



Protein For Life: Review of Optimal Protein Quantity, Distribution, Sustainable Sources and the Effect on Appetite in Ageing Adults.

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Highlights:

- The Reference Nutrient Intake (RNI) for protein (0.75 g per kg of body weight) may be insufficient in inhibiting age-related loss of muscle mass and strength (sarcopenia).
- Meeting daily protein requirements in an ageing population requires consideration of both protein type (plant and animal sources) and distribution (when consumed).
- There is a paucity of data to fully investigate the effect of plant proteins on appetite control, satiety and food intake across body weight ranges and ages.
- Food-based solutions for healthy ageing requires consumer focus and collaboration between industry and academia.

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Summary

With an ageing population, food solutions are urgently needed to promote health and independence later in life. In part, this can be achieved by maintaining muscle mass and strength as people age. New evidence suggests that current dietary recommendations for protein intake may be insufficient to achieve this goal and that people might benefit by increasing their intake of high-quality protein on three daily occasions. However, the negative environmental effects of increasing animal-protein production are a concern and alternative, more sustainable protein sources should be considered. It is still unclear how the transition towards diets high in plant proteins affects the appetite in overweight, normal weight and underweight adults as they age, and whether it is not problematic for individuals at risk of malnutrition. This is because protein is more satiating than other nutrients. The review considers the protein needs of an ageing population (>40 years old), sustainable protein sources, appetite-related implications of diet high in plant proteins, and related areas for future research.

Introduction

In the UK, it is projected that by 2035 the majority of the population will be aged 40 or older ([ONS, 2012](#)). Aside from financial implications, dietary guidance is needed to maintain or improve the health and wellbeing of those in this cohort. Adequate intake of protein is one of the key nutritional factors to maintain independence, predominantly by preventing loss of muscle mass and strength (sarcopenia), frailty and associated comorbidities in later life ([Wolfe, 2012](#); [Bauer et al., 2013](#); [Bradlee et al., 2017](#)). At present, both academia and the food industry are failing to identify and address the needs of this ageing population, with affordable, palatable and practical food solutions.

It is debatable at what exact point in life muscles start to age. A gradual decline in muscle mass is observed from the third decade of life ([Lexell et al., 1988](#)), with a 30-50% decrease reported between the ages of 40 and 80 ([Faulkner et al., 2007](#)). Muscle strength is correlated with muscle mass and rapidly declines after the age of 50 ([Hayashida et al., 2014](#); [Larsson et al., 1979](#)). The beginning of the fourth decade of life might be therefore optimal for implementing appropriate dietary changes, to prevent or delay the onset of sarcopenia. Accordingly, throughout this review an 'ageing adult' is used to refer to a person aged 40 and older.

Previous work has focused on identifying the optimal protein amount, timing and type of protein in sarcopenia prevention. A number of studies have found that that intake exceeding the Recommended Daily Allowance (RDA) may be preferential in preserving muscle mass and functions in ageing adults ([Campbell et al., 2001](#); [Wolfe et al., 2008](#); [Bauer et al., 2013](#); [Deutz et al., 2014](#); [Philips et al., 2016](#)). In addition, the pattern of protein consumption was suggested to be of greater importance than the total daily amount consumed ([Bollwein et al., 2013](#)), which will be discussed in the next section. The evidence from these studies is however limited to investigating the effects of different types of animal proteins on muscle health ([Dideriksen et al., 2011](#); [Cermak et al., 2012](#)), and the effects of plant proteins (other than soy) have not been adequately studied.

Plant-based nutrition has received much attention in the past decade ([FAO, 2010](#); [Nadathur et al., 2017](#)). The ever-growing demand for foods naturally rich in protein is part of an ecological debate around whether more sustainable sources should be encouraged ([Wu et al., 2014](#)). High animal proteins consumption observed in developed countries ([FAOSTAT, 2009](#)) raises health and environmental concerns. Firstly, dietary patterns composed of animal products have been associated with increased risk of obesity, diabetes, cardiovascular disease mortality and prostate cancer ([Shu et al., 2015](#); [Jannasch et al., 2017](#); [Shimazu et al., 2007](#); [Rosato et al., 2014](#)). Secondly, animal products consumption requires large areas of dedicated land, water, nitrogen, and fossil energy for production and transportation ([FAO, 2012](#); [Gerber et al., 2013](#)). The result is the emission

of large amounts of greenhouse gases (GHG) (IPCC, 2006). The health benefits of plant-proteins (as a more sustainable alternative) in sarcopenia prevention have not yet been extensively investigated.

Furthermore, the effects of plant proteins on muscle protein synthesis (MPS) were scarcely investigated in the context of appetite. In particular, it has not been yet established whether plant proteins trigger similar appetite-related responses in underweight, normal weight and overweight individuals while they age. Filling this research gap is crucial to assess whether nutritional strategies can maximise nutritional status of the ageing adult, or the contrary, compromise daily energy intake, thus contributing to malnutrition. More generally, insight of this kind may help consumers to make healthy food choices and will inform the development of nutritionally balanced products that promote healthy ageing.

The purpose of this review is to:

- summarise evidence regarding the optimal quantity and daily distribution of protein intake in ageing adults;
- present current knowledge about sustainable proteins intake in the context of appetite control;
- identify the areas for future research and challenges in introducing novel food solutions to consumers.

2. Optimal protein intake

2.1. Daily quantity

The current international Recommended Dietary Allowance (RDA) for protein is 0.8 g per kg of body weight (bw), regardless of age (FNB, 2005; WHO, 2007). In the UK, the Reference Nutrient Intake (RNI) is 0.75 g/kg/bw (COMA, 1991). These recommendations are derived as a minimum amount to maintain nitrogen balance and are not optimised for physical activity level (PAL). Individuals with low PAL have decreased rates of protein utilisation and therefore higher protein requirements in comparison to those who are more active (Butterfield & Calloway, 1984). Considering that physical activity decreases with age (Hallal et al., 2012), this is an important factor when protein needs are evaluated. Furthermore, the body of an ageing adult undergoes multiple physiological changes which alter protein utilisation, and thus requirements, i.e., anabolic resistance, insulin resistance, impaired digestion, inflammation, and decreased IGF-1 levels (Wolfe et al., 2008; Bauer et al., 2013; Deutz et al. 2014; Phillips et al., 2016). The adequacy of current protein recommendations has also been challenged because of potential methodological pitfalls. First, the nitrogen-balance method used in the majority of pooled studies may not be accurate, due to possibly unaccounted routes of nitrogen input and output (Millward, 2001; Bauer et al., 2013). A second limitation is that nitrogen-balance studies require controlled, clinical environment, hence the protein requirement assessment is relatively short-term (Millward, 2001). Data regarding long-term evaluations of protein needs in ageing adults, with a use of novel, more accurate assessment techniques, is scarce and is identified as an academic research priority (Rand et al., 2003).

Acknowledging all these factors, and supported by a large body of new evidence, the International PROT-AGE Study Group (Bauer et al., 2013) and European Society for Clinical Nutrition and Metabolism (ESPEN) (Deutz et al., 2014) concluded that daily requirement of healthy individuals over 65 years is 1.0-1.2 g protein/kg/bw. A further increase is recommended for individuals with acute or chronic illnesses (1.2-1.5 g protein/kg/bw) and severe illnesses, injuries, or malnutrition (2.0 protein g/kg/bw) (Bauer et al., 2013; Deutz et al., 2014). Although these new recommendations have been formulated for adults >65 y, this is only an agreed conceptual cut-off point. Since it has been estimated that 0.5-1% of muscle mass is lost annually from the age of 50 (Abellan, 2009), an increased dietary protein intake may be required earlier in life in order to mitigate the muscle ageing process. One of the longest (14-week) interventional studies to date revealed that in adults aged 55-77, ingestion of 0.8 g protein/kg was associated with decreased mid-thigh muscle area and decreased urinary nitrogen excretion, suggesting that the current RDA might be below the actual requirements of an ageing adult (Campbell et al., 2001). The link between protein consumption at

the RDA level and adverse health outcomes was also confirmed in longitudinal observational studies. As discovered by Houston and others (2008), older adults (70-79 y) whose daily protein intake was 1.1 ± 0.4 g/kg/bw had lost 40% less lean body mass over the course of three years than those who consumed 0.8 ± 0.3 g/kg/bw.

In summary, protein requirements vary on individual basis and depend on various factors, such as age, health status and PAL. These factors are not reflected in current recommendations for the general population. Therefore, an increased intake of dietary protein from around midlife is probably justifiable, and merits further research.

2.2. Daily distribution

Apart from the total daily intake, per-meal protein quantity and daily frequency of protein ingestion have also been shown to play an important role in preserving muscle mass and function. It is estimated that consumption of two to three meals a day, each containing ~25-30 g of protein, is optimal for the stimulation of 24-h muscle protein synthesis (MPS) in healthy adults (Paddon-Jones & Rasmussen, 2009; Symons et al., 2009; Mamerow et al. 2014; Loenneke et al., 2016; Farsijani et al., 2017). This approximate quantity is thought to be sufficient, both for younger and healthy older adults (Symons et al., 2009).

Interestingly, 'the more, the better' approach is not necessarily optimal. Symons and colleagues (2009) compared the effects of 30 g of lean-beef protein/meal to 90 g/meal ingestion on MPS in young (35 ± 3 y) and older adults (68 ± 2 y) and found there was no additional benefit of increased protein consumption in either age category. Moore and colleagues (2015) added to the existing evidence by finding the per-meal threshold in relation to body weight and reporting age-related differences. In this study, protein utilisation plateaued after the ingestion of 0.24 g of whey and egg protein/kg/bw in young men (~22 y) and after 0.40 g/kg/bw in older men (~71 y) (Moore et al., 2015). The estimated per-meal threshold after consuming a plant protein-rich meal is still unknown, particularly in the cohort of ageing adults (Gorrißen & Witard, 2017).

Some studies argue that consuming a much higher dose of protein on one daily occasion (pulse feeding) can stimulate a higher anabolic response than smaller doses across multiple meals (Arnal et al., 1999; Bouillanne et al., 2013; Bouillanne et al., 2014). Arnal and colleagues (1999) reported that women (mean age 68 ± 1 y) who consumed ~80% of daily protein at noon during the trial had improved nitrogen balance, when compared to women who consumed the same amount of protein spread over four meals (21.5 \pm 0.5, 31.2 \pm 0.2, 19.1 \pm 0.5, 28.3 \pm 0.5 % of daily protein intake). However, the spread pattern tested in this study stipulates the risk, that none of the four meals contained the required bolus of 25-30 g protein per serving, resulting in this treatment being less effective. Reports

by Bouillanne and colleagues (2013; 2014) were in line with Arnal's findings, suggesting that pulse feeding was more effective in improving lean mass index in older adults. However, since participants in these studies were recruited from very old (mean age 84.1 y) hospitalised patients at risk of malnutrition the results should be cautiously interpreted and cannot be generalised to younger (40-80 y), healthy adults.

In most Western societies, the daily pattern of dietary protein ingestion is skewed regardless of age or sex, with the lowest amount of protein being consumed in the morning and the greatest in the evening meal (Almoosawi et al., 2012; Berner et al., 2013; Tieland et al., 2015; Cardon-Thomas et al., 2017). As shown in a British cohort study that has followed the dietary intake of adults aged 36 y for 17 years, the protein content of meals has gradually shifted toward the evening, with the steadier increase being observed in men (Almoosawi et al., 2012). Although these results refer to years 1982-1999, evidence suggests, that this trend has been sustained because it is mirrored in data collected more recently from other countries. Data from U.S. National Health and Nutrition Examination Survey (NHANES) (Berner et al., 2013) stated that in 2006 the average protein intake (g/meal) among women aged 51-71 was 11.9±0.4 (breakfast), 17.9±0.5 (lunch) and 30.4±0.7 (dinner) with snacks constituting of 7.4±0.3 (Berner et al., 2013). The intake (g/meal) in men was higher and accounted for 15.8±0.5, 23.2±0.8, 43.5±1.0 and 10.5±0.5, respectively (Berner et al., 2013). Results from this study have also confirmed that the same pattern was observed in a ≥71 y group. However, the amount of protein consumed in each meal was lower in both sexes, in comparison to the younger age group (Berner et al., 2013). Regarding the population of the very old community-dwelling adults, the pattern of daily protein distribution appears to have its peak at mid-day. The Newcastle 85+ study revealed (Mendonça et al., 2017), that the highest amount of protein in this British cohort was consumed at lunch time, accounting for ~35% (around 20 g) of daily protein intake, followed by dinner ~21% (12 g), and lower at two consecutive morning occasions (11 and 10.5%, respectively).

The commonly observed among ageing adults uneven pattern of protein ingestion stipulates the risk of insufficient stimulation of MPS, even when RDA on a daily basis is being met. Meaning, the stimulation with a meal containing ~25-30 g of protein occurs only once a day, during the main meal (lunch or dinner). As suggested by Bollwein and others (2013), the protein distribution at older age is of higher importance than the total daily amount per se. In his study, the recommendation of 0.8 g/kg/bw was exceeded by all participants (> 75 y), even those from the lowest quartile of protein intake. No differences were observed between frailty status and daily protein intake. However, those with more uneven distribution were most prevalent in the frail group, characterised by lower walking speed and higher exhaustion (Bollwein et al., 2013). Because the ingestion of high-protein

meal before sleep has been shown to increase overnight MPS ([Kouw et al., 2017](#)), this dietary habit should be sustained. In addition, to stimulate 24-h MPS, enriching the content of remaining meals with high-quality protein should be strongly encouraged, to ensure sufficient dose of protein in each meal.

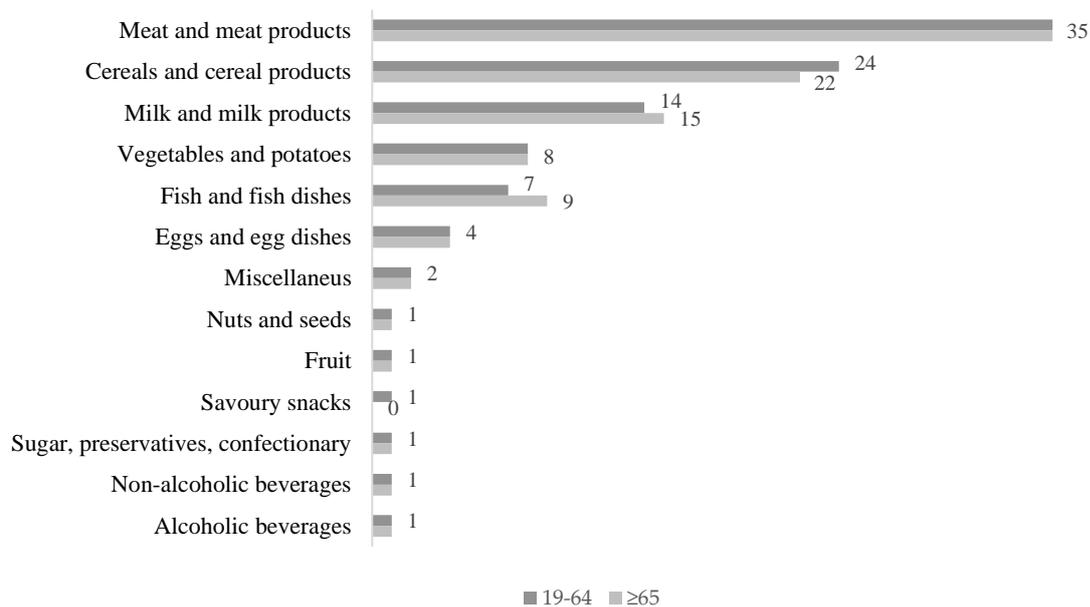
Although discussed recommendations regarding optimal protein quantity and distribution seem to be well supported, it has to be noted that most studies have analysed outcomes related solely to animal proteins and muscle health, omitting the accompanying effects of protein ingestion on appetite. Placing these findings in this context would provide valuable insight and guidance for adults who also need to limit or increase their daily energy intake in order to optimise nutritional status.

3. Dietary sources of protein

3.1. Protein consumption in the UK

Dietary proteins are found in animal-based foods, plant-based foods, and alternative sources such as algae, bacteria, and insects. Globally, plant-based foods are the leading source of protein, constituting of 57% of daily protein intake, followed by meat (18%), dairy (10%), fish and shellfish (6%) and other animal products (9%) ([FAO, 2010](#)). In contrary, the main source of protein in the British diet is animal-originated, contributing to nearly 2/3 of total daily protein intake ([FSA & PHE, 2016](#)). In 2013/2014 the percentage distribution of protein intake from animal-based products in adults aged 19-64 was as follows: 'meat and meat products' (35%), 'dairy' (14%), 'fish' (7%) and 'eggs' (4%) (see [Figure 1](#)). The distribution was very similar in adults ≥ 65 y, although the contribution from 'dairy' and 'fish' was slightly higher than in the younger group (15%, and 9%, respectively). In the category 'meat and meat products' and in adults aged 19-65, the most popular foods were 'chicken and poultry' (13%), followed by processed meat (7%), 'beef and veal' (6%), 'bacon and ham' (4%), 'pork' (3%) and 'lamb' (2%). Plant proteins were derived mostly from 'cereals and cereal products' (24%) – predominantly from 'rice, pasta and bread' food group (18%) - followed by 'vegetables and potatoes' (8%), 'fruit' (1%), and 'nuts and seeds' (1%). Again, this distribution did not differ greatly between the age groups, apart from cereals being a slightly lower contributor to the daily protein intake in adults ≥ 65 y (22%). The remaining 6% of protein source is difficult to classify, and comprised items such as savoury snacks, confectionary, beverages, and miscellaneous foods ([FSA & PHE, 2016](#)).

Figure 1. Percentage contribution (%) of food groups to average daily protein intake in the UK in 2013/2014: adults aged 19-64 and ≥65 y.



Source: National Diet and Nutrition Survey Rolling Programme Years 2013-2014 (NDNS, 2016)

Alternative protein sources are not commonly consumed in Western countries. The exception is mycoproteins - vegetarian meat substitutes – which have increased in popularity over the last three decades, and with a trend that is expected to continue in future (Nadathur et al., 2017). Cultured meat (‘lab-grown’) as an alternative source of protein is currently understudied. However, the profitability in the nearest future, and consumers’ acceptance of this product is still in question (Verbeke et al., 2015).

3.2. Protein quality

There is debate about the optimal source of protein and numerous quality assessment measures have been proposed (Millward et al., 2008). The most commonly applied method to assess protein quality involves the calculation of a Protein Digestibility Corrected Amino Acid (PDCAA) Score, or Digestibility Indispensable Amino Acid (DIAA) Score (Schaafsma, 2012; Vliet et al. 2015). In general, animal-based foods are recognised as a superior source of protein because they have a complete composition of essential amino acids, with high digestibility (>90%) and bioavailability (FAO/WHO, 1991). Animal proteins have higher PDCAA scores than plants, suggesting greater efficiency in muscle anabolic processes (Vliet et al., 2015). For example, proteins found in milk, whey, egg casein and beef have the highest score (1.0), while scores for plant-based proteins are as follows: soy (0.91), pea (0.67), oat (0.57) and whole wheat (0.45) (Vliet et al., 2015). However, proteins do not occur in foods in isolation and the entire food matrix should to be considered when

health benefits are evaluated (Millward et al., 2008). Apart from protein, animal-based foods provide heme-iron, cholecalciferol, docosahexaenoic acid (DHA), vitamin B12, and recently studied creatinine, taurine, carnosine and conjugated linoleic acid (CLA); all compounds not present in plant-based foods (Olmedilla-Alonso, 2008). Thus, moderate consumption of high quality, unprocessed animal-based foods should not be entirely discouraged. On the other hand, foods of animal origins contain saturated fatty acids (SFA), which are associated with increased risk of cardiovascular disease, dyslipidaemia and some forms of cancers (Bernstein et al., 2010; Chan et al., 2011; Sacks et al. 2017), with processed meat being classified as group 1 carcinogen (Bouvard et al., 2015).

Plant proteins are often described as incomplete, due to the insufficient amounts of all nine essential amino acids and the effect of limiting amino-acid (FAO/WHO, 1991). Although protein content and amino acid composition vary between plant species, in general, protein found in legumes are limited in methionine and cysteine; cereals (lysine, tryptophan); vegetables, nuts and seeds (methionine, cysteine, lysine, threonine); seaweed (histidine, lysine) (Woolf et al., 2011). In addition, the digestibility and bioavailability of plant proteins is lower than those from animal sources, due to the high content of dietary fibre and plant bio-compounds (also called phytochemicals), e.g. trypsin inhibitors, phytates, saponins or tannins. (Sarwar et al., 2012). Interestingly, regarded in the past as anti-nutritional compounds, phytochemicals are now regaining popularity and have been shown to have a beneficial effect on i.a. regulating blood glucose level, improving lipid profile and reducing the risk of certain cancers (Schlemmer et al., 2009). Moreover, the amino acid which has been shown to play an important role in MPS is leucine (Norton et al., 2009). Leucine supplementation can increase the rate of MPS in young adults and reduces lean mass loss in middle-aged adults (52±1 y) during periods of bed rest (Churchward-Venne et al., 2014; English et al., 2016). According to PROT-AGE recommendations, 2.5-2.8 g of leucine per meal is sufficient to reach anabolic threshold and optimise MPS (Bauer et al., 2013). This amino-acid is relatively abundant in certain plants, with the highest amounts found in dried seaweed (4.95g/100g), dry-roasted soy beans (3.22/100g), roasted pumpkin seeds (2.39g/100g), dry-roasted peanuts (1.53g/100g), cooked lentils (1.29g/1 cup) and barley flour (0.71g/100g) (USDA, 2017).

As suggested by other authors, solutions to maximise essential amino-acids content of plant foods include: amino-acid complementation (consuming cereals and pulses in one meal), consuming higher amounts of plant-based products on a more frequent basis or enhancing the nutritional quality of crops through genetic engineering (Gorissen & Witard, 2017; Vliet et al., 2015; Sands et al., 2009). More studies are needed to evaluate the effectiveness of plant proteins in the prevention of muscle mass and strength loss. Sources other than soy and foods that are complementary in terms of amino-acid composition (e.g., composed of more than one plant) have been poorly studied.

3.2. Plant proteins as a sustainable alternative

It is estimated that by 2030 the world's population will reach 8.5 billion, with 1.4 billion being over 60 years old (UN, 2015). Both projected changes pose serious challenges to a food-supply system that will need to meet the nutritional needs of both an ageing and expanding population. Proteins are the macronutrient most extensively discussed in the context of feeding the world for two reasons. Firstly, it plays a critical role in preventing protein-energy malnutrition (PEM) and promotes healthy muscle ageing. Secondly, global protein demand generates environmental implications associated with supplying animal-based foods; continuously the most preferable among consumers' source of dietary protein (Macdiarmid et al., 2012).

Exploring alternative protein sources and transitioning towards more sustainable, plant-based diets have been at the forefront of 21st century research (FAO, 2010; Nadathur et al., 2017). According to the Food and Agriculture Organisation (FAO) definition, sustainable diets have "low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are protective and respectful of biodiversity and ecosystems, culturally acceptable, accessible, economically fair and affordable; nutritionally adequate, safe and healthy; while optimizing natural and human resources" (FAO, 2012, p. 7). It has been well documented that plant-based diets can lower the risks of diabetes, cardiovascular diseases, hypertension, obesity, metabolic syndrome, and mortality, as well as prevent some forms of cancers (Yokoyama et al., 2014; Wang et al., 2015; Huang et al., 2012). However, a rapid transformation to a vegetarian diet is unlikely to be feasible on the global scale, and it is still debatable whether it is optimal for human health, e.g., due to the risk of elevating homocysteine levels (Obersby et al., 2013). Therefore, new guidelines are being developed, promoting a mixed, yet more sustainable dietary pattern, with increased intake of plant foods and reduced intake of meat (PHE, 2016). At a population level, these dietary changes, as proposed in the British 'Eatwell Guide', are expected to increase life expectancy, decrease disability-adjusted life years (DALYs), and decrease the incidence of diabetes, cardiovascular diseases and colorectal cancer (Cobiac et al., 2016). Currently, food consumption in the UK deviates markedly from these dietary recommendations. Scarborough and colleagues (2016) have modelled the changes that would be required in order to meet the recommendations outlined in the 'Eatwell Guide'. They found that the consumption of beans, pulses and other legumes would need to substantially increase (by 85%), while the consumption of red meat and processed meat would have to fall by 75%. These results clearly illustrate the highly desirable shift in dietary protein sources. More recent guidelines consider sustainability and endorse the gradual replacement of animal proteins with plants-based proteins.

However, the recommended intake of these alternative sources of proteins remains to be determined.

4. Plant proteins and appetite control

As concluded earlier, there is strong evidence that an ageing adult would benefit from an increased (>1.2g/kg/bw) and continuously sustained intake of protein for optimal MPS and muscle loss prevention (Bauer et al., 2013; Deutz et al., 2014). Ideally, proteins should be consumed three times a day with a dose of around 25-30 g of high-quality, yet sustainable protein in each meal (Symons et al., 2009; Mamerow et al. 2014; Loenneke et al., 2016; Farsijani et al., 2017). However, the increased consumption of plant proteins found in whole foods (e.g., legumes, cereals, vegetables) stipulates more than one change in diet composition, i.e. apart from the increased percentage of energy yielded from proteins, dietary fibre - an integral element of all plant diets – can also be elevated considerably (Mudryj et al., 2012). Diet high in both protein and fibre was demonstrated to support successful weight-loss (Morenga et al., 2010). Therefore, the incorporation of increased amounts of high-protein and high-fibre foods provides a promising strategy for overweight and obese individuals. On the other hand, it can raise concerns whether satiety will not be intensified by the two components, resulting in reduced appetite in individuals at risk of malnutrition. It is still unclear whether plant proteins affect the appetite in the same way as animal proteins, and whether they compromise subsequent energy intake. It needs to be emphasised however, that self-reported appetite is not necessarily a predictor of energy intake (Holt et al., 2016). This section will briefly explain appetite-related mechanisms and will discuss the existing evidence regarding the potential effect of diet high in plant proteins on appetite, across body mass index (BMI) categories.

4.1. Hunger, satiety and appetite mechanisms

It is important to stress that hunger and appetite are nonsynonymous terms. Hunger is defined as a physical 'need to eat' (usually caused by a long inter-meal interval), while appetite is a 'desire to eat' (Johnstone, 2012). Satiety, in contrast, is a state of fullness, after hunger is suppressed (Johnstone, 2012). Hunger and satiety are crucial elements of appetite assessment, which are usually scored with the use of visual analogue scales (Flint et al., 2000). Although a great deal of research has studied the phenomenon of appetite, the mechanisms are still not entirely explored. In simple terms, hunger, satiety and appetite can be directly or indirectly stimulated by hormonal responses from: i) pancreas, e.g. secretion of insulin, glucagon, pancreatic polypeptide (PP) and amylin; ii) adipose tissue, e.g. leptin and adiponectin; iii) gastrointestinal tract, e.g. ghrelin, glucagon-like peptide 1 and 2 (GLP-1, GLP-2), cholecystokinin (CKK), gastric inhibitory polypeptide (GIP), polypeptide YY (PYY), oxyntomodulin and serotonin; and iv) hypothalamus, e.g. dopamine,

neuropeptide Y, growth hormone releasing peptide (GHRP) (Suzuki et al., 2011; de Graaf et al, 2011). Some hormones or peptides promote appetite (orexigenic) and other work antagonistically, by suppressing it (anorexigenic) (Suzuki et al., 2011; de Graaf et al, 2004). Apart from physiological factors, the sensorial exposure to food (e.g. sight, smell, taste) has been shown to increase appetite (Sørensen et al., 2003). As such, people may report the appetite in the absence of hunger. A novel finding is that the individual's protein status can affect the response to food cues. Griffioen-Roose and colleagues (2014) discovered, that protein deprivation modulated reward responses in the brain and increased the preferences for savoury foods.

Described mechanisms have been suggested to be dependent on the individual's body mass status and age (Bowen et al., 2006; MacIntosh et al., 1999). The most consistent finding is that hunger and appetite tend to be reduced in older individuals (anorexia of ageing) (Moss et al., 2012; Giezenaar et al., 2016). Yet, it has not been explored how the foods high in plant proteins may influence the described physiological, sensorial and psychological responses and whether they change with body weight status and age. Because of the sparsity of evidence, studies with younger participants have been included in this review's section.

4.2. Overweight and obese

High protein diets have been shown to be an effective weight-loss strategy for overweight and obese individuals by reducing hunger (Dhillon et al., 2016), producing greater satiety in comparison to carbohydrates and fats (Weigle et al., 2005) and contributing to the increased energy expenditure and diet-induced thermogenesis (Bray et al. 2015; Weigle et al. 2005). Most, but not all studies, confirmed the effect of high-protein diet on postprandial appetite suppression and subsequent reduction in energy intake (Weigle et al., 2005; Johnstone et al., 2008). To date most trials in overweight and obese adults have focused on the effects of animal proteins (e.g. meat, whey, casein) and it is unclear, if replacement with plant proteins would have a similar effect on appetite. In addition, previous studies involving high-protein diets tended to use foods that are low in carbohydrate (Astrup et al., 2004). The shift towards plant-based proteins in their natural (not-isolated) form eliminates the potential ketogenic effect of a high-protein diet because these alternatives (e.g., pulses, cereals and vegetables) also tend to be rich in carbohydrate.

When soy proteins were studied, the effects on appetite and weight loss-related outcomes appeared to be similar to those stimulated by animal proteins ingestion. Neacsu and colleagues (2014) investigated appetite responses to high-protein weight-loss diets among obese men (mean BMI 34.8kg/m²), aged 34-71 y old. The study demonstrated that weight loss was observed in both (meat and soy) diets, however, the magnitude of weight loss did not differ significantly between the

intervention groups. Moreover, no significant differences in hunger, fullness or desire to eat were observed between the participants following diets with different protein sources. Although plasma concentration of ghrelin and PYY differed slightly between the diets, the net area under the curve (AUC) revealed that the response patterns were similar (Neacsu et al., 2014). The results of this study were however, restricted to soy proteins.

Vegetarian protein sources, other than soy, were studied by Scully and colleagues (2017) who compared effects of buckwheat and fava beans proteins on appetite in participants aged 23-63 years old (BMI 19.3-38.9kg/m²). The results revealed no significant differences in terms of motivation to eat or appetite in comparison to the baseline, and between the two diets studied. No differences to the baseline diet reported in the latter study indicates, that the shift towards plant proteins does not have to compromise the appetite in normal, overweight and obese individuals (Scully et al., 2017). However, the age and BMI ranges were vast in this study, and it would be interesting to analyse these effects in a larger sample, accounting for potential age- and body weight status-related differences.

In contrast, some studies have reported the differences between animal and plant proteins in terms of its energy expenditure (EE) and thermogenesis. For example, Mikkelsen and others (Mikkelsen et al., 2000) found that pork protein generated a 2% higher 24h EE than the soy protein diet in overweight men (mean age 26±3.2 y; BMI 28.9±1.7 kg/m²). This was suggested to be due to the higher biological value of animal proteins.

4.3. Normal weight

Plant proteins (similarly to animal proteins) have been shown to induce fullness more effectively in normal weight subjects than in obese individuals, even when plant sources other than soy were tested. This can be explained by possible impairments in appetite control mechanisms observed among people with higher BMI (English et al., 2002; Klok et al., 2007). An interesting study by Nilsson and others (2013) investigated the effects of an evening meal composed of brown beans on appetite-regulating hormones in young adults (23.8±0.7 y; BMI 22.5±0.6 kg/m²). They found a significant increase in PYY (by 51%) and decrease in ghrelin and hunger feeling (by 15 and 14%, respectively), when compared to the reference meal (white wheat bread). Although the observed responses were believed to be induced by the colonic fermentation caused by the starch found in brown beans, the protein-induced satiety response cannot be entirely ruled out.

Several studies did not find significant differences between animal and plant proteins in terms of appetite control in normal weight adults. Lang and colleagues (1998) compared satiating effects of egg albumin, casein, gelatin, soy, pea and wheat gluten protein among young, healthy men. No

significant differences were found between protein source and satiety, subsequent energy intake and insulin secretion. The authors suggested that carbohydrate and fat content of experimental meals may have affected the observed responses. A year later, the same research group reported different effect of casein, gelatin and soy protein ingestion on glucose, insulin and glucagon kinetics (Lang et al., 1999). No effects were reported in terms of 24h energy intake and have shown only a weak impact of protein source on the satiety. Similar findings were obtained by Douglas and colleagues (2015), who compared the effects of two high-protein meals (beef vs. soy) on appetite, satiety and food intake in young adults (mean age 21 ± 1 y; BMI 23.4 ± 0.6). To account for potential confounders, two types of meals were compared: macronutrient and fibre-matched (24 g of either beef or soy protein), and size-matched (beef: 24 g protein/1g fibre; soy: 14 g protein/5 g fibre). Under both conditions studied, fullness and postprandial PYY and GLP-1 plasma concentration increased as anticipated. However, no differences between meat and soy protein ingestion were observed. Importantly, no differences were also observed in subsequent energy intake and the time when the next meal was requested (Douglas et al., 2015). In contrary, a recent study in young, normal weight men observed, that high protein plant meal (beans and peas) resulted in lower appetite, hunger and food consumption and higher fullness and appetite, when compared to meat-based meal (veal and pork) (Kristensen et al., 2016). This finding is however restricted to young adults only. In summary, results from discussed studies indicate that high-quality proteins, regardless of the source have similar effect on appetite in normal weight adults and could be therefore be used interchangeably.

4.4. Underweight

To our knowledge, no study has thoroughly investigated the effects of various plant proteins on appetite in underweight, ageing adults. Moreover, it remains inconsistent whether protein-induced satiety decreases with age. Giezenaar and others (2015) compared the effect of age on appetite suppression and energy intake in normal weight young (18-34 y) vs. older men (69-80 y). They found that in older adults, protein ingestion suppressed the energy intake to a lower extent than in the young controls (by 1% and 15%, respectively). However, this study tested whey proteins (on two loading levels, 30 and 70 g) and it can only be speculated that plant proteins would have had a similar effect.

Since soy proteins have been shown to suppress appetite in a similar way to animal proteins in normal weight and overweight subjects, this vegetarian alternative may not be optimal for adults who are older or at risk of malnutrition. Protein found in other pulses, cereals or nuts might be the answer, yet this research field is still lacking sufficient evidence. Food solutions for this population

group appear to require separate investigation; perhaps a form of food, rather than the protein source, is of greater importance, e.g. few studies have shown that proteins in a liquid form, suppress appetite less than solid foods (Martens et al., 2011; Giezenaar et al., 2017). Hence, products targeting this population group could be in the form of high-protein soups, puddings or smoothies. Undoubtedly, high-quality, sustainable protein sources, effective in MPS stimulation, which at the same time do not compromise the appetite are highly sought after as a subject of future research.

In summary, data regarding the effects of plant proteins on appetite in adults with different body weight status is limited. The message from the existing evidence points towards the hypothesis that plant proteins trigger similar responses to animal proteins, particularly when soy proteins were studied. The appetite suppression effect is observed mainly in normal weight and overweight individuals. The appetite suppression response in underweight subjects appears to be somewhat reduced when animal proteins are ingested (Giezenaar et al., 2015; Soenen et al., 2014), which allows a speculation that increased intake of plant proteins should not mitigate energy intake at individuals at risk. This, however, needs to be verified in future studies. Other factors that affect appetite are still currently studied, e.g. FTO gene polymorphism. One study by Huang and colleagues (2014) revealed that people with the specific allele of this gene may respond differently to high-protein diets, presenting lower food cravings and appetite than people without this allele. It is possible, that more research in this newly emerged field will advance the understanding of protein-appetite associations and perhaps explain the inconsistencies in results reported to date.

5. Areas for future research

5.1. Consumer-focused

More research is needed to explore how to build consumer's awareness about the importance of sufficient protein intake for healthy ageing. At the moment, high-protein foods are mainly targeted to athletes and those who aim to lose weight. The market offer of real food solutions is still modest, and the majority of high-protein products are in the form of nutritional supplements. The critical question is, whether the increased intake of protein for muscle health will be in the future promoted among general population of ageing adults, and whether this message will be supported by policy makers and national guidelines, in a similar manner to the salt and sugar reduction recommendations. Moreover, the current UE labelling regulations do not allow to indicate the purpose of the high-protein product content (e.g. health claims). Hence, today's consumers may lack the essential knowledge of the potential health benefits associated with high-protein product consumption.

Furthermore, it would be interesting to learn more about consumer's attitudes towards increasing the consumption of sustainably sourced proteins: i) whether they are ready to make more environmentally friendly choices by replacing animal proteins with those from plants (see: [Vanhonacker et al., 2013](#)) and ii) do they have the knowledge and cooking skills, that allow for the incorporation of various plant proteins into every-day diet? Perhaps, at the introductory phase, ready meals and snacks high in plant proteins would be a preferred consumer choice. Next, what would be the optimal plant protein carrier, e.g. soup, snack (biscuits), food-on-the-go (sandwich, wrap)? While answering these questions it would be worthwhile to investigate potential acceptance and effectiveness of two routes: new product development (NPD) and product reformulation. The latter, could be achieved through a 'health by stealth' strategy which has shown to be successful elsewhere, e.g. gradual reduction of salt in products aimed at children ([Buttriss, 2013](#)). In the protein scenario, animal-based ingredients in commonly consumed products could be gradually and partially replaced with plant alternatives, giving the consumer time to adjust to a new flavour, smell, texture.

Lastly, more evidence regarding age-, BMI- and sex-related differences in appetite responses to plant protein meals is needed. Most studies to date were conducted in young men or young mixed-sex samples ([Neacsu et al., 2014](#); [Scully et al., 2017](#); [Mikkelsen et al., 2000](#); [Nilsson et al., 2013](#); [Lang et al., 1998](#); [Douglas et al., 2015](#)) with no comparisons between sexes being drawn. It was previously reported, that hunger, satiety and appetite responses are different in women and men ([Cornier et al., 2010](#)). To our knowledge, no studies have yet investigated the effects of high-protein plant diet on appetite, accounting for sex differences in adults from different age groups and with different nutritional status.

5.2. Industry-focused

One of the key identified challenges in new product development is the palatability of foods high in plant proteins. The pleasantness of the diet is an interesting area of appetite and satiety research. It has been shown, that apart from the self-perceived hunger/fullness and postprandial hormones secretion, a central nervous system response to a high protein meal ingestion is of an equal significance ([Journel et al., 2012](#)). Although the results are inconclusive, in general, meals high in animal proteins are scored higher on palatability scales than high-protein vegetarian alternatives ([Kristensen et al., 2016](#)). However, it has been suggested that the regular exposure to meat alternatives can positively influence product's liking over time ([Hoek et al., 2013](#)). It would be therefore important to explore and evaluate potential methods to increase the palatability of plant-based foods.

Furthermore, the industry would need to address the product design challenge related to the incorporation of the required amount of 25-30 g of high-quality plant proteins into one meal. This would need to be obtained with preserving a sensible volume size and preferably without the use of isolates and concentrates, to maximise the benefits of the natural food matrix. Lastly, it would be worthwhile to assess which sustainable (yet nutritious) protein sources would be most feasible to grow and produce in the UK. Wheat and barley are one of the most commonly grown crops in Britain (DEFRA, 2017). Schoeder and colleagues (2009) compared the effect of barley, rice and wheat on appetite and found that while no significant differences were observed in terms of subsequent energy intake, a high-fiber barley snack significantly reduced hunger sensation in comparison to rice and wheat. Soy proteins were most extensively studied type of vegetarian protein and other types of plant proteins have not been yet thoroughly investigated.

6. Conclusions

The currently recommended protein intake for ageing adults may not be sufficient for muscle mass and strength maintenance. To minimise the adverse health and environmental effects of excess animal protein consumption, incorporation of sustainably sourced plant proteins may be a promising strategy. Unfortunately, healthy and environmentally friendly food solutions helpful in promoting healthy ageing are still in the conceptual phase. Although the evidence regarding the effects of plant proteins on appetite is scarce, available data points towards the positive effects of replacing animal proteins with plant-originated in normal weight as well as overweight/obese individuals. More studies are needed to rule out the effect of protein-induced satiety after plant proteins ingestion in underweight adults.

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