on several databases such as EBSCO HOST and Science Direct. Google Scholar was also used as a complementary search engine. Research that has addressed the extraction and functional characterisation of proteins from plant sources was critically evaluated and the findings are discussed herein. Additionally, the pinch points that exist in the use of plant-based proteins as alternatives to animal proteins in food processing are highlighted in this review.

Keywords Alternative proteins, animal proteins, functional properties, plant proteins, protein extraction, sustainability.

Introduction

The increase in global population has a related impact of the demand of food production for adequate nutrition. There is often a progressive use of land for animal and plant production, which could potentially be devoted to agriculture, and this can compromise the provision of adequate human nutrition.

Proteins from animal sources have in the past been used as conventional food proteins and presently still constitutes a large part of food production. Proteins from animal sources, predominantly milk and egg proteins, have been highly studied for many decades. However, some authors have reported the production of 1 kg of animal protein to require up to 6 kg of plant protein (Aiking, 2014). Additionally, animal production has been shown to be a major contributor to anthropogenic gas emissions, which has been suggested to play a significant role in global warming.

Even though the environmental impact of animal husbandry has been documented, a reluctancy in the reduction of meat and meat products consumption and an increasing trend in the production of meat and meat products has been seen in some countries (Fig. 1) with the developed countries consuming more meat *per capita* than the developing countries (Figs. 2 and 3). Studies in, for example, Africa have identified that the increasing urbanisation was associated with increased consumption of meat, dairy and fish at home and in the form of processed foods (Cockx *et al.*, 2019). At least part of this was shown to be down to animal products being viewed as superior in nutritional quality to plant-based sources (Berrazaga *et al.*, 2019).

A growing awareness of the environmental impact of animal production and the claimed health and nutritional benefits of plant-based diets has resulted in

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doi:10.1111/ijfs.16467

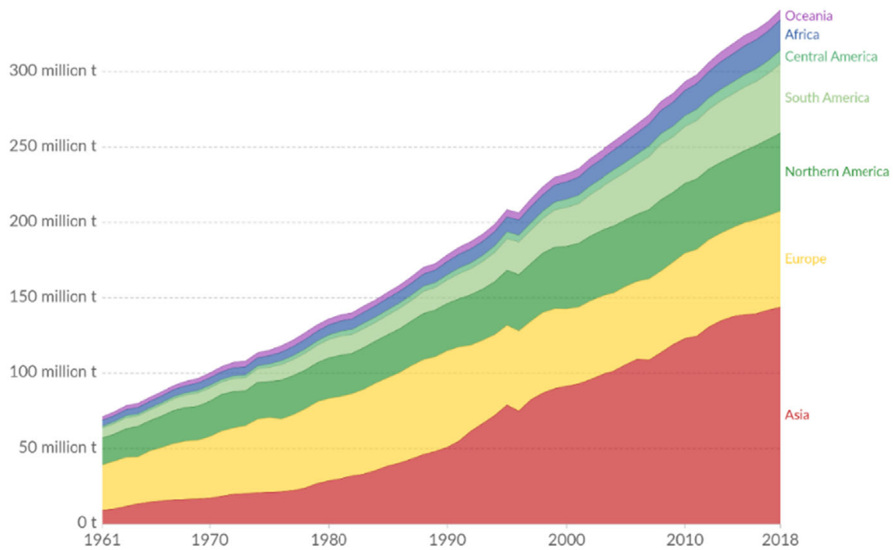

Figure 1 Global meat production from 1961 to 2018. Source: UN Food and Agricultural organisation (FAO). The use of this figure is allowed under Creative Commons licence: https://creativecommons.org/licences/by/4.0/.

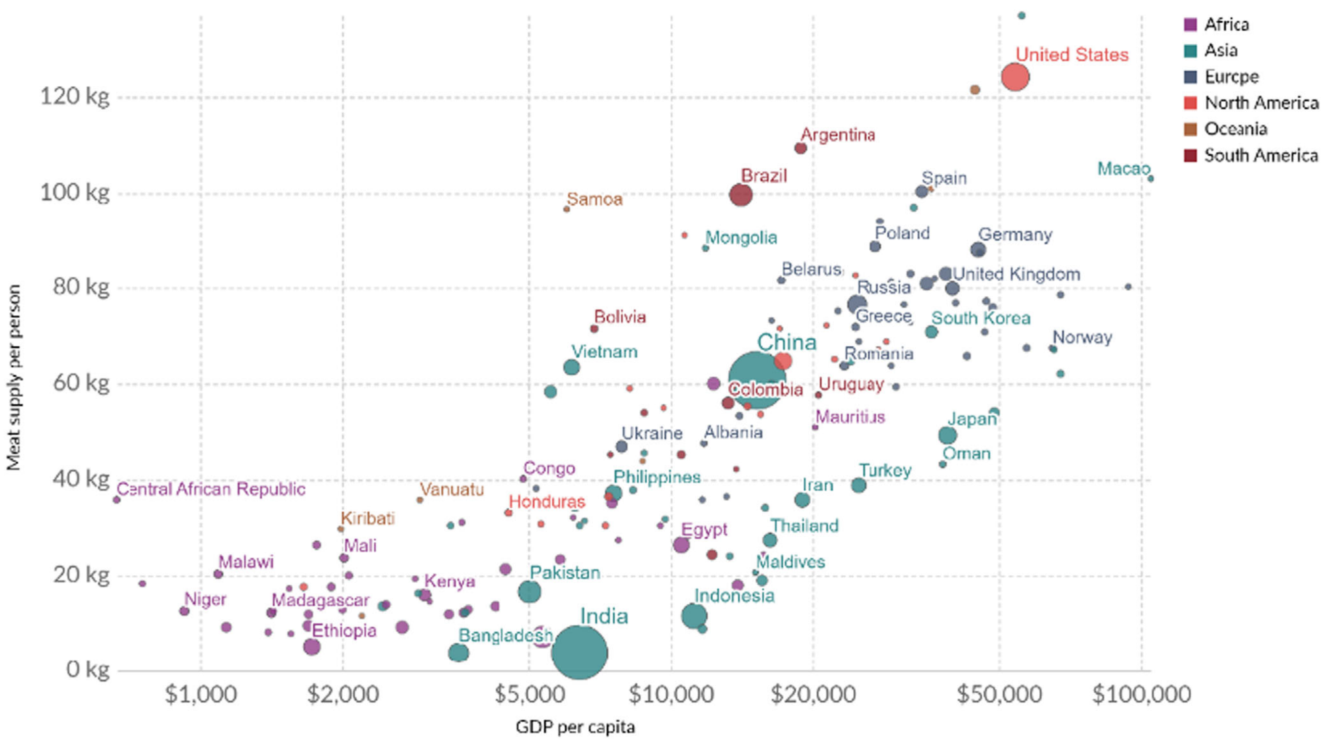

Figure 2 Meat consumption vs. gross domestic product (GDP) *per capita* in 2017. The average meat consumption *per capita* is measured in kg/year vs. GDP measured in 2011 international unit – $. Source: UN Food and Agricultural organisation (FAO). The use of this figure is allowed under Creative Commons licence: https://creativecommons.org/licences/by/4.0/.

an increase in research that has been carried out to find alternative proteins to animal-based protein sources. It is worth noting that with (i) increased research on the functional characteristic, (ii) the analysis of the production costs, (iii) the understanding of consumers' knowledge and perception of the

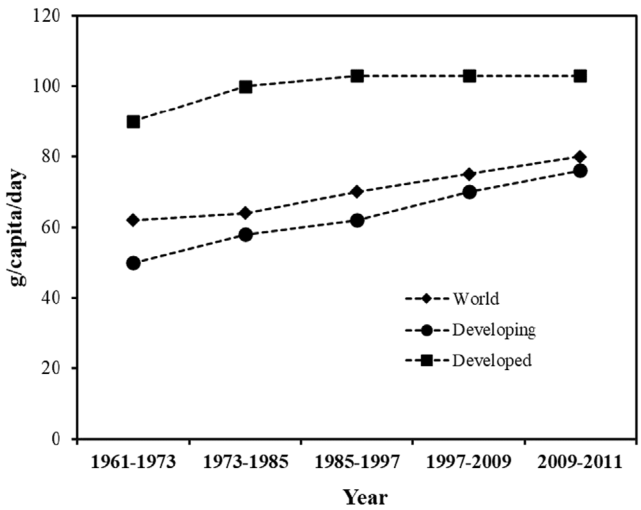

Figure 3 Evolution in protein consumption *per capita* (g/capita/day). Authors' analysis based on food balance and population data obtained from http://faostat3.fao.org.

nutritional and health impact, in addition to (iv) their willingness to purchase and consume, culturally acceptable alternative protein sources may be one of the best available options to respond to the growing demand for meat.

Even though research has been carried out on alternative sources of proteins, the question remains as to whether these sources are indeed the solution to sustainable food production as there is still a paucity of knowledge on the real impact of extraction processes, the cost of production, protein yield and quality, and the pinch points that exist in the use of proteins from plants as alternative protein sources. Therefore, this review aims to shed light on the contribution of alternative protein sources to sustainable food production. Some alternative protein sources that have been researched and used as potential substitutes for animal proteins are reviewed, and the extraction, functional characterisation and the application of alternative proteins is discussed. Additionally, the nutritional value of alternative proteins is highlighted, and some pinch points that exist in the use of alternative protein sources in food production are corroborated. To achieve this, relevant literature was searched on several databases such as EBSCO HOST (which included Academic Search Complete) and Science Direct. Google Scholar was also used as a complementary search engine and the findings are presented herein.

Plant-based protein sources

Proteins from plant sources are mainly considered as more environmentally sustainable and renewable alternatives to animal-based ones. Additionally, the production of plant proteins has been associated with less deforestation and climate change as it does require much less land and emits much fewer greenhouse gases compared to animal husbandry (Nikbakht Nasrabadi *et al.*, 2021). Some plant-based proteins from different sources are presented in Fig. 4. These proteins can also be isolated from sustainable and cheap sources such as by-products of crop and oil industries and plant-derived wastes from agriculture, and this can have an impact on the reduction of food waste. However, for plant-based proteins to be used as alternatives, there is a need for the protein to be extracted and characterised in terms of the functional properties and hence the following section will mainly focus on the extraction and functional characterisation of plant-based proteins.

The extraction and characterisation of plant proteins

Extraction of plant proteins

Proteins exist in nature as heterogenous mixtures of different types of proteins. Hence to end up with proteins that are different in protein profile, quality and functionality, extraction and purification are usually carried out. The extraction of proteins from various plants such as pea (Munialo *et al.*, 2014a), lentil (Jarpa-Parra, 2018), almond (Maykish *et al.*, 2021) and lupins (Pelgrom *et al.*, 2013) among others have been carried out. Extraction and purification of the protein using different methods may result in a different protein profile, quality and functionality (Ismail *et al.*, 2020). Protein isolates of plant-based flours can be obtained using a variety of methods and techniques, which mainly depend on the raw material and its proximate composition (Boye & Barbana, 2012).

The production of plant-based protein concentrates that vary in the protein content (between 50% and 80% protein) and protein isolates that tend to have >80% protein can broadly be categorised into either aqueous or dry fractionation. The initial step involves the raw materials that contain a high content of oil such as pulses and oilseeds, undergoing oil extraction. The final step of extraction usually involves the use of membrane filtration and in particular, ultrafiltration is used to concentrate the protein into either a concentrate or an isolate depending on protein content. It is worth noting that the production of the concentrate or isolate can also include an additional step of acid precipitation of protein at their isoelectric pH, which facilitates the concentration process and drying (Berghout *et al.*, 2014). These steps tend to be laborious and take a considerable amount of time before the

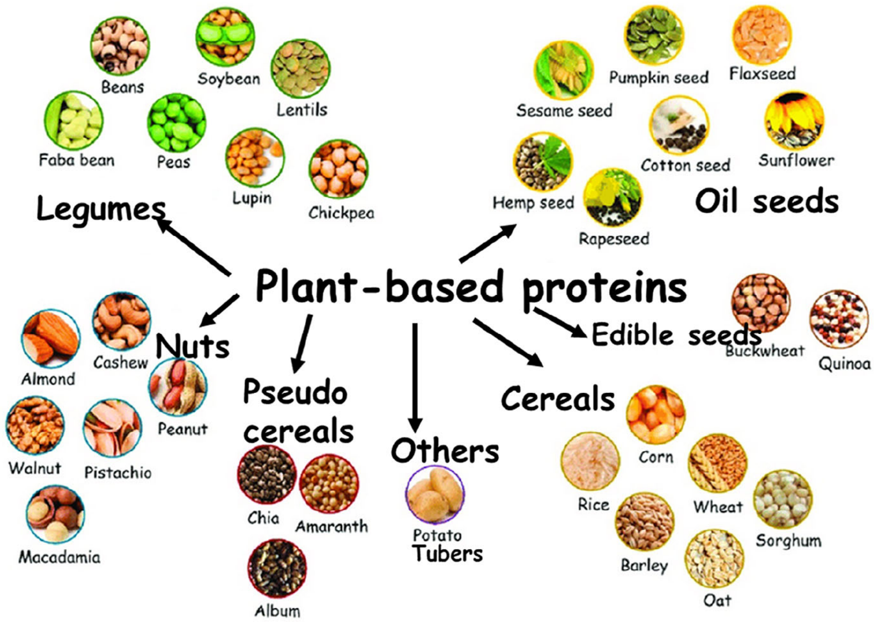

Figure 4 Major sources of plant-based proteins. Adapted from (Nikbakht Nasrabadi *et al*., 2021).

final protein extract can be obtained. Considering the lengthy steps involved in the aqueous extraction of proteins, some researchers have worked on dry fractionation, which involves milling of the seeds and solvent extraction of oil followed by air classification where the protein particles are separated from starch granules and husks in a cyclone-type separator (Pelgrom *et al*., 2013). Even though the aqueous extraction process gives a higher purity than dry fractionation (45%–55% protein), several processing steps are needed, and this makes it more expensive than dry fractionation. The other downside of aqueous fractionation is the yield of protein tends to be lower and to increase this, there is a need for the extract to be concentrated. The concentration of the extracts can be done by drying them and this can result in other issues such as structural changes that would have a concomitant impact on the functional properties of the protein. Additionally, aqueous extraction does require the use of NaOH to adjust the pH during the extraction process and depending on the volume and the concentration of NaOH that is used, potential safety issues arise. It has been suggested that the preparation of concentrates by aqueous extraction is cheaper than isolate preparation. Albeit aqueous extraction is still more expensive than dry fractionation (Ismail *et al*., 2020). The final step in protein extraction is the drying of the extract. The various drying methods and their effects on nutritional, functional and microbial properties have been compared by several authors and discussed elsewhere (Kamau *et al*., 2018; Huang *et al*., 2019).

Functional characterisation of some plant-based proteins

Plant-based proteins are considered functional ingredients as they can be used in various food formulations as thickening and gelling agents, stabilisers of emulsions and foams, and binding agents for fat and water. Additionally, some plant-based proteins have biological activities such as antioxidant or antimicrobial characteristics (Jafari *et al*., 2020). Similar to proteins from other sources, proteins from plant sources will have inherent different structural characteristics that contribute to differences in both their reactivity and solubility under various extraction conditions (Wang *et al*., 2020). Thus, there is a need for the development of dry and aqueous extraction protocols, which would enhance the yield and purity of protein whilst maintaining the structural integrity and functionality (Ismail *et al*., 2020).

Several authors have reported on the functional characterisation of proteins from plant sources. For instance, Munialo and co-workers have reported on the functional properties of the gel formation of pea proteins as a function of either pH or ionic concentration (Munialo *et al*., 2015). Some other authors have characterised soy protein based on their functional properties such as foaming and emulsification (Matsumiya & Murray, 2016). Other emerging or novel plant protein sources have also been discussed in terms of their functional applications (Yang & Sagis, 2021). However, in most of the studies that looked at proteins from plant sources, the authors showed that to be able to arrive at comparable functionality as proteins of animal origin, higher concentrations of the proteins obtained from plants were needed (Munialo *et al*., 2014a). If higher concentrations are needed to achieve comparable functionality as animal proteins, there remains a challenge in the cost of production as then more materials are needed when formulating products that have similar characteristics, and this can result in a higher production cost. The other challenge that has been reported when proteins from plant origin are used includes the issue to do with the taste and the sensorial characteristics of the final products. Some proteins from plant sources after being extracted have been shown to have inferior sensorial attributes to animal counterparts, and this will be discussed later on.

The functional properties of plant proteins are affected by several factors such as pH, protein concentration and ionic strength among others as aforementioned. Ursu and co-workers investigated the influence of pH on the functional properties of *Chlorella vulgaris* species of microalgae. In their study, an alkaline solution at either pH 7 or pH 12 was used to enhance the yield of the solubilisation of the protein. The final protein matrix exhibited lower emulsifying capacity and emulsion stability, while solubilisation under pH 7 was reported to induce lower protein yield even though the proteins showed a higher emulsifying capacity and emulsion stability (Ursu *et al*., 2014). The oil and water absorption capacity and foaming properties of *Chlorella pyrenoidosa*, *Arthrospira platensis* and *Nannochloropsis oceanica* species of microalgae were also determined. *Nannochloropsis oceanica* was shown to exhibit the highest water absorption capacity per g of protein compared to *Chlorella pyrenoidosa* and *Arthrospira platensis* (Fradinho *et al*., 2020). The variation in the water binding capacity of the protein isolate was attributed to the hydrophilic-hydrophobic balance of amino acids, protein conformation and other intrinsic characteristics of the protein (Hyrslova *et al*., 2021).

Even though the study above elucidated the effect of pH on the functional properties of microalgae, there is also the issue of the campestris variety that plays an important role in the observed differences in the functional properties. This is something that is very common across various types of plants that can be extracted to yield proteins. Some studies were conducted on lupin proteins and the variety was shown to impact the protein content as well as the ability of the proteins to gel. For instance, Billy and co-workers failed to observe gel formation for the untreated and treated isolated lupin proteins of the *Lupinus angustifolius* variety at 15% (w/w). Contrastingly, 15% (w/w) of protein isolated from the *Lupinus albus* variety of lupin formed a gel (Lo *et al*., 2021). Several varieties of pea protein were shown to contain a statistically different concentrations of 7S and 11S. The extractability of pea protein was significantly influenced by the ratio of these proteins. Varieties of pea that contain a higher level of 7S, and/or a lower level of 11S proteins, were shown to not only have higher extractability than the others but also solubility, emulsifying properties and foaming capacity. These functional properties were pH-dependent (Barac *et al*., 2010). The influence of the variety on the functional properties of the protein has also been observed in wheat (Maucher *et al*., 2009) and soy (Riblett *et al*., 2001) among others. Given the myriad of factors that have the potential of affecting the functional properties of proteins from plant sources, continuous research needs to be carried out to establish optimal conditions that would necessitate the production of alternatives that would mimic and hence be used as alternatives to proteins from animal sources. The ways that can be used to improve the functional properties of plant-based proteins also need to be reviewed.

The application of plant proteins in meat alternatives

The consumption of meat has over centuries been regarded to be an essential part of a healthy diet. However, in the recent past, the increasing production and consumption of meat at global scale has triggered environmental concerns about land and water requirements, pollution and greenhouse gas emissions (Machovina *et al*., 2015) and biodiversity loss (Machovina *et al*., 2015). Many consumers are becoming increasingly aware of the impact of meat consumption on the environment mainly because of the higher greenhouse gas emissions from animal production and this has resulted in a reduction in meat consumption (Tilman *et al*., 2011). Other issues include animal welfare, and an increased use of antibiotics to treat animals, which is thought to be an issue especially if these antibiotics make their way to the food chain and could result in an increase in antibiotic resistance. This conundrum has stimulated a search for alternatives, including plant-based meat proxies and meat alternatives from various animal and novel sources (*e.g.* insects, cultured meat, algae). The definition and the types of meat alternatives that are available as sources of protein are summarised in Table 1 whereas Table 2 provides a summary of plant proteins that are used for plant-based meat analogues.

Plant-based meat alternatives (PBMA) are the most common given that plant proteins and food-grade ingredients are used during their manufacture hence their safety is approved, and the production cost is

Table 1 The definition and the types of meat alternatives as protein sources

Definition	Type
Traditional meat from farm animals	Conventional meat
Meat analogues that are made of plant and fungus proteins	Plant-based meat analogue
Artificial meat, that is produced using stem cell technology	Cultured meat
Meat from genetically modified animals	Modified meat
Insect used as food resources	Edible insects
Fabricated meat made of native or non-native food materials with 3D printing system	3-D printed meats

Adapted from (Lee *et al.*, 2020).

Table 2 Plant proteins that are used for plant-based meat analogues

Protein	Plant	References
Glycinin, Vicilin	Legumes	(Lemken *et al.*, 2019)
β conglycinin	Soybeans	(Zhang *et al.*, 2021)
Legumin, Albumins, Globulins, Glutelins	Oil seeds	(Asgar *et al.*, 2010)
Gluten (Gliadins, Glutenins)	Wheat, rye and barley	(Doty & Doty, 2012; Maningat *et al.*, 2022)

feasible (Estell *et al.*, 2021). PBMA are also deemed to have good nutritional value, and this has resulted in their continuous development. However, their palatability has remained to be a critical obstacle for consumer acceptability (Lee *et al.*, 2020). Consequently, different ingredients are added during the manufacturing process with the aim of improving the texture and flavour of plant-based meat analogues. PBMA are also reported to contain several anti-nutrients such as protease inhibitors, α-amylase inhibitors, lectin, polyphenols and phytic acid (McAuliffe *et al.*, 2023). Even though these compounds are known to have some positive effects, such as anticarcinogenic, anti-obesity, lymphocyte stimulation, antioxidant effects, among others (Lee *et al.*, 2020), their negative effects have also been reported (Munialo & Andrei, 2023). This poses a research challenge to understand (i) the impact of the extra ingredients that are added to mimic or enhance the texture and flavour of meat analogues on the nutritional quality, and consequently, consumers health, (ii) the impact of the anti-nutrients on health especially given the fact that some of the processing methods that are used in the production of meat alternatives could result in concentrating these anti-nutrients to levels that could impact the health of the consumers with the cumulative effect of their ingestion being taken in to consideration, (iii) the increase in the production cost where the cost of the extra ingredients contributes to the final cost of the product and these makes the meat alternatives become more expensive and (iv) the nutritional quality of these meat alternative especially in terms of the protein content, which tends to be lower than that of conventional meat (Lee *et al.*, 2020). Thus, an improvement of the functional properties and the nutritional profile of alternative proteins such as plant proteins is needed in order for them to be successfully used as alternatives to animal-based proteins.

Improvement of the functional properties of plant proteins

To enhance the functional properties of plant proteins, several processes can be considered. These include the modification of the proteins and plant breeding, and this will be discussed subsequently.

Protein modification

The majority of proteins of plant origin such as pea (Munialo *et al.*, 2014b), flaxseed (Nasrabadi *et al.*, 2019) and soy proteins (Lee *et al.*, 2016) are heterogenous in nature and contain a mixture of different proteins with variable fractions, that have a wide range of isoelectric point. Therefore, to improve their functionality, the modulation of their characteristics is highly required. Additionally, plant-based proteins are often characterised by the presence of some specific plant residuals, which are believed to be anti-nutrients as aforementioned (Nikbakht Nasrabadi *et al.*, 2021). These anti-nutrients in plants are synthesised with certain biological roles that are meant to protect plants and seeds from insects, fungi, viruses and other organisms. Some of the methods that are used in protein modification can also be effective in lowering or eliminating the undesirable effects of these anti-nutrients (Avilés-Gaxiola *et al.*, 2018). Moreover, some proteins that are derived from plant sources have limited applications in food products because of their undesirable tastes, such as bitterness, which may be masked by some methods of modification (Zeeb *et al.*, 2018). The modification methods that are used for food applications should be selected carefully given that these methods can have some substantial impacts on the functional, nutritional value and organoleptic properties of proteins from plant sources. In general, modification of proteins alters the molecular structure or a few chemical groups of a protein and this can result in the improvement of techno-functionality and bioactivity.

Different methods have been used in modifying plant-based proteins to widen their applications in the food industry. These include physical methods (such as heating, gamma irradiation, sonication and extrusion), chemical (such as glycation, acylation, pH shifting and phosphorylation), biological (such as enzymatic and fermentation) and others such as complexation (including protein, polysaccharide, phenolics or surfactants) and amyloid fibrillisation. These methods have been discussed in detail elsewhere (Nikbakht Nasrabadi *et al*., 2021).

Even though several strategies can be employed to enhance the functional properties of proteins from plant sources, the safety of the final product is the key to determining the method of choice. Some methods such as glycation do not involve the use of exogenous chemicals and no chemical or toxic by-products are produced (Chen *et al*., 2016) and hence from the food-safety regulations point of view, this method can be a desirable chemical modification approach for plant-based proteins. This would fully align with the increasing trend of 'clean-label' ingredients (Nikbakht Nasrabadi *et al*., 2021). Although glycation is considered a safe and efficient protein modification method, Oliver and colleagues have reported some adverse effects on the nutritional value of proteins, which was mainly attributed to the loss of bioavailability of lysine, which is an essential amino acid (Oliver *et al*., 2006). Thus, there is need for glycation to be optimised to ensure minimal impact on the nutritional quality when being used as a protein modification method.

The use of most of the physical (Li *et al*., 2020) and biological (Arteaga *et al*., 2020) methods can be more important at the industrial level for the improvement of plant-based proteins. Physical methods have the potential benefits for scaling up even though their application may be impacted by the overarching energy costs hence there is a need for these methods to be re-evaluated and analysed in terms of the energy costs to fully align with sustainable developing goals.

The use of biological methods such as enzymes and fermentation to enhance the quality of plant-based proteins is also attracting interest given the implication of low energy-consuming and environmentally friendly processes, which additionally do not lead to the production of by-products that are toxic (Nikbakht Nasrabadi *et al*., 2021). However, the cost of enzymes can become a limitation when it comes to the large-scale application of enzymatic modification as a strategy to enhance the functional properties of proteins. The other downside of enzymatic modification is the final protein hydrolysates, which are often linked with a strong bitter and/or in some cases astringent after-taste (Arteaga *et al*., 2020) and this introduces another technological challenge to deal with the off-notes and some strategies that can be employed will be discussed later one.

Amyloid fibrillisation is a recent protein modification strategy, which has been reported to be both effective and efficient (Pang *et al*., 2020). However, given that this method is new in food technology, there is still ongoing research to fully assess their biosafety as well as their digestion fate: even though all indications that are available to date, nevertheless point to a safe use in food applications (Nikbakht Nasrabadi *et al*., 2021).

The design of modified plant-based proteins that have improved nutritional, sensorial and techno-functional properties has the potential of opening new opportunities within food and nutrition in addition to allowing for the design of innovative and novel complex foods that are based on plant proteins.

Plant breeding

Several studies have shown the impact of variety on the functional properties of protein from plant sources, and some of this was due to the variation in the protein yield that was variety dependent. As such, one would wonder what are the possible strategies that could be used to ensure similar or comparable protein yield despite the plant variety. One possible way that could be used is in plant breeding, where genetic principles are applied to produce more useful plants that have improved characteristics, for example a higher protein quality. However, some authors have shown that when the protein quality is improved during crop production, there has always been a reduction in the yield (Ufaz & Galili, 2008). The findings suggest that a major effort would be to find ways of incorporating these improved protein characters into good genetic backgrounds so that a successful variety is produced.

Various food biotechnological approaches can be used to produce crops that have improved protein quality. Some researchers have suggested combining conventional breeding with transgenes encoding where the editing machinery of the plants can be removed and the 'edited plant' with improved protein quality can be considered as 'non-GMO plants' (Tien Lea *et al*., 2016). Additionally, genetic and in particular protein engineering and or modification can be carried out, which could include different genomic and post-genomic strategies that would expand the functional ability and the synthesis, *in vivo* and *in vitro*, of proteins. These proteins would carry novel chemical, physical and biological properties (Lilley & Eckstein, 1989) and end up being used in various food applications. Various strategies such as chimeragenesis, site-specific mutagenesis and *de novo* protein engineering can be employed, and an in-depth description of these methods can be found elsewhere (Balabanova *et al*., 2015). These methods require good genetic knowledge as well as continued research before being introduced and used in food production. Additionally, there may be an element of resistance when it comes to the final consumer perception and acceptance of proteins that have been genetically modified. However, a study on the societal aspects of genetically modified foods has shown the genetic modification of plants and microorganisms to be more accepted compared to those in animals (Tadich & Escobar-Aguirre, 2022).

Even though the goal of the modification would be to enhance the quality and yield of protein, the safety of the final product is of ultimate priority. The food industry will not be expected to carry out all the research to come up with a plant variety that works well in terms of protein yield and quality, and which would have a concomitant impact on the functional properties. However, this opens an opportunity for collaboration between the food industry and various stakeholders to work hand in hand to come up with joint solutions.

Nutritional issues of plant proteins

Plant-based proteins are mainly considered a sustainable option compared to animal-based proteins. Plants in general contain a higher level of bioactive compounds such as phytonutrients that can play an important role in the prevention of several diet-related diseases such as cancer. There is also a good amount of fibre present in plants, which will contribute toward the general health of an individual on a plant-based diet compared to a counterpart that consumes mainly animal-based diets (Munialo & Andrei, 2023). However, the anabolic effect of plant-based proteins tends to be lower than animal proteins, which are mainly attributed to their lower amino acid content (especially leucine), lower digestibility, as well as the general deficiency in other essential amino acids, such as lysine or sulphur amino acids (Berrazaga *et al*., 2019). There are strategies such as the modification of the proteins that can be used to enhance the availability and the quality of these amino acids (Ufaz & Galili, 2008). However, to the best of the author's knowledge, such strategies are yet to be applied in the food industry and hence there is a need for further research to explore the efficacy of such improvements and the impact on the nutritional quality and safety of the final food product.

The amount of protein that is present in the whole plant tends to differ from the amount of protein that can be extracted or used in the production of animal alternatives. For instance, soybean contains about 40 w.b.% compared to soy protein isolate (SPI), which has a protein content of 85–90 w.b.% or soy protein concentrate (SPC), which has 65–70 w.b.% protein content (Preece *et al*., 2017). When one compares these concentrations, the extracts seem to have a higher concentration than the original soy. However, depending on the way that extraction was carried out and subsequent treatments such as drying which in some cases does include lyophilisation (Preece *et al*., 2017) or spray drying (Wang *et al*., 2020) can result in structural changes and a concomitant effect on the solubility of the proteins (Munialo *et al*., 2022). Thus, the use of these extracts in food processing can impact the protein content of the final product, which would end up being lower than the original protein content in the whole seed, cereal, legume, nuts or pulses among other. The whole extraction process of proteins remains to be ambivalent as there are a lot of resources that are needed but the final extract even though would have a higher protein content may not necessarily end up being fully incorporated into food production and this impacts the nutritional quality of the final products.

Flavour, taste and allergenicity

Persistent flavours that can be perceived by the consumer are one of the challenges of using plant-based proteins in food processing (Ismail *et al*., 2020). Off-flavours present in soy proteins have been reported (Rackis *et al*., 1979). These off-notes were attributed to lipoxygenase-initiated peroxidation of unsaturated fatty acids (MacLeod *et al*., 1988), which is a common occurrence that is related to the source of the raw material, processing and/or storage (Ismail *et al*., 2020). The presence of compounds such as aldehydes, alcohols, ketones, their ester derivatives and methoxypyrazines was reported in raw, stored and cooked peas (Malcolmson *et al*., 2014).

Several strategies to mitigate against off-flavours and aromas have been attempted in pea and other plant protein sources. These approaches range from the selection of germplasm that is absent or contain diminished odd notes, the use of better purification processes, the inclusion of extra fermentation steps, the use of bitter inhibitors, the adaptation of post-processing marinating/seasoning matrix for flavour (MacLeod *et al*., 1988; Malcolmson *et al*., 2014) through to the recent developments such as the application of supercritical fluid extraction, where CO_2 and ethanol have been used to remove the problematic compounds from pea protein isolate (Vatansever *et al*., 2022). However, given that aroma is the sum of a pattern of the responses of numerous receptor types, there have been several technological challenges that hinder the implementation of this technique in masking off flavours in plant-based proteins. This leaves a challenge and paucity of knowledge on how to mitigate these issues and hence the food researchers and the food industry needs to carry out accurate profiling of flavour, which could lead to the identification of approaches that eliminate the problematic off-flavours rather than an attempt to mask them.

Allergenicity of plant-based proteins is another issue of concern when it comes to their application within the food industry. Food allergies are adverse immune responses to certain food proteins. Allergens in proteins from plant origin are more of the major factors that inhibit their wide applications. Therefore, it is important for the allergenicity of plant-based proteins to be reduced and this would result in plant protein ingredients that have enhanced functionality, digestibility and nutrient bioavailability (Fadimu *et al.*, 2023). Several strategies have been suggested that can be used to reduce the allergenicity of plant-based proteins and this range from thermal treatments (such as moist heat, dry heat, autoclaving, microwave and frying) to non-thermal techniques (such as ultrasonication, radiation, pulse electric field, cold plasma and high-pressure processing) (Li *et al.*, 2016). These processing techniques may result in the modification of the structure of allergens at the molecular level (for instance via aggregation, deamidation and hydrolysis) or the modification of the interactions of allergens with other food components, for example via formation of complexes or Maillard reaction (Fadimu *et al.*, 2023). Some of these processes that are used to reduce the allergenicity of proteins can have a concomitant impact on the proteins as this could result in protein denaturation and aggregation, in addition to structural changes in the proteins. Changes in protein structure can interfere with the digestibility and bioavailability of proteins. Thus, more research in to the reduction of allergenicity of plant-based proteins using ways that have minimal impact on protein quality are needed in order to broaden the applications of these proteins in food processing and manufacture.

Pinch points for the use of plant proteins for sustainable food

The issue of plant-based protein alternatives being more sustainable remains to be a debatable global issue among various researchers. For instance, in a recent work, Bryant reported plant-based animal product alternatives to be healthier and more environmentally sustainable than animal products (Bryant, 2022). These research findings have, however, been criticised by Loveday and Henry because of the scope of the analysis and subsequently their interpretation being limited. They further suggest that the impact of various processes that are used in the production of meat analogies such as 'cooking, fermentation, curing etc. on the final nutritional composition of the products, were not addressed in addition to the research failing to distinguish between processed and intact meat products (or their analogues)' (Loveday & Henry, 2022). Munialo and co-workers discussed the water footprint of the production of dairy alternatives. Plant-based protein foods were also reported to be nutritionally inferior to products that are made using animal-based proteins (Munialo *et al.*, 2022). The concentration of proteins from plant origin that are needed to achieve comparable functional properties of proteins from animal sources have been reported to be higher (Munialo *et al.*, 2014a) and this could have a cost impact on the final product. Some issues still need to be addressed to have a clear roadmap to sustainable production and consumption of plant-based protein alternatives. Other aspects such as nutritional aspects and the taste and flavour of plant-based protein alternatives also need to be addressed. Thus, it does seem like the adoption of alternative proteins in food production is locked in a vicious cycle of increasing production costs, consumer perception and acceptance and technological challenges to mimic the taste and texture of proteins from animal sources. For one to be able to evaluate whether alternative proteins are the sustainable solutions to animal protein sources, this circle needs to be broken, and this calls for concerted effort, collaboration and work that involves various stakeholders.

Conclusion

Alternative proteins such as proteins from plant origin have the potential of contributing toward the reduction of the environmental impact of animal husbandry. Comparatively, plant-based proteins have much lower greenhouse gas production and fewer resources are needed in their production. However, when it comes to the processing that may include the extraction of the proteins, several challenges include laborious methods, which is mainly the case with aqueous extraction or structural changes that may occur as a result of the processing, for example drying. The yield and the quality of the protein are affected by several factors such as the variety of the plant and hence several strategies need to be researched that can help enhance the protein yield. There are also pinch points in the incorporation of plant-based proteins in food products such as their nutritional value, which is often suggested to be inferior to that of the animal counterparts. Additionally, proteins from plant origin are shown to have antinutrients as well as the presence of off flavour and taste. Allergenicity of these proteins is also another issue that needs to be addressed before these proteins can be effectively used as replacers of proteins from animal origin. As such, there is still more work that needs to be done to evaluate the sustainability of plant-based proteins and this will enhance their applications in the food industry.

Acknowledgment

Mr Stephen Giles is acknowledged for critical reading of the manuscript.

Author contributions

Claire Darizu Munialo: Conceptualization (lead); investigation (lead); writing – original draft (lead); writing – review and editing (lead).

Ethical guidelines

Ethics approval was not required for this research.

Conflict of interest

None.

Peer review

The peer review history for this article is available at https://www.webofscience.com/api/gateway/wos/peer-review/10.1111/ijfs.16467.

Data availability statement

Research data are not shared.

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