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Novel plant-based meat alternatives: future opportunities and health considerations

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Abstract

Current food systems threaten population and environmental health. Evidence suggests reduced meat and increased plant-based food consumption would align with climate change and health promotion priorities. Accelerating this transition requires greater understanding of determinants of plant-based food choice. A thriving plant-based food industry has emerged to meet consumer demand and support dietary shift towards plant-based eating. 'Traditional' plant-based diets are low energy density, nutrient dense, low in saturated fat and purportedly associated with health benefits. However, fast-paced contemporary lifestyles continue to fuel growing demand for meat-mimicking plant-based convenience foods which are typically ultra-processed. Processing can improve product safety and palatability and enable fortification and enrichment. However, deleterious health consequences have been associated with ultra-processing, though there is a paucity of equivocal evidence regarding the health value of novel plant-based meat alternatives and their capacity to replicate the nutritional profile of meat-equivalents. Thus, despite the health halo often associated with plant-based eating, there is a strong rationale to improve consumer literacy of plant-based meat alternatives. Understanding the impact of extensive processing on health effects may help to justify the use of innovative methods designed to maintain health benefits associated with particular foods and ingredients. Furthering knowledge regarding the nutritional value of novel plant-based meat alternatives will increase consumer awareness thus support informed choice. Finally, knowledge of factors influencing engagement of target consumer subgroups with such products may facilitate production of desirable healthier plant-based meat alternatives. Such evidence-based food manufacturing practice has the potential to positively influence future individual and planetary health.

Context

Food systems have the potential to promote both human and planetary health but currently pose a significant threat to both[1,2]. Global population, expected to reach approximately 10 billion by 2050, longer life expectancy, increased income, and urbanisation will increase demand on global resources[3–6]. The projected increase in demand for food (50%) and animal-derived food (70%) will add substantial pressure to an already failing food system while animal husbandry, it is argued, also has an overall negative impact on environmental sustainability[7,8]. Some estimates suggest food production is already responsible for approximately one third of anthropogenic greenhouse gas emissions[9–12]. Meat and dairy also require more land and water use than foods of plant-based origin, potentially furthering deforestation and biodiversity loss[13–16]. Although historically considered an essential dietary component, providing vitamin B_{12}, iron and calcium, overconsumption of meat, particularly processed meat, has been associated with certain deleterious health consequences[17–19].

International recognition of this challenge has led to global strategies to accelerate transition towards a healthier, more sustainable food system[5,20]. These include the UN Sustainable Development Goals and the Paris Agreement of Climate Change[3,6]. However, the complexity and multi-faceted nature of this problem emphasises the need for strong multi-sectoral partnerships[21–23]. Extensive evidence suggests that reduced meat and increased plant-based food consumption would align with both climate change and health promotion strategies[6,17,24–26].

Current animal-based protein consumption is unsustainably high[27]. In 2021, global meat consumption was estimated to be 328 million metric tons and is expected to increase approximately 70% by 2050[7,8,28,29]. High intakes of red and processed meat have been associated with increased risk of non-communicable diseases including type 2 diabetes, colorectal cancer and reduced life expectancy[30–34]. Indeed, the World Health Organisation (WHO) classifies red meat as a Group 2A carcinogen (likely cause of cancer) and processed meats as a Group 1 carcinogen (known cause of cancer)[35], with the World Cancer Research Fund recommending restriction of red meat consumption to three or less portions per week and avoidance or restriction of processed meat[36]. However, guidance does not support the total elimination of meat as a key source of energy and nutrition[18,21]. Against this backdrop, however the WHO have endorsed animal-derived foods for high-quality nutrition in children aged 6 - 23 months[37] and Adesogan *et al.*[38] challenge the notion that one-size-fits all. In many developing countries animal-sourced protein consumption is limited and nutrient intake often suboptimal, reinforcing the need to tailor recommendations to different regions to prevent exacerbating current public health challenges. Additional benefits also warrant careful consideration: the livestock sector provides increased food and nutrition security, a living income for many, and contributes to national revenue, particularly in more deprived populations[16,38,39]. Nonetheless, estimates suggest that to sustainably feed 10 billion people, a significant reduction in meat consumption of ~50-75%, accompanied by increased consumption of plant-based foods (see Table 1) is required[6,8,40]. It is noted that replacing 3% of daily energy intake derived from processed red meat with plant-derived sources could reduce risk of all-cause mortality by 12%[41]. Furthermore, substituting 1kg of beef-derived protein with kidney bean sources could offer an 18-fold reduction in land use[42]. Heterogeneity in modelling methods used to estimate the required intake of plant-derived proteins remains however[6,43–46]. Whilst EAT-Lancet[6] recommend a daily intake of 25g soybeans plus 50g of beans, lentils and peas, other suggested increases in legumes, beans, pulses nuts and oil seeds vary between 26-30g per day[45–47].

Currently, 21% of the UK population identify as flexitarian (12.5% as meat-free) and 39% report reducing meat intake, while consumption of plant-based products between 2008-2011 and 2017-2019 doubled[48,49]. Globally, 40% report reducing meat intake while 10% avoid red meat although these changes may have been accelerated by the recent Covid-19 global pandemic[49,50]. Increased consumer awareness of zoonosis, coupled with the food chain disruption during the pandemic may have facilitated a dietary shift to reduce meat consumption[50]. However, to achieve the UK climate change commitments, an additional 20% reduction in high carbon meat and dairy would be required over the next decade[48]. Novel plant-based meat alternatives (PBMAs; see Table 1) designed to replicate the preparation methods, organoleptic and nutritional qualities of meat-based equivalents, may offer a viable avenue to help facilitate the required dietary shift[7,8,11,21,51,52]. This gradual shift towards reduced meat consumption and increased engagement with plant-based foods has resulted in a reportedly thriving plant-based food industry[48]. However, accelerating this transition requires a greater understanding of the factors influencing plant-based food choice. It should be noted that there is a lack of consensus regarding a universal definition for numerous terminologies in the current review. For clarity, the current review will use the definitions outlined in Table 1.

INSERT TABLE 1 HERE

Traditional Plant-Based Diets versus Consumption of Novel Plant-Based Meat Alternatives

Consumer enthusiasm to adopt healthier, more sustainable diets has led to an increase in plant-based dietary patterns such as vegetarianism, veganism and flexitarianism[49,51]. ‘Traditional’ plant-based diets are frequently characterised as low energy density, nutrient dense, low in saturated fat and associated with a range of health benefits including healthier BMI and protection against cardiovascular disease[53–55]. A large body of evidence also recognises the role of plant-based dietary patterns in reducing risk of all-cause mortality[55–58]. Naghshi *et al*.[55] reviewed 32 prospective cohort studies and reported plant-based protein consumption was significantly associated with reduced risk of all-cause mortality and cardiovascular disease mortality. Furthermore, a 3% increase in energy derived from plant proteins was associated with a 5% reduced risk of all-cause mortality[55]. While the authors reported no association between plant-based protein consumption and cancer mortality, other studies have inferred that 'traditional' plant-based diets may protect against cancer and mortality[56,59–61].

Extensive epidemiological evidence also supports the adoption of 'traditional' plant-based diets to facilitate weight management[62–64]. For example, Tran *et al.*[65] systematically reviewed twenty-two studies, eight of which demonstrated significantly reduced body weight and/or BMI. Whilst most studies applied the gold-standard randomised controlled trial (RCT) study design, heterogeneity in methodology, such as restrictions on dietary fat intake, limited generalisability. Furthermore, some studies failed to consider confounding factors such as physical activity, limiting the internal validity. A more recent study, which did not emphasise restricted energy intake, involved a six-month five-arm RCT[64]. Participants were randomly assigned to a low fat, low glycaemic index; vegan (n=12), vegetarian (n=13), semi-vegetarian (n=13), pesco-vegetarian (n=13) or omnivorous (control, n=12) group dietary pattern. All intervention group participants attended dietitian-led group meetings for six months. While significant weight reduction was demonstrated across all dietary groups at six months, the vegan dietary group demonstrated significantly greater weight loss (-7.5% ± 4.5%) compared to the semi-vegetarian (-3.2% ± 3.8%), pesco-vegetarian (-3.2% ±3.4%) and omnivorous groups (3.1% ± 3.6%). However, it should be noted that no significant difference was reported between the vegan and vegetarian dietary groups.

Although current evidence demonstrates health benefits linked to 'traditional' plant-based consumption, much of the literature base relies on large-scale, historic, observational studies in restricted populations thus increasing risk of inherent methodological bias[66–71]. For example, Kwok *et al.*[69] systematic review and meta-analysis identified the positive impact of a vegetarian diet on risk of cardiovascular disease mortality based on studies of Seventh Day Adventist communities. However, it should be noted that the healthy lifestyles behaviours associated with this population typically includes regular physical activity and abstinence from alcohol and tobacco. Thus, the influence of potential confounding variables on cardiovascular outcomes limits the generalisability of findings to the wider population.

The fast-paced nature of contemporary lifestyles has increased demand for convenience foods as opposed to adoption of 'traditional' plant-based diets leading to a rapid expansion of PBMAs designed to mimic sensory attributes of meat[72,73]. Unlike 'traditional' whole plant foods, PBMAs undergo considerable processing to effectively deliver tasty, convenient substitutes for meat and meat-products[52,74,75]. Such novel products may be deemed inferior to minimally processed, 'traditional' plant-based foods with regard to impact on sustainability and health[18,21,52,76–79]. However, PBMAs are not designed to replace whole plant foods but instead to offer a steppingstone in the transition away from meat to increased plant consumption[8,21,52]. For example, meat-eaters are more likely to replace a beef burger with a plant-based equivalent as this substitute does not require substantial dietary change. Thus future investigations focussing on the perceived benefits of plant-based meat versus meat-based equivalent products are warranted in order understand consumer demand.

Consumer Perceptions Influencing Plant-Based Food Choice

There are a wide range of complex interacting factors that influence an individual's food-related behaviours[80,81]. Taste, cost and convenience have all been reported as primary drivers underpinning general and plant-based food choice[52,81]. Increased awareness of animal welfare, environmental sustainability and individual health has increased demand for plant-based foods more aligned with aspirational factors[14,15,18,52].

INSERT FIGURE 1 HERE

Primary Drivers

Cost

The perceived high cost of PBMAs presents a barrier to consumer engagement[74,82–84]. Numerous cross-sectional surveys have reported affordability as a significant determinant of current and future engagement with PBMAs[1,16,81,82,85]. Clark and Bogdan[85] reported that Canadians considered cost more important than availability and convenience (47%, 39% and 34%, respectively) and a recent European survey[86] highlighted a reluctance to pay for plant-based burgers amongst older adults. Sociodemographic factors and annual income of respondents may confound survey responses[16,87] with cost recognised as a salient product attribute amongst low-income groups and those with lower education outcomes and engagement with PBMAs reportedly being higher amongst individuals with higher socioeconomic status[76,85]. Consumer segment may also influence response: meat consumers cited cost of Quorn as a negative attribute while vegetarians were reportedly more ambivalent[84]. Whilst the interrelationship between dietary pattern and sociodemographic characteristics warrants further investigation it is clear that affordability of novel PBMAs is a key consideration when it comes to their adoption across a range of consumer segments[74,81,82,88–91].

Convenience

Convenience, and its perceived influence on self-efficacy, may also restrict engagement with plant-based foods(74,81,92). A Dutch focus group study identified that the preparation time for a desirable meal with PBMAs was perceived to be significantly greater than that needed for an equivalent meat-based meal(93). This is supported by a Finnish survey where one third of individuals perceived the preparation of plant-based meals to be more challenging compared to meat-based equivalents(94). The availability of PBMAs in UK supermarkets is also highlighted as a barrier to engagement(84) though degree of importance of convenience varies across consumer segments with flexitarians valuing convenience more than meat-avoiders(20,81,84). Demographic factors may be important confounders here since meat-eaters and flexitarians are more likely found in households with children, thus value time-convenience more, compared to meat-avoiders(88,95,96). Developing and marketing widely available PBMAs that are easy to cook and contextually appropriate substitutes to meat may accelerate adoption of plant-based dietary patterns.

Taste

Novel PBMAs differ from the early generation PBMAs, such as soya and tofu, in that they mimic sensory attributes of meat(31,73). Bryant(52) reported that PBMAs that successfully replicated the taste and texture of processed meat have the greatest potential to replace meat-based equivalent products. Several studies have emphasised that desirable sensorial qualities, including taste, texture, appearance and smell are crucial to achieving consumer acceptance and engagement(24,31,49,81,84,97,98). 86% of US adults cited taste as a driver of purchase intent ahead of price (68%)(99). This supports the results of a recent Norwegian study(97) which reported 78% of consumers considered taste the most salient determinant of food purchase. However, reproducing desirable meat characteristics poses a significant challenge. For example, the higher lipid content in meat-based equivalents adds taste and texture that is limited in PBMAs making them less juicy(8,13,49,100). Furthermore, legumes as a replacement protein source may negatively impact the flavour(13,51). Thus, taste can simultaneously also be considered as a barrier(74,83,84,101).

Several studies cite lack of familiarity(40,98) and food neophobia (an individual's unwillingness to try novel foods) as playing a crucial role in the acceptance of PBMAs(82). Regular consumers of PBMAs score significantly lower in the Food Neophobia Scale compared to non-users and occasional users(76). Hence, novel products resembling familiar meat-based foods may mitigate against neophobia(31). However, increased processing to mimic meat results in foods that are further removed from the perceived 'natural state'(83,102). While there is no universal definition of what comprises a 'clean label' product it typically refers to consumer desire for foods that have undergone minimal processing, using familiar ingredients and excluding ‘additives’[102–104]. In contrast, novelty may also be a potential motivator in people who are curious to try new foods[80].

The influence of hedonic characteristics of pleasure elicited in response to *perceived* sensory characteristics may also pose a barrier to the adoption of PBMAs[31,76]. Michel *et al.*[74] reported consumer associations between meat and “delicious” in contrast to PBMA and “disgust”. Although consumer perceptions offer valuable insights, they are self-reported and are not direct comparisons of consumer acceptance. Thus, it has been suggested that consumers may react differently to a novel product which they can actually taste/smell before purchasing[105]. Slade[105] conducted a hypothetical choice experiment where participants indicated their willingness to purchase a range of burger products. Despite being informed that all burgers tasted the same, 65% of respondents indicated they would purchase the beef burger in contrast to the plant-based burger and cultured meat burger (21% and 11%, respectively) with 4% stating they would purchase neither option. However, the hypothetical nature of the study design restricts findings to perceived taste not actual taste. Hedonic tests would generate a more reliable indication of actual sensorial acceptance versus perceived acceptance[40]. Schouteten *et al.*[100] conducted a sensory analysis experiment under blind, expected and informed conditions. The study again reported stronger preference for the meat burger versus the plant-based burger under all conditions and across both consumers and non-consumers. Participants attributed negative sensorial qualities, including a lack of juiciness, dryness and off flavouring, to the plant-based burger compared to the meat-based equivalent. Another sensory evaluation reported similar findings, highlighting the inability of plant-based nuggets to replicate their meat-based equivalent and critiquing the off-flavours of plant-based nuggets that included a beany aftertaste[106].

Sustained adoption of PBMAs is also influence by taste[1,16,82]. 42% of North Americans cited perceived taste as the reason for not trying to increase purchase of protein alternatives in a recent Mintel report[85]. In addition, Collier *et al.*[87] highlighted focus group participants’ disappointment in PBMAs ability to replicate the taste of meat. In fact, missing the taste of meat has been cited as the most common factor, after health, for returning to a meat-based diet[107]. High meat attachment and high levels of food neophobia have been noted as significant barriers to adopting PBMAs[1,31]. Meat attachment may also be associated with an emotional response to meat abstinence, strong enough to overcome the reported negative health impact of meat[108]. Additionally, the influence of the taste of plant-based foods as a barrier to adoption varies across different consumer segments with males more likely to reject plant-based foods as not being tasty[94] and approximately twice the number of women citing taste as a driver of regular PBMA consumption[82]. Of interest is the finding that while omnivore/flexitarian subgroups demand products mimicking sensory properties of meat, vegan and vegetarians are more likely to accept non-meat mimicking substitutes[49,76].

Aspirational Drivers

While primary drivers of cost, taste and convenience are important, animal welfare, environmental impact and health have a significant influence on food choice[81].

Animal Welfare

Animal welfare has long been a driver of meat-avoidance though concerns regarding differing global meat rearing standards and live animal transportation issues continue to influence the gradual reduction in meat consumption in both the UK and worldwide[26,32,109]. The reported degree of its relative importance as a driver of both meat-avoidance and adoption of PBMAs varies however, with some studies suggesting it to be a key factor (amongst ~45-65% of respondents)[82,83,110] and others suggesting it is of lesser importance[81,111,112]. Neff *et al.*[112] found as few as 12% of respondents in the US cited animal welfare as the reason for reduced meat consumption in contrast to other factors such as cost and health. Inconsistency in findings may be the result of variation across consumer subgroups[74,76], with rural consumers less influenced than urban consumers[98], and personal experience of animal husbandry or limited access to large supermarkets also influencing this phenomenon[85,98]. Vegetarian and vegan consumers also tend to place greater value on the welfare of animals[54,58,63,89–92].

Environment

Estimates of the extent to which environmental awareness influences the popularity of and engagement with plant-based food varies[48,80,81,105,116]. A recent cross-sectional survey[82] found over 80% of respondents cited environmental reasons as the primary driver behind regular PBMA consumption. In contrast, Circus and Robison[83] reported only 21.6% of respondents reduced meat for environmental reasons. In addition, a recent Food Standards Agency survey[117] reported 36% of respondents were willing to try plant-based proteins for sustainability reasons compared to health (39%) and safety (44%). This supports the findings which suggest that personal health has a greater influence on the adoption of plant-based eating compared to environmental sustainability amongst omnivores and semi-vegetarians (32.9% and 20.3%, respectively)[118]. Thus, personal health gains may outweigh altruistic factors when it comes to reducing meat and consuming more plant-based foods.

Historically low levels of public awareness of the environmental impact of meat consumption may partially explain the so far limited dietary shift towards plant-based[31,40,92,101]. Macdiarmid *et al.*[119] highlighted a substantial lack of awareness in focus groups regarding the impact of meat consumption upon climate change and a mutual perception that personal consumption was negligible in addressing environmental sustainability. However, socio-economic status has been shown to influence awareness[9,85] and, more recently following publication of EAT-Lancet and media coverage of the issue, awareness has been heightened[1,6]. Estell *et al.*[110] reported over 80% of survey respondents agreed that following a plant-based diet is environmentally friendly. Despite increased awareness however, only a small minority of consumers are willing to change meat consumption behaviour[49,115,120]. Demographic characteristics of study respondents predicts consumer behaviour[40,108] with age and gender noted to influence both degree of awareness and importance of environmental impact of meat consumption, appearing to be greatest amongst younger adults, Millennials and females compared to older adults and males[9,40,74,82,113].

While it appears altruistic drivers of animal and environmental welfare are important to consumers, they are consistently identified as secondary to health[20,40,97,105,108,113,114,121,122]. Parry and Mitchell[123] highlight that perceived importance of altruistic factors was at least 20% lower than other attributes including taste and health when purchasing plant-based products (see Table 1). Furthermore, concern for the environment (12%) and animal welfare (12%) was substantially lower than health (50%) as a driver for reduced meat consumption[112]. This emphasises the salient role of health in driving meat reduction and increased engagement with plant-based foods.

Health

Excessive red and processed meat consumption has been associated with deleterious health consequences such as increased risk of type 2 diabetes, colorectal cancer and reduced life expectancy[30–34]. In contrast, 'traditional' plant-based dietary patterns are noted to maintain cardiovascular health, reduce obesity and prevent or improve the management of type 2 diabetes[48,49,98,120]. Increased consumer awareness of putative health benefits may therefore have fuelled a dietary shift to reduce animal-sourced food products and increase engagement with plant-based foods[20,31,32,40,48,80,81,84,97,103,118,122].

The perceived health benefits of consuming plant-based foods relate to their predicted nutritional composition (low energy density, low saturated fat content, rich micronutrient profile), and the likely associated physiological effects of dietary adoption (altered cardiometabolic risk and reduced risk of overweight / obesity)[76,84,93,111,113,118,124–126]. Elzerman *et al.*[93] highlighted that PBMAs were perceived as healthier than meat amongst Dutch consumer focus groups. This supports the conclusions of cross-sectional surveys where the term 'nutritious' was associated with plant-based eating and plant-based burgers were considered healthier than their meat-based equivalent[127,128]. While the online nature of these studies restricts validity of findings, a recent sensory evaluation reported meat-based burgers were deemed 'unhealthy' compared PBMAs[129]. Once again, demographic differences exist with females and middle aged-older consumers more likely to be influenced by health drivers[16,68,75].

When it comes to weight control there are contrasting findings. Hoek *et al.*[76] identified weight control as a motive to try PBMAs across consumers and non-consumers. However, weight loss was not a strong health-related motive for plant-based product adoption amongst plant-based food and beverage product consumers and non-consumers in the UK and Republic of Ireland[98]. Moreover, Culliford and Bradbury[9] concluded that weight loss was perceived to be substantially less influential compared to health when determining food choice (76% and 12%, respectively).

Health concerns have been described as a 'double-edged sword'[81]. Particularly restrictive plant-based dietary patterns (e.g., veganism) may be associated with nutrient deficiency or insufficiency[31]. Thus, a lack of awareness regarding the health benefits of regular consumption of PBMAs may enhance the perception that they are nutritionally inferior and limit consumer engagement[31,109]. Elzerman *et al.*[93] reported that although most focus group participants perceived PBMAs to be healthy (e.g., high in protein and low in saturated fat), concerns were raised regarding digestibility, suitability for children (particularly regarding nutritional needs) and a lack of clarity in relation to their health value. The reported perception that meat is a necessary component of the diet and thus its avoidance raises health concerns may be a key reason for meat-excluders returning to meat consumption[76,94,107,125].

Leroy and Cofnas[130] emphasised the juxtaposition between consumer health-related motivations and the arguably ultra-processed nature of PBMAs[31,48,131]. Excessive consumption of, so-called 'ultra-processed' foods (UPF; see Table 1) has been argued to elevate risk of obesity and associated comorbidities such as cardiovascular disease[131]. This may explain the findings of Mullee *et al.*[118] who reported nearly a quarter of respondents perceived habitual consumption of vegetarian foods to be 'unhealthy'. Jahn *et al.*[31] also identified degree of processing, even processes that are paradoxically designed to enhance nutritional quality (such as fortification), as an important factor in consumer product evaluation and reduced product desirability.

While clearly many factors are associated with engagement with plant-based foods, health plays a salient role in consumer decisions and behaviour[103,122]. More research is needed regarding the specific health-related drivers beyond weight loss. Furthermore, the current evidence base highlights variation in drivers and barriers associated with plant-based food engagement amongst different sub-groups of consumers. This reinforces the need for a strong, evidence-based, whole systems approach to facilitate effective and sustainable dietary behaviour change. It also reinforces the fact that a one-size-fits all approach is not sufficient to accelerate engagement with PBMAs. Instead an increased understanding of the specific needs and barriers within different subgroups of consumers is required to effectively tailor new product development and marketing strategies to meet those needs. Application of segmentation theories to divide populations into smaller subgroups based on similarities, can enable consumer segments to be targeted with a more customised strategy. Studies within the current research field have segmented according to sociodemographic factors, dietary patterns and product usage[9,76,84,97,98,110,112,123,125,126]. However, using models of behaviour change to identify sub-groups more pre-disposed to engage with innovative PBMAs has the potential to accelerate adoption[81]. For example, Roger's Diffusion of Innovation identifies predisposition to change while the Transtheoretical Model describes the process of intentional behaviour change[132,133]. Together these models would enable investigation of perceptions of, drivers of and barriers to the adoption of novel PBMAs relative to specific population subgroups.

Novel Plant-Based Meat Alternatives: Health Considerations

Despite the paucity in evidence regarding the impact of novel PBMAs on health, a limited number of published studies have indicated their adoption may be associated with a range of health benefits. Notably, a systematic review and meta-analysis of RCTs investigating the impact of plant-protein consumption on lipaemia proposed that protein itself may be responsible for the health-associated benefits[134]. Hence, processing whole-plant food into protein isolates may not necessarily compromise their health value. A RCT[135] comparing the impact of PBMAs with animal-derived meat across a range of health risk factors in thirty-six healthy omnivorous adults randomised participants to either plant-animal or animal-plant sequence and instructed them to consume ≥2 servings of the intervention meat product per day while ensuring consumption of other (non-study) foods was comparable in each phase (8-weeks each). PBMA consumption was associated with cardioprotective changes including significantly lower trimethylamine-N-oxide concentrations (PBMA mean = 2.7μM ± 0.3 v meat mean = 4.7μM ± 0.9; mean difference = -2.0 [95% CI -3.6, -0.3]), LDL-cholesterol concentrations (PBMA mean = 109.9mg/dL ± 4.5 v meat mean = 120.7± 4.5; mean difference = -10.8 [95% CI, -17.3, -4.3]) and weight (PBMA mean = 78.7kg ± 3.0 v meat mean =79.6kg ± 3.0; mean difference= -1.0 [95% CI -1.5, -0.5]) compared to meat consumption. It should be noted that the level of dietary control was limited as participants were able to consume chicken or fish in the plant-arm and self-selected all other dietary components. However, this in turn increases the generalisability and external validity of the study findings. A recent RCT[136] also demonstrated positive changes in the gut microbiome when substituting several meat-based meals per week for PBMA meals, resulting in a significant increase in butyrate-production pathways and significant decrease in the Tenericutes phylum; attributes associated with a healthy gut microbiome. Zhou *et* *al.*[137] also reported higher levels of dietary fibre from the digestion of PBMAs compared to meat that may increase satiation after consumption of the PBMA.

There is conflicting evidence regarding the impact of plant-based foods upon appetite[138–140]. Williamson *et al.*[141] conducted a three-way crossover study in overweight subjects (n = 42) investigating the satiating efficacy of a mycoprotein pasta preload and a tofu pasta preload compared to an isocaloric chicken pasta preload, closely matched for protein and organoleptic characteristics. The authors concluded pre-loading with mycoprotein and tofu led to significantly lower food intake compared to chicken preloading (138.7g, 135.2g and 158.3g, respectively). A similar study[138] reported plant-based protein (beans/peas) to be significantly more effective than energy and protein matched animal-based protein (veal/pork) on subjective markers of appetite in a healthy cohort of male participants (n = 43). In contrast, no differences were found between plant-based (fava beans/split peas) and meat-derived (veal/pork) protein meals, matched for energy, macronutrient and fibre, in a single-blinded RCT[139]. Similarly, a recent double-blind RCT[142] also reported no significant differences regarding markers of appetite between a lamb burrito and a plant-based meat burrito meal. However, it should be noted that the study meals were not matched for protein which may have influenced the results. In addition, Neacsu *et al.*[143] suggested plant-based and meat-based high protein diets had a similar impact on gut-peptide hormones and subjective appetite responses. However, a randomised crossover study demonstrated increased peptide YY, glucagon-like peptide 1, amylin and thalamus perfusion following consumption of a plant-based meal compared to an energy and macronutrient matched meat-based meal[140,144]. Proposed satiating mechanisms include high dietary fibre content (promoting short chain fatty acid production) in addition to modification of gastric hormone secretion and gastric emptying related to appetite suppression[145,146]. Grundy *et al.*[147] also described how dietary fibre encapsulates macronutrients to regulate digestion, while soluble dietary fibre increases viscosity in the gastrointestinal tract which in turn may slow macronutrient digestion. However, extensive processing is associated with nutrient loss and UPFs are noted to be limited in appetite-regulating nutrients such as dietary fibre and protein[148,149]. Thus, the influence of processing on the capacity of commercial PBMAs to elicit fullness needs further investigation. Furthermore, while the RCT study design is considered the gold standard method, there is an urgent need for longitudinal data to evaluate the long-term consequences of habitual consumption of PBMAs on appetite and health.

Ultra-Processed Foods

Many novel PBMAs are typically classified as ultra-processed, according to the NOVA definition[96,131]. While processing improves safety and, shelf-life and fortification enhances nutrient content, deleterious health consequences have been associated with ultra-processing. For example, so-called UPFs are noted to contain less appetite-regulating nutrients such as dietary fibre and protein. Additional concerns relate to higher levels of saturated fat, salt and free sugar content and inclusion of additives such as artificial colours, flavours and preservatives[131,150–152]. Moreover, a recent systematic review and meta-analysis by Suksatan and collegues[153] demonstrated a signficant dose-response association between UPF consumption and risk of all-cause mortality.

Gehring *et al.*[96] noted greater UPF consumption within meat reduction or avoidant diets compared to omnivorous diets in the French NutriNet-Santé cohort. This supports the notion that while novel PBMAs facilitate reduced meat consumption, their health value needs further consideration[48]. However, there is a lack of consensus as to whether all UPFs can be labelled 'unhealthy'. In fact, Derbyshire[154] argued that some UPFs demonstrate 'healthy' nutritional profiles. For example, the authors[154] highlighted fifty 'ultra-processed' food products (characterised according to the NOVA classification system) that were identified as 'healthy' food products according to the 2011 and 2018 Nutritional Profiling tool. This and similar findings have led to criticism of NOVA as an ambiguous classification system[155–159]. Additional concern relates to the use of one umbrella term of "ultra-processed" to describe a diverse range of processing techniques which have distinct functions[156]. Nonetheless, there is a paucity of evidence supporting the detrimental health consequences associated with ultra-processing upon both the nutritional and mechanistic quality of foods, specifically in relation to PBMAs[4,150,151].

Nutritional Profile of Novel Plant-Based Meat Alternatives

Limited published scientific evidence is inconclusive regarding the health value of novel PBMAs and their capacity to replicate the nutritional profile of meat-equivalents. Curtain and Grafenauer[160] reported that most PBMAs demonstrated a healthier nutrient profile than meat-based equivalents in their audit of Australian supermarkets. For example, PBMAs were significantly lower in energy density, total fat, saturated fat and significantly higher in dietary fibre. However, the sodium content of PBMAs was particularly high, with only 4% of products classified as 'low in sodium'. In fact, plant-based mince had six-fold higher sodium content than the meat-based equivalent while meat sausages had significantly greater sodium than PBMAs. A similar study in the UK[161] also reported significantly higher sodium levels in all categories except sausages and reinforced concerns by identifying approximately three-quarters of products having salt content greater than their maximum salt reduction target. The authors also reported significantly lower protein content in four out of six PBMA categories. However, although the study targeted fourteen UK retailers for PBMAs, Covid-

19 restrictions meant that only one supermarket was targeted for meat-equivalent products. Consistency in search method for both product types would increase rigour in future research.

Tonheim *et al.*[162] recently conducted a similar survey investigating PBMAs available on the Norwegian market. Again the Covid-19 pandemic restricted the range of suppliers and data collection was undertaken in two phases. The authors compared PBMAs to their meat-based equivalents in two categories: 'regular' meat and 'healthy' meat (identified with a Keyhole symbol, a labelling scheme identifying healthier food products)[163]. These 'healthy' meats were typically reduced fat alternatives to 'regular' meats. PBMAs were typically lower in energy content compared to 'regular' meat, though they contained more energy than their 'healthy' meat comparator. PBMAs were generally lower in saturated fat and higher in dietary fibre than either category of meat comparator. There was also between product variation in salt content. While salt content was more favourable in the plant-based meatballs versus both meat-equivalents, it was greater than both meat-equivalents in other product categories with plant-based mince demonstrating a ten-fold greater salt content than the 'healthy' meat comparator. In contrast, Boukid and Castellari[164] reported no significant difference in sodium content between the four burger products (vegetarian, red meat, fish and poultry based) in their survey of the EU burger market.

Heterogeneity both within and between product categories was also demonstrated in other similar studies[160,165–167]. Fresán *et al.*[10] reviewed 56 PBMAs according to their protein source and concluded that despite some between product variation, the nutritional profile demonstrated no substantial differences. Meanwhile, Bohrer[166] reported the nutritional composition of a plant-based burger to be similar to that of a McDonald's® beef patty but found differences in meatballs where the plant-based version was lower in energy, saturated fat and higher in dietary fibre compared to the meat-based equivalent. In addition, *safe*food[167] identified chicken alternatives to be less favourable on a number of nutritional components including energy density, protein, saturated fat, sugar and salt in their audit of PBMAs in Irish supermarkets. However, the method of product categorisation may have influenced the findings[167]. For example, while other studies[160–162,168] typically selected an equivalent meat-based product as a comparator, the authors[167] compared all chicken alternatives, including breaded, battered and plain alternative products, to a skinless, grilled chicken breast. Similarly, while other studies[160,161,168] compared plant-based mince to beef mince, the authors[167] compared plant-based alternative steaks, mince, meatballs and Bolognese to beef mincemeat. This method of categorisation limits the reliability of study findings as the selected meat product does not reflect a suitable comparator. This highlights a substantial challenge for research conducted within this area. For example, a robust feeding trial, would require an appropriate comparator arm which includes an element of blinding across a range of factors including sensory attributes, cooking technique and nutritional profiling. However, a major limitation in the above studies is the omission of micronutrient analysis. As meat is considered a valuable vehicle of vital micronutrients such as vitamin B_{12}, zinc, iron and calcium, vitamin and mineral content should be considered when evaluating nutritional value of PBMAs[17,18,160].

More recent studies have considered micronutrient alongside macronutrient composition in their evaluation of PBMAs[168–170]. These studies used similar methods, identifying PBMAs via a search of defined supermarkets and extracting nutritional information from product packaging, front of pack information and both supermarket and manufacturer websites. While there was substantial between product variation, the studies generally reported PBMAs to be lower in saturated fat, richer in dietary fibre and substantially higher in sodium than their meat-based comparator. However, despite reporting an intention to analyse micronutrient content of PBMAs, D'Alessandro *et al.*[169] failed to present data for these variables. While Bryngelsson *et al.*[168] reported that a large proportion of PBMAs lacked micronutrient information, the limited data highlighted a wide variation between product categories. For example, while PBMAs were typically richer in iron and folate compared to their meat-equivalent, vitamin B_{12} was noted to be higher in plant-based sausages, lower in bacon, and similar within the nugget product range. However, these data were derived from a very limited number of products as information for iron, folate and vitamin B_{12} were provided on 13%, 6% and 6% of products, respectively.

Cole *et al.*[170] restricted their analysis to burger categories (imitation burger, vegetarian burger and conventional beef burgers) and highlighted variation in vitamin and mineral content. For example, although the imitation burger demonstrated comparable levels of iron, it was significantly richer in vitamin A, C and D, potassium and calcium compared to the meat-based equivalent. However, the authors were unable to obtain information regarding a range of vitamins and minerals that are key components of beef, including zinc, vitamin B_{12}, phosphorus and magnesium. This may reflect that in the EU labelling of vitamin and mineral information on packaged food labelling is at the discretion of the manufacturer and highlights a limitation of evaluating micronutrient value through Nutrition Facts labelling[171]. Meanwhile, Harnack *et al.*[172] used food ingredient information alongside Nutrition Facts labelling to develop recipes and estimate nutritional value of selected beef alternative products in contrast to meat counterparts. They reported plant-based ground beef to be a rich source of dietary fibre with comparable levels of iron compared to ground beef but highlighted a shortfall in protein, zinc, and vitamin B_{12} alongside substantially higher sodium content. Again, the authors acknowledged that inaccurate labelling and limitations in the Food and Nutrition Database used to develop recipes increased the risk of inaccurate calculations of nutritional value.

Two studies[173,174] have investigated nutritional composition using laboratory analysis techniques. Although it wasn't reported, it could be inferred that the associated time and cost-burden may have resulted in restricted focus of these studies[173, 174] to single product categories (burger products). Both studies[173,174] concluded that the plant-based burger products were able to demonstrate a comparable nutritional profile and richer content of certain minerals although there was again variability between products. However, in contrast to other studies where PBMAs were reported to be lower in saturated fat content but contain substantially more sodium, De Marchi and colleagues[174] reported no significant difference in sodium or saturated fat content between plant-based and meat-based burgers. However, the comparable levels of saturated fat may be attributed to use of particular ingredients in the selected products such as coconut oil in the plant-based burgers[175].

A more recent study conducted a comprehensive nutritional analysis of a large range of PBMAs (hot and cold categories) versus their meat-based counterparts using four national nutrient databases and laboratory analyses[176]. The authors support previous study findings[160,161,168,170] where despite substantial variation between PBMA product ranges, PBMAs were demonstrated to have lower energy density, total and saturated fat but considerably higher sugar and sodium levels compared to their meat-equivalent. In addition, analysis of micronutrients demonstrated similarities to other reports where PBMAs were notably higher in calcium, phosphorus and iron[168,170]. In contrast to other studies, the authors analysed a greater range of micronutrients and highlighted substantial between product heterogeneity. For example, while levels of micronutrients, such as folate, vitamin B_6, E and K, were either comparable or superior to their meat-based comparator, others demonstrated a significant shortfall, in particularly vitamin B_{12} and zinc. Similarly, the study was unable to detect vitamin D within PBMAs; highlighting the need for manufacturers to consider fortification of certain products to ensure sufficient nutrient content. This supports previous studies that have raised concern regarding the level of and/or bioavailability of nutrients such as vitamin B_{12}, zinc and iron in plant-based diets and the need to consider meal plans and supplementation to avoid nutrient deficiency[172,177–179]. For example, plant-foods are a primary source of non-haem iron, which has much lower bioavailability compared to haem iron, the predominant form present in animal-derived foods; reinforcing the need for PBMA fortification[175,177,180,181]. However, fortification of PBMAs with vitamin B_{12}, iron and zinc is inconsistent with under a quarter of products fortified with these nutrients[160,168,181]. Tso and Forde[18] recently compared a model omnivorous reference diet to model diets replacing animal-derived products for either 'traditional' plant-based foods or novel plant-based products (e.g., PBMAs). Acknowledging the variability in fortification of plant-based products, the authors excluded fortified products from their reference diets. The findings highlighted that novel plant-based products were unable to meet dietary requirements for a range of nutrients including zinc and vitamin B_{12} in contrast to the omnivorous reference diet. While this study was a hypothetical comparison, it yet again reinforces the need to consider fortification methods to protect against deficiency for diets incorporating PBMAs.

Ultimately, these findings demonstrate the inconsistent nutrient profile of PBMAs and highlight the challenge of successful replication of meat-equivalents. There are multiple confounding variables that may have influenced the heterogeneity of the reported findings including geographical location, product search methods and measurement tools used. For example, despite being deemed a reliable tool, questions have been raised regarding the ability of the UK Nutrient Profiling Index to reflect current consumption behaviour and recent revisions have been made to the model to address such limitations(182). Furthermore, while the Healthy Star Rating system has been praised for inclusivity and understandability, it is contextualised to Australia and New Zealand(183). However, a key limitation of these tools is that they fail to consider the potential impact of degree of processing on the nutritional and mechanistic quality of food products and there is a need for greater understanding of the possible impact of this on the health benefits associated with particular ingredients. For example, processing can increase or decrease the bioavailability, digestibility, nutritional and functional characteristics of particular foods and ingredients(184). Furthermore, the potential impact of antinutrients commonly present in PBMAs, such as phytate and tannins, requires further understanding, particularly regarding possible positive or negative interactions within the food matrix in addition to their potential inhibition of the absorption of other key vitamins and minerals(184). In addition, despite some inconsistency, the majority of studies highlighted considerably higher levels of sodium in PBMAs and some authors attributed this to ultra-processing(96,131). This is concerning given the association between high sodium intake and increased risk of non-communicable disease such as cardiovascular disease(185,186).

Thus, without further clarification on the impact of processing, categorising UPFs as 'healthy' may inflate the so-called 'health halo' surrounding PBMAs(131). Current paucity in knowledge, coupled with the rapid expansion of the PBMA market means there is a growing urgency for more scientific evidence to address this ambiguity and a strong rationale to improve consumer literacy of PBMAs(110,131).

Conclusion

The equivocal nature of the limited published findings, specifically in relation to the health value of novel PBMAs, raises concern as to whether consumers are using historic evidence related to 'traditional' plant-based dietary patterns to make assumptions. While such products may not align with aspirational, ‘traditional’ plant-based food consumption, one must consider whether these novel products do offer a healthier alternative to meat-based equivalents. With the exception of sodium and possibly some micronutrients, the current evidence suggests this may be the case. If so, this raises the question whether accelerating the adoption of these products will create a good compromise with incremental benefits to public health and climate change targets while meeting consumer demand.

Food manufacturers are now recognising the urgency to deliver products with healthier nutrient profiles, emphasising the need for rigorous studies which consider a range of variables such as level of processing and nutritional composition. Understanding the impact of extensive processing on health effects may help to justify the use of innovative methods designed to maintain health benefits associated with particular foods and ingredients. In addition, furthering knowledge regarding the nutritional value of PBMAs will identify opportunities to enhance their health profile and promote consumer capacity to make informed food choices.

Finally, a clearer understanding of factors influencing engagement of target consumer subgroups with PBMAs may support production of desirable healthier plant-based foods. Such evidence-based food manufacturing practice has the potential to positively influence future individual and planetary health.

Figure Legends

Figure 1: Key factors influencing individual plant-based food choice adapted from Szejda and Parry[187].

Tables

Table 1: definitions of key terminology referred to in the current review

Terminology	Defined as
Traditional Plant-Based Diet	A diet based on minimally processed plant foods that are low energy density, nutrient dense and low in saturated fat. Examples include fruit and vegetables, wholegrains, pulses, legumes, nuts and unsaturated oils.
Plant-Based Food	Any food or food product derived from plants. Examples include whole foods (e.g., fruit and vegetables) and commercially available products (e.g., tofu, plant-based meat and plant-based dairy alternatives).
Plant-Based Products	Commercially available novel food and beverage products, derived from plants. Many of these are designed to mimic the preparation methods, sensorial qualities, and nutritional profile of animal-based equivalents (e.g., plant-based meat alternatives and plant-based dairy alternatives). This could also include commercially available vegan food products designed to appeal to those following plant-based diets. Examples include nut butters, pulse-based ready meals and vegetable burgers.
Plant-Based Meat Alternative	Commercially available novel food products, derived from plants, that are designed to mimic the preparation methods, sensorial qualities, and nutritional profile of meat-equivalents. The term 'plant-based meat alternative' is often used interchangeably with 'plant-based meat analogue' and 'plant-based meat substitute'. Examples include plant-based burgers and plant-based sausages.
Ultra-Processed Food	Defined by NOVA as: "Products involving formulations of ingredients, most of exclusive industrial use, typically created by a series of industrial techniques and processes"[188,189].

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