



American
Society for
Nutrition

Excellence in
Nutrition Research
and Practice

The American Journal of CLINICAL NUTRITION

journal homepage: <https://ajcn.nutrition.org/>



Original Research Article

Plant-based meat alternatives and cardiometabolic health: a systematic review and meta-analysis



Rubén Fernández-Rodríguez¹, Bruno Bizzozero-Peroni^{2,3,*}, Valentina Díaz-Goñi^{2,†},
Miriam Garrido-Miguel^{2,4,5}, Gabriele Bertotti^{6,7}, Alberto Roldán-Ruiz^{6,7}, Miguel López-Moreno^{6,7}

¹ Department of Physical Education and Sports, Faculty of Sports Science, Sport and Health University Research Institute (iMUDS), University of Granada, Granada, Spain; ² Health and Social Research Center, Faculty of Nursing, Universidad de Castilla-La Mancha, Cuenca, Spain; ³ Instituto Superior de Educación Física, Universidad de la República, Rivera, Uruguay; ⁴ Research Network on Chronicity, Primary Care and Health Promotion (RICAPPS), Cuenca, Spain; ⁵ Faculty of Nursing, Universidad de Castilla-La Mancha, Albacete, Spain; ⁶ Diet, Planetary Health and Performance, Faculty of Health Sciences, Universidad Francisco de Vitoria, Pozuelo, Madrid, Spain; ⁷ School of Physiotherapy, Faculty of Health Sciences, Universidad Francisco de Vitoria, Madrid, Spain

ABSTRACT

Background: Plant-based meat alternatives (PBMA) are emerging in global markets. However, the effects of substituting meat for PBMA on cardiometabolic health are uncertain.

Objectives: This study aimed to determine the effects of replacing meat consumption by PBMA on cardiometabolic parameters in adults.

Methods: Five databases were systematically explored from inception to July 2024, searching for RCTs assessing the effects of replacing meat consumption by PBMA on cardiometabolic parameters in adults without cardiovascular diseases. Meta-analyses were conducted when ≥ 4 studies addressed the same outcome (i.e. blood lipids, blood pressure, fasting glucose, and body weight). Pooled raw mean differences (MDs) with their 95% CIs were estimated using a random-effects method. Sensitivity analyses were conducted to assess the robustness of our estimates.

Results: Eight publications from 7 RCTs comprising 369 adults (60% females; mean age range: 24–61 y) were included. The substitution of PBMA for meat was associated with significant reductions in LDL-cholesterol: -0.25 mmol/L (95% CI: -0.42 , -0.08 mmol/L; $I^2 = 65.8\%$; $n = 7$), total cholesterol (TC): -0.29 mmol/L (95% CI: -0.52 , -0.06 mmol/L; $I^2 = 64.8\%$; $n = 6$), and body weight: -0.72 kg (95% CI: -1.02 , -0.42 kg; $I^2 = 0\%$; $n = 5$). No significant changes were shown in HDL-cholesterol, triglycerides, blood pressure, or fasting glucose concentrations. Sensitivity analyses considering mycoprotein-based alternatives showed a significant reduction in LDL-cholesterol (MD: -0.37 mmol/L; 95% CI: -0.61 , -0.13 mmol/L; $I^2 = 52.5\%$; $n = 4$), and TC (MD: -0.39 mmol/L; 95% CI: -0.56 , -0.21 mmol/L; $I^2 = 0\%$; $n = 4$).

Conclusions: Our findings suggest substituting PBMA for meat for ≤ 8 wk lowered TC (6%), LDL-cholesterol (12%), and body weight (1%) in adults without cardiovascular diseases. PBMA may facilitate the transition to a plant-based diet, but long-term studies are needed to evaluate their cardiometabolic effects.

This trial was registered at PROSPERO as CRD42024556191.

Keywords: plant-based meat food, meat substitutes, cardiovascular disease, diet, planetary health

Introduction

Planetary health concerns play a pivotal role in current dietary guidelines [1,2] and international reports [3,4], promoting a reduction in animal-based foods, especially red and processed meat whereas increasing plant-based food intake [5]. High consumption of red and processed meat has been linked to increased risk of different chronic

noncommunicable diseases [6], including cardiovascular diseases (CVDs) and diabetes, as well as overall increased risk of all-cause mortality [7]. Added to the lower environmental impact [8,9], a recent microsimulation study estimated that reducing or replacing meat consumption with plant-based foods could result in lower risk or prevalence of noncommunicable chronic diseases [6], including CVDs [6], metabolic disorders [10,11], and cancer [6].

Abbreviations: CRP, C-reactive protein; CVD, cardiovascular disease; PBMA, plant-based meat alternative; TC, total cholesterol; TG, triglyceride; UPF, ultraprocessed food.

* Corresponding author.

E-mail address: Bruno.Bizzozero@uclm.es (B. Bizzozero-Peroni).

† BB-P and VD-G contributed equally to this work.

<https://doi.org/10.1016/j.ajcnut.2024.12.002>

Received 6 September 2024; Received in revised form 28 November 2024; Accepted 4 December 2024; Available online 7 December 2024

0002-9165/© 2024 American Society for Nutrition. Published by Elsevier Inc. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Despite recommendations aimed at reducing meat consumption, a range of factors hinder the implementation of these dietary guidelines, with sensory aspects related to meat representing a great challenge [12, 13]. Traditional plant-based, minimally processed meat replacements such as tofu, tempeh, or textured soy/pea protein present great nutritional value but do not replace organoleptic characteristics and other eating experiences of meat [14]. On the contrary, plant-based meat alternatives (PBMA) (i.e. burger patties, minced plant-based meat, sausages, or meatballs) [15] are designed to mimic the appearance, aroma, flavor, texture, and other eating experiences of meat and meat products. We used the term alternative as an umbrella term that encompasses the most common terms in this topic [i.e. substitute (for culinary purpose), replacement (for nutritional properties), and analog (for both culinary and nutritional attributes)] [16]. These novel PBMA have emerged to keep up with consumer and market demands and the growing population's reduced meat intake [14]. The global market for PBMA expansion trend is expected to increase to ~\$30 billion by 2025 and \$85 billion by 2030, according to the Union Bank of Switzerland estimates [17,18].

The currently available PBMA exhibit variability in terms of their ingredients, processing grade, and nutritional value [19]. Although PBMA are derived from traditional, healthy plant-based protein sources such as soy, legumes, grains, and nuts [20], during their processing, less desirable nutrients may be introduced, such as saturated fat, sodium, and sugar [21], potentially turning these processed products into unhealthy options [22]. Indeed, PBMA are classified as ultraprocessed foods (UPF) according to NOVA classification because they are “formulated mostly or entirely from substances extracted from foods or derived from food constituents” (e.g. pea protein isolate, soy protein isolate and concentrate, fungi-based foods, and cereals-based foods) [23]. A recent analysis concluded that the Nutri-Score front-of-pack label effectively differentiated PBMA with poor nutritional quality; however, according to NOVA criteria, 73% of PBMA were considered UPF (compared with 92% of the meat products) [24].

Recently, a literature review pointed out that PBMA might have a cardioprotective effect when replacing meat consumption, mostly owing to PBMA having lower saturated fatty acid content and more fiber [25], which could reduce LDL-cholesterol concentrations. A previous systematic review and meta-analysis explored the impact of PBMA and mycoprotein-based meat alternatives on cardiometabolic biomarkers, showing reduced total cholesterol (TC), LDL-cholesterol, and triglycerides (TGs) when participants replaced meat with PBMA [26]. However, they included minimally processed PBMA such as textured vegetable protein in 5 of 12 studies [26]. In addition, non-RCTs were included, which reduced the reliability of the causal relationship due to potential biases such as selection bias. Therefore, a systematic review and meta-analysis specifically analyzing the evidence from RCTs on the role of novel PBMA in risk factors for cardiometabolic disease is still lacking. Therefore, our review aimed to determine the effects of novel PBMA compared with those of meat consumption (habitual diet) on cardiometabolic parameters (i.e. blood lipid profile, blood pressure, fasting blood glucose, and body weight) in people without CVDs.

Methods

The Cochrane Collaboration Handbook [27] guideline and the PRISMA [28] statement were followed. The systematic review protocol was registered in the PROSPERO database (reference number: CRD42024556191).

Data sources and search strategy

Two independent reviewers (GB and ARR) systematically examined Medline, Cochrane CENTRAL, Embase, Scopus, Web of Science, and GreenFILE from inception to 9 July, 2024. The search strategy was based on the patient, intervention, comparison, outcome, and study design (PICO) approach. A third reviewer (MLM) supervised the accuracy of the searches. Search strategies for each database are provided in Supplemental Table 1.

Eligibility criteria

The PICO(s) framework for study selection was as follows: 1) participants: adults (aged 18 y or older) without diagnosed CVDs; 2) intervention: different protocols with PBMA [e.g. plant-based burger, plant-based sausages, plant-based mince, mycoprotein-based (grounds, nuggets, and patties)]; 3) comparator: animal-based/meat consumption (chicken, beef, fish, processed meat, and red meat) and following the habitual diet; 4) outcomes: parameters related to cardiometabolic health (i.e. blood lipid profile, blood pressure, fasting blood glucose, body weight, body fat percentage, insulin, and inflammatory markers such as C-reactive protein (CRP)); and 5) study design: RCTs. There were no restrictions for any specific language, as recommended by international criteria [28]. We did not consider those RCTs that used traditional PBMA, which were not designed to resemble meat (e.g. tofu, tempeh, or seitan); insect-based meat alternatives; or cultured meat. Before the screening by title and abstract, duplicate records were removed using the automated Endnote tool v.20.6. After this, title and abstract screening was conducted by 2 reviewers (GB and ARR) supervised by a third coauthor (MLM). Finally, each report was assessed against the eligibility criteria by the 2 independent reviewers, and a third coauthor (RFR) was contacted to solve conflicts between initial reviewers about eligibility criteria. The reasons for the exclusion of studies after a full-text review are detailed in Supplemental Table 2.

Data collection

Two reviewers (GB and ARR) independently extracted the following information from each article: 1) first author name and year of publication; 2) type of RCT (parallel or crossover); 3) funder; 4) population characteristics; 5) sample size and proportion of female participants; 6) BMI; 7) baseline meat consumption (grams per day); 8) tools used to assess adherence to dietary guidelines; 9) type of PBMA used; 10) study duration; 11) comparator (nonintervention, dietary advice, habitual diet, and animal-based and/or meat consumption); 12) outcomes analyzed and main results obtained for parameters related to cardiometabolic health. A third coauthor (RFR) independently assessed the accuracy of the extracted data.

Risk of bias

Each study was evaluated independently by 2 authors (MGM and VDG) in each of the domains of bias contained in the Cochrane risk-of-bias tool for randomized trials (RoB 2.0) [29]. Disagreements between initial authors were solved by a third coauthor (RFR). The validity of studies was judged for 5 potential bias domains: 1) randomization process, 2) deviations from intended interventions, 3) missing outcome data, 4) measurement of the outcome, and 5) selection of the reported result. The overall risk of bias for each study was scored as follows: 1) low risk of bias when a low risk of bias was determined for all domains; 2) some concerns when ≥ 1 domain was assessed as raising some concerns but not at high risk of bias for any single domain; or 3) high risk of bias when high risk of bias was reached for ≥ 1 domain or some

concerns in multiple domains [29], which affects the validity of the results. The risk-of-bias visualization (robvis) web application was used to develop the figures for the risk-of-bias assessments [30].

Data synthesis

A meta-analysis was conducted when ≥ 4 studies addressed the same outcome [31]. When a quantitative synthesis was not possible, the cardiometabolic outcomes of the included studies were synthesized narratively. As important between-study heterogeneity was anticipated, a random-effects method was used to pool the raw mean differences (MDs) in cardiometabolic outcomes between the PBMA and control groups. The method by DerSimonian and Laird method was applied to estimate the heterogeneity variance [32]. Heterogeneity across the included studies was assessed using the I^2 metric, which was classified as not important (0%–40%), moderate (30%–60%), substantial (50%–90%), or considerable (75%–100%) [27]. The corresponding P values were also considered [27].

For each study, pre–post means [33–36] and their SDs or SEs within PBMA interventions and control conditions were extracted to calculate the between-group MDs and their 95% CIs. Three RCTs reported the MDs with their 95% CIs or SEs between PBMA interventions and control conditions [37–39]. One study specified the MDs within intervention and control groups [34]. Additionally, according to the Cochrane recommendations [27], the paired MDs between the intervention and control groups in crossover RCTs were entered into the meta-analysis with parallel RCTs under the generic inverse variance. In the absence of pre–post correlation data in parallel RCTs, the pre–post correlation coefficients reported by Pavis et al. [34] were applied. Where studies reported pre–post changes in cardiometabolic outcomes as medians and IQRs [35], the method by McGrath et al. [40] was applied to estimate the means and SDs. In those cases where RCTs reported effect estimates with their SEs [33,34], SDs for meta-analysis were calculated using the following formula: $SD = \sqrt{n} \text{ SE}$ [27]. To facilitate interpretation and comparison between studies, in 1 RCT [38] the results of glucose and lipid concentrations in milligrams per deciliter were transformed into millimoles per liter using online calculators [41,42]. In those studies reporting postinterventional follow-up results, the longest period was selected [37]. Finally, the raw difference in means between PBMA interventions and control conditions was used because all studies measured cardiometabolic outcomes on the same scale (i.e. millimoles per liter for glucose, HDL-cholesterol, LDL-cholesterol, triglycerides, and TC; millimeters of mercury for systolic and diastolic blood pressure; and kilograms for body weight). Negative MD values indicate that PBMA interventions reduced pre–post cardiometabolic outcomes compared with control conditions following trial interventions.

Sensitivity analyses were carried out to assess the robustness of the summary estimates by maintaining the predominant PBMA protocol (i.e. mycoprotein-based interventions) [33,34,36,39] and health status. In case of studies that reported adjusted MDs, we considered these in our analyses; thus, 3 studies reported adjusted MDs [37–39] based on order and phase [38] and randomly assigned group, visit, interaction between visit and randomly assigned group, baseline meat consumption and sex [37]; and age, BMI, and habitual alcohol intake [39].

All analyses were conducted using the Comprehensive Meta-Analysis software (version 4; Biostat) and R software (version 4.2.3; R Foundation for Statistical Computing, Vienna) with the *metafor* package [43].

Results

Literature search

We considered 1833 studies for title and abstract review after removing duplicates. A total of 22 studies were fully assessed according to the eligibility criteria, 14 of which were excluded (1 of them was identified by citation searching) for the reasons described in Supplemental Table 2. Finally, 8 publications reporting results from 7 RCTs were included in this systematic review and meta-analysis (Figure 1). Among them, 44 comparisons (7 for HDL-cholesterol and LDL-cholesterol, 6 for TG and TC, 5 for glucose and body weight, and 4 for systolic and diastolic blood pressure) between PBMA interventions and control conditions were included in the meta-analysis.

Study characteristics

Table 1 summarizes the main characteristics of the included studies. The RCT designs applied were parallel in 5 studies [33–37] and crossover in 2 studies (3 articles) [38,39,44]. Studies were conducted between 1990 and 2024 in 3 different countries (i.e. the United Kingdom, the United States, and Singapore).

The included studies comprised 369 adults (60.2% females; $n_{\text{int}} = 184$; $n_{\text{con}} = 185$), with a mean age ranging from 24.0 to 60.8 y. The majority of RCTs included healthy individuals [33,37–39,44], except 3 that targeted participants with specific conditions, including elevated risk of diabetes [35], hypercholesterolemia [36], and overweight [34]. The mean BMI ranged from 23.1 to 32.1 kg/m^2 in the PBMA groups and from 21.9 to 33.1 kg/m^2 in the control groups.

The mean length of the interventions ranged from 1 to 8 wk. Intervention groups were defined as dietary instructions to substitute animal-based meats with PBMA (maintaining the intake of other dietary components). Interventions included different marketed options of PBMA (Beyond Meat, The Vegetarian Butcher, Impossible foods, Omnifoods, or The Meatless farm) [35,37,38,44] and mycoprotein-based interventions (Quorn food products) [33,34,36,39]. Most studies were funded by different plant-based companies: Marlow Foods, Ltd [33,34,36,39], Pinduoduo, Inc [35], and Beyond Meat, Inc [38,44], except for the study by Bianchi et al. [37], which was funded by a global charitable foundation (Wellcome) [37]. Table 1 shows the details of interventions in terms of duration, frequency of consumption, and type of PBMA.

The control conditions applied by the RCTs were to follow habitual [36,37] or animal-based meat [33–35,38,44,45] diets. Of the RCTs that applied dietary instructions to consume the plant-based foods instead of animal-based meats (maintaining the intake of other dietary components), 3 included processed, red, and white meats [35,38,44]; 2 included fish, processed, red, and white meats [33,34]; and 1 included processed and red meats [39].

Seven publications evaluated HDL-cholesterol and LDL-cholesterol [33–39]; 6 each analyzed TGs [34–39] and TC [33–37, 39]; 5 each assessed glucose [33–35,38,39] and body weight [33,35, 37–39]; 4 estimated blood pressure [35,37,38,45]; 3 examined serum insulin [33,35,38]; 2 each evaluated body fat percentage [37,39], HOMA-IR [33,35], IL-6 [33,44], and trimethylamine-*N*-oxide [38,39]; and 1 publication each analyzed blood C-peptide [34], CRP [35], fructosamine [33], HOMA for β -cell function [35], insulin-like growth factor 1 [38], IL-10 [44], IL-12 β [44], IL-18 [44], neurotrophin-3 [44], transforming growth factor- β [44], and TNF [44].

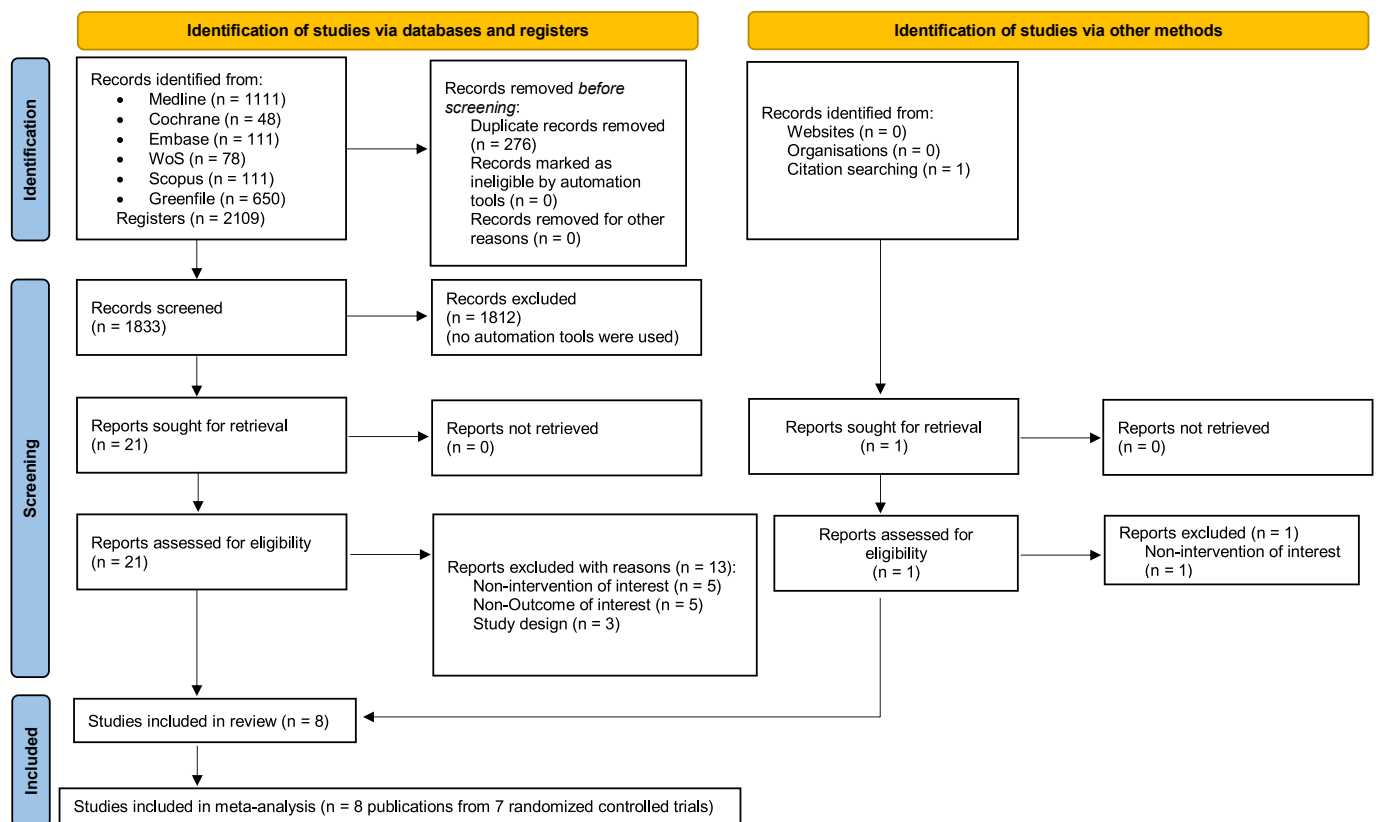


FIGURE 1. Flow diagram of the study selection (PRISMA 2020).

Risk of bias

The risk-of-bias assessment with the RoB 2.0 Cochrane tool is shown in [Supplemental Figure 1](#). The studies selected for the review showed variability in the different quality assessment domains. Only 1 RCT obtained a low risk-of-bias score in all domains analyzed. Four publications of 8 (50%) were judged with some concerns and 3 publications (37.5%) with high risk of bias owing to deviations from the intended intervention, bias in the measurement of the outcome, and bias in the reported results domains. The bias identified in the different studies was mainly because double blinding was unfeasible owing to the nature of the dietary intervention.

Meta-analysis

[Supplemental Table 3](#) shows the primary data related to cardiometabolic outcomes reported from included RCTs in the meta-analyses. The significant MDs of PBMA interventions compared with control conditions on cardiometabolic outcomes were as follows: 1) -0.25 mmol/L (95% CI: -0.42 , -0.08 mmol/L; $I^2 = 65.8\%$; $n = 7$) for LDL-cholesterol ($n_{\text{int}} = 174$; $n_{\text{con}} = 175$); 2) -0.29 mmol/L (95% CI: -0.52 , -0.06 mmol/L; $I^2 = 64.8\%$; $n = 6$) for TC ($n_{\text{int}} = 159$; $n_{\text{con}} = 163$); and 3) -0.72 kg (95% CI: -1.02 , -0.42 kg; $I^2 = 0\%$; $n = 5$) for body weight ($n_{\text{int}} = 136$; $n_{\text{con}} = 134$) ([Figure 2](#) and [Supplemental Figure 2](#)). In addition, no statistically significant MDs were observed in other cardiometabolic outcomes after trial intervention periods. Specifically, the pooled MDs of PBMA interventions compared with control conditions were as follows: 1) -0.04 mmol/L (95% CI: -0.15 , 0.07 mmol/L; $I^2 = 10.3\%$; $n = 5$) for glucose ($n_{\text{int}} = 112$; $n_{\text{con}} = 116$); 2) -0.01 mmol/L (95% CI: -0.06 , 0.04 mmol/L; $I^2 = 24.1\%$; $n = 7$) for HDL-cholesterol ($n_{\text{int}} = 177$; $n_{\text{con}} = 180$); 3) 0.05 mmol/L (95% CI: -0.10 , 0.21 mmol/L; $I^2 = 48.4\%$; $n = 6$) for TGs ($n_{\text{int}} = 167$; $n_{\text{con}} =$

171); (iv) -0.21 mm Hg (95% CI: -2.52 , 2.11 mm Hg; $I^2 = 34.4\%$; $n = 4$) for systolic blood pressure ($n_{\text{int}} = 126$; $n_{\text{con}} = 124$); and 5) -0.06 mm Hg (95% CI: -1.63 , 1.51 mm Hg; $I^2 = 31.8\%$; $n = 4$) for diastolic blood pressure ($n_{\text{int}} = 126$; $n_{\text{con}} = 124$) ([Figure 2](#) and [Supplemental Figure 2](#)).

The results of the sensitivity analyses are detailed in [Supplemental Table 4](#). MDs between PBMA intervention and control groups for cardiometabolic outcomes were consistent with our main findings and remained statistically significant for LDL-cholesterol, TC, and body weight. Specifically, the sensitivity analysis conducted including only mycoprotein interventions reported a significant beneficial effect on LDL-cholesterol (MD: -0.37 mmol/L; 95% CI: -0.61 , -0.13 mmol/L; $I^2 = 52.5\%$; $n = 4$) and TC (MD: -0.39 mmol/L; 95% CI: -0.56 , -0.21 mmol/L; $I^2 = 0\%$; $n = 4$), whereas those in healthy population were significant on lowering LDL-cholesterol (MD: -0.18 mmol/L; 95% CI: -0.36 , -0.001 mmol/L; $I^2 = 63.7\%$; $n = 4$) and body weight (MD: -0.73 kg, 95% CI: -1.05 , -0.41 kg; $I^2 = 0\%$; $n = 4$).

Comparisons not included in the meta-analysis

The MDs for specific cardiometabolic changes between PBMA interventions and control conditions were not meta-analyzed when the number of RCTs was limited ($n < 4$). [Table 1](#) summarizes the main results of the included studies in the systematic review only. In summary, significant beneficial effects on blood C-peptide [34], IL-7 [44], and neurotrophin 3 [44] concentrations were observed in favor of PBMA intervention groups compared with those in control groups. In turn, there were no statistically significant differences in body fat percentage [37,39], fructosamine [35], HOMA β -cell function [35], HOMA-IR [33,35], insulin-like growth factor 1 [38], inflammatory biomarkers (i.e. CRP, IL-6, IL-10, IL-12B, IL-18, transforming growth

TABLE 1
Characteristics of the included studies.

Author (year)	Design	Country	Funder	Population characteristics	n (% female)	Age (y), mean ± SD	BMI (kg/m ²) or weight (kg)	Baseline meat consumption (g/d)	Adherence	PBMAs	Length (wk)	Comparator	Outcomes	Outcomes not included in meta-analyses
Bianchi et al. [37], 2021 (RE-MAP)	RCT; Parallel	UK	Wellcome Trust, Our Planet Our Health program [Livestock, Environment, and People (LEAP)]	Healthy adults	115 (65.5) IG: 58; CG: 57	IG: 33 ± 11; CG: 37 ± 12	IG: 25.5 ± 5.6; CG: 25.2 ± 5	IG: 130; CG: 134	7-d food diaries	Mycoprotein-based, vegetable-based, and pulse-based meat substitutes (self-selected)	4 (8-wk follow-up)	No intervention or additional dietary advice	Weight, body fat percentage, blood pressure, and blood lipid	No statistically significant differences in body fat percentage
Coelho et al. [33], 2021	RCT; Parallel	UK	Marlow Foods, Ltd (BTW as grant holder)	Healthy adults	20 (60)	IG: 24 ± 11 (SEM); CG: 24 ± 1 (SEM)	IG: 23 ± 1 (SEM); CG: 23 ± 1 (SEM)	—	Document and diary to track compliance, log meal times, and provide recipe information	Mycoprotein-based, twice daily (Quorn Foods)	1	Meat/fish at lunch and dinner	Glucose, serum insulin, blood lipid, IL-6, and uric acid	No statistically significant differences in serum insulin, IL-6, and uric acid concentrations
Crimarco et al. [38], 2020 (SWAP-MEAT)	RCT; crossover	USA	Beyond Meat, Inc	Healthy adults	36 (66.7) plant-animal: 18; animal-plant: 18	Plant-animal: 49.3 ± 11.7; animal-plant: 51.1 ± 16.0	Plant-animal: 27.4 ± 5.2; animal-plant: 28.3 ± 5.3	—	Cronometer data and weekly portioning survey	PBMAs (Beyond Meat)	8 (no washout)	≥2 servings of meat products per day	Weight, glucose, insulin, blood pressure, blood lipids, TMAO, and IGF-1	No statistically significant differences in insulin and IGF-1
Crimarco et al. [44], 2022 (SWAP-MEAT)	RCT; crossover	USA	Beyond Meat, Inc	Healthy adults	36 (66.7) plant-animal: 18; animal-plant: 18	Plant-animal: 49.3 ± 11.7; animal-plant: 51.1 ± 16.0	Plant-animal: 27.4 ± 5.2; animal-plant: 28.3 ± 5.3	—	Cronometer data and weekly portioning survey	PBMAs (Beyond Meat)	8 (no washout)	≥2 servings of meat products per day	Inflammatory biomarkers (IL-6, IL-7, IL-18, TNF-α, IL-12β, IL-10, TGF-β, NT-3)	No statistically significant differences in IL-6, IL-18, TNF-α, IL-12β, IL-10, TGF-β
Farsi et al. [45], 2023 (Mycomeat)	RCT; crossover	UK	Partly funded by Marlow Foods Ltd	Healthy adults	20 (0)	30.4 ± 7.92	24.0 ± 2.87	221.60 ± 176.87 (meat); 80.25 ± 83.47 (red and processed meat)	—	Mycoprotein (Quorn)	2 (4-wk washout)	240; red and processed meat	Weight, body fat percentage, glucose, blood lipids, blood pressure, and TMAO	No statistically significant in body fat percentage and TMAO
Pavis et al. [34], 2024	RCT; parallel	UK	Marlow Foods, Ltd	Adults with overweight	72 (63); IG: 33; CG: 39	IG: 41 ± 3; CG: 46 ± 2 (SEM)	IG: 32 ± 1 (SEM); CG: 33 ± 1 (SEM)	—	Multiple-pass 24-h dietary recalls	Mycoprotein-based (Quorn)	4	Meat (chicken, beef, fish, dairy)	Glucose, blood lipids, and C-peptide	↓C-peptide
Toh et al. [35], 2024	RCT; parallel	Singapore	Pinduoduo, Inc (HongKong Walnut Street, Ltd)	Adults with elevated risk of diabetes	89 (60.7) IG: 44; CG: 45	IG: 60 ± 8; CG: 59 ± 8	IG: 23.2 ± 2.4; CG: 21.9 ± 2.5	Animal-based protein: IG: 2.3 ± 0.6; CG: 2.4 ± 0.6	3-d food records were collected 4 times across the intervention period	PBMAs diet fixed quantities (Beyond Meat, Impossible Foods, OmniFoods, The Vegetarian Butcher)	8	Animal based (2.5 servings/d)	Weight, glucose, insulin, blood lipids, blood pressure, CRP, HOMA-IR, HOMA β-cell function, and fructosamine	No statistically significant differences in insulin, CRP, HOMA-IR, HOMA β-cell function, and fructosamine concentrations
Turnbull et al. [36], 1990	RCT parallel	UK	Marlow Foods, UK	Adults with hypercholesterolemia	17 (70.6) IG: 9; CG: 8	19–48	16.9–32.1	—	Intake in the metabolic unit under supervision	191 mycoprotein (Quorn)	3	Iso-caloric amounts of meat	Blood lipids	No statistically significant differences in APO-A1 and APO-B concentrations

APO, apolipoprotein; CG, control group; CRP, C-reactive protein; IG, intervention group; IGF, insulin-like growth factor; IS, insulin sensitivity; NT, neurotrophin; PBMA, plant-based meat alternative; TC, total cholesterol; TGF, transforming growth factor; TMAO, trimethylamine *N*-oxide.

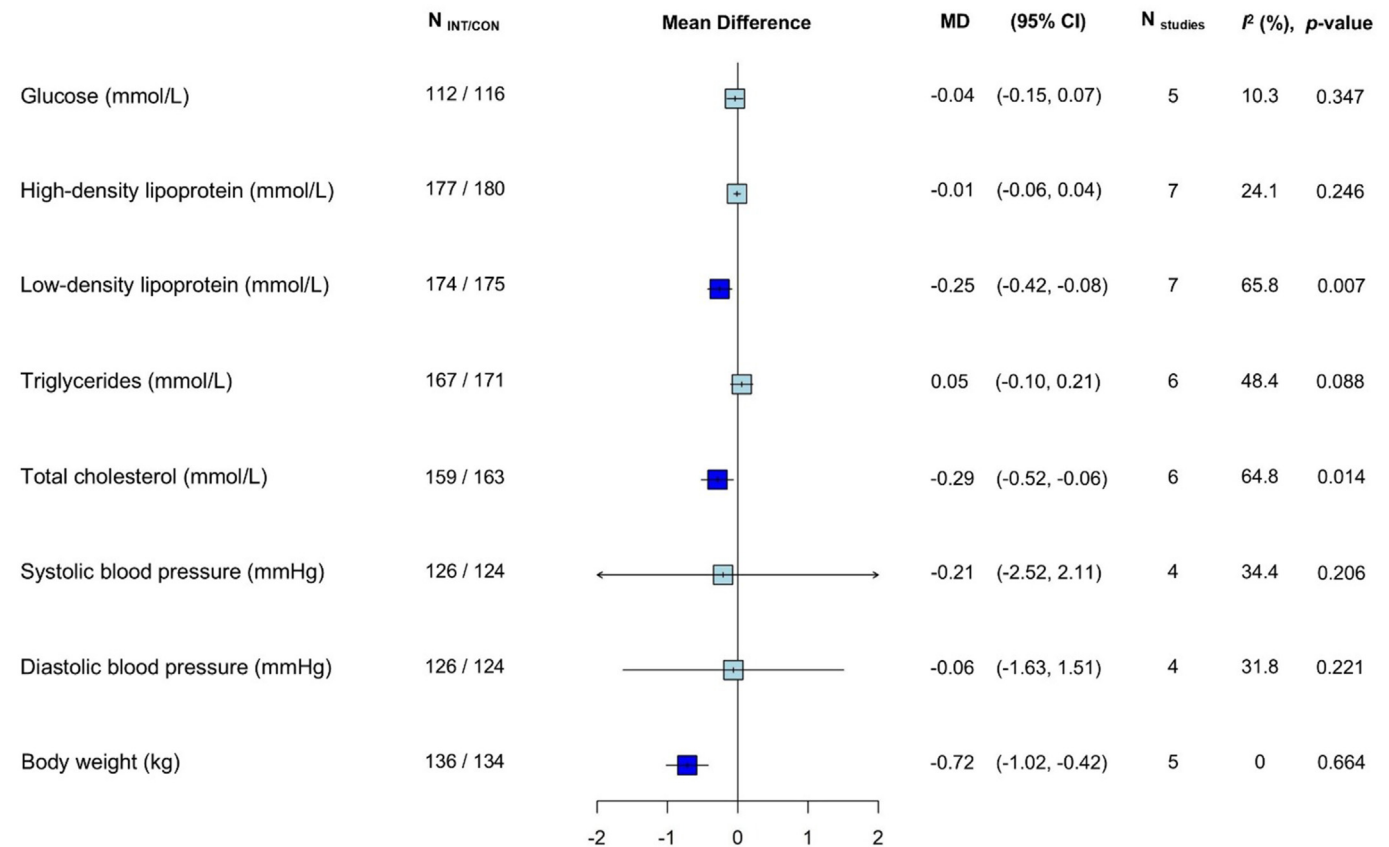


FIGURE 2. Pooled MDs for the effect of plant-based meat alternatives compared with control groups on cardiometabolic health outcomes in adults. The values are derived from meta-analyses of unstandardized between-group MDs, using the method by DerSimonian and Laird to estimate the heterogeneity variance. Blue square means significant MDs ($P < 0.05$) and light blue square nonsignificant MDs. CON, control group; INT, intervention group; MD, mean difference.

factor β , and TNF) [33,35,44], serum insulin [33], and apolipoproteins A1 and B [36] after comparing PBMA interventions and control conditions. For trimethylamine-*N*-oxide, 1 study [38] showed beneficial effects in favor of PBMA intervention groups compared with those of control groups, whereas another study did not show significant differences [39].

Discussion

Our systematic review and meta-analysis suggest that replacing meat consumption for PBMA for 1–8 wk diminishes TC, LDL-cholesterol, and body weight in people without CVDs. No significant reductions in HDL-cholesterol, TG, blood pressure, and fasting blood glucose were detected. Our sensitivity analyses considering only mycoprotein-based substitutes consistently showed significant reductions in TC and LDL-cholesterol as well as in body weight in healthy participants. Given the short duration of the studies, these significant reductions in TC (6.6%), LDL-cholesterol (12.1%) and body weight in favor of PBMA might be considered although, in the case of body weight, it was not a clinically significant weight loss reduction (1%).

Our findings indicated that, compared with meat consumption, the intake of PBMA significantly reduced TC (−0.29 mmol/L) and LDL-cholesterol (−0.25 mmol/L). Additionally, a reduction in body weight (−0.72 kg) was found when replacing meat consumption for PBMA. These results align with a previous meta-analysis [26] in which RCTs were included that considered both traditional meat substitutes

(textured vegetable protein) and novel PBMA that significantly differ in nutritional composition. Current evidence has demonstrated the beneficial effects of whole or minimally processed plant-based dietary patterns on cardiovascular health [46,47]. PBMA, unlike traditional meat substitutes, are classified as UPFs, the fourth group according to the NOVA classification system [48]. A recent analysis of a large UK Biobank cohort study concluded that a higher dietary intake of plant-sourced non-UPFs was associated with reduced risk of cardiovascular events, whereas a higher intake of plant-sourced UPFs was linked to increased risk of CVDs [49]. These findings indicate that substituting plant-sourced UPFs with plant-sourced non-UPFs is associated with a reduction of 7% and 15% in CVDs incidence and CVD-related mortality, respectively. These values are comparable with those observed when plant-sourced non-UPFs was replaced with animal-sourced UPFs. Nevertheless, the consumption of meat alternatives represented 0.2% of the total energy intake, rendering it difficult to ascertain their impact. Previous studies have reported that replacing meat with whole plant foods, such as legumes, induces significant changes in cardiometabolic parameters such as TC and LDL-cholesterol, which are greater than those observed with PBMA [50,51]. In addition, the cardiometabolic effect of PBMA might depend on the type of meat they replace, with increased benefits when red and processed meats are substituted. This highlights that PBMA should not replace whole plant foods but serve as a transition from meat consumption to higher plant food intake.

Our meta-analysis revealed no statistically significant differences when PBMA were compared with meat consumption concerning

blood pressure and fasting blood glucose. Although the energy content of PBMA is typically lower than that of meat [25], it exhibits considerable variability depending on the type of PBMA. For instance, some PBMA can exceed the energy density of certain meat sources (Supplemental Table 5). Furthermore, the impact of replacing meat with PBMA on body weight might vary across different study populations. The 2 RCTs included in our meta-analysis that demonstrated reductions in body weight with PBMA intake were conducted on overweight individuals ($\text{BMI} \geq 25 \text{ kg/m}^2$) [37,38], whereas no differences in body weight were observed in RCTs conducted on individuals with a normal weight according to BMI [33,35,39]. Concerning blood pressure, it is well established that a high consumption of sodium in the diet is a major contributing factor to the development of hypertension [52]. Although PBMA tend to have a higher sodium content than meat [53], this potential negative effect could be counterbalanced by the presence of other beneficial dietary components in these products, such as dietary fiber [54]. This may partially explain the lack of change observed in blood pressure levels when meat intake was replaced with PBMA. Finally, no difference has been identified in postprandial plasma glucose concentrations in response to a PBMA intake compared with those to meat products [55]. Epidemiologic studies have demonstrated that substituting red meat with plant-based alternatives is associated with enhanced insulin sensitivity, as assessed by fasting glucose and insulin concentrations [56]. These effects appear inferior to those reported with the replacement of whole plant foods, such as legumes, nuts, or whole grains [56]. The processing of PBMA has been demonstrated to result in an increased glycemic index, which could potentially attenuate the beneficial effects on glucose metabolism observed in whole plant-based foods [57]. Accordingly, the limited duration of the RCTs included in our meta-analysis may have been inadequate to discern differences in plasma glucose concentrations, underscoring the necessity for longer-term studies.

Although there are considerable differences in the nutritional composition of different PBMA, they tend to exhibit a more favorable nutritional profile than do meat products [53,58]. In particular, PBMA are typically characterized by a reduced proportion of saturated fats and dietary cholesterol, but an increased content of carbohydrates, fiber, and polyunsaturated fats (Supplemental Table 5) [25]. Therefore, the cardiovascular impact of consuming PBMA may be attributed to the nutrients they contain, as well as the reduced intake of meat products. For instance, the results of multiple regression analyses of RCTs indicate that replacing saturated fat intake with an equivalent energy amount of PUFA, MUFA, or carbohydrates results in a reduction in LDL-cholesterol and TC concentrations [59]. Similarly, there is a documented correlation between dietary cholesterol and elevated plasma LDL-cholesterol [60]. Consequently, some of the benefits observed in TC and LDL-cholesterol concentrations associated with the consumption of PBMA in comparison with meat products may be attributed to a reduction in saturated fat and cholesterol intake added to the replacement of these with unsaturated fats and carbohydrates. Another dietary component that may be associated with the benefits of PBMA on the lipid profile is dietary fiber. Despite the reduced fiber content of these products in comparison with whole plant foods, it is still higher than that found in meat products (Supplemental Table 5) [61]. A higher intake of dietary fiber has been shown in numerous studies to be associated with a reduction in TC and LDL-cholesterol concentrations [61,62]. It has been suggested that dietary fiber may diminish the absorption of cholesterol in the small intestine [63]. The fermentation of dietary fiber by the gut microbiota results in the release

of short-chain fatty acids, which have been demonstrated to inhibit hepatic cholesterol synthesis and, thereby, contribute to a reduction in LDL-cholesterol concentrations [64]. In this sense, previous research has suggested that replacing meat with PBMA may have health benefits for the gut microbiota [45,65]. Nevertheless, PBMA products differ in their nutrient composition and we cannot assume that all will have the same impact on cardiovascular parameters. Therefore, adequately powered RCTs assessing disease risk factors and long-term observational studies evaluating disease outcomes are needed.

In the sensitivity analysis, a reduction in TC and LDL-cholesterol was observed in studies considering only mycoprotein-based foods such as PBMA. Mycoprotein is a dietary ingredient derived from fungi, comprising 25% fiber by dry weight and 6% by wet weight [66]. The dietary fiber content of mycoprotein products is typically higher than that of other PBMA, which may be a contributing factor to the favorable effects observed on cardiovascular disease risk [66]. Similarly, the saturated fat content (0.7 g/100 g), which is lower than that of other PBMA (3.2 g/100 g), and the higher unsaturated fat content (2.3 g/100 g) may also be associated with the reductions in TC and LDL-cholesterol in interventions with mycoproteins (Supplemental Table 5) [66]. Finally, these findings suggest that the cardioprotective effect of PBMA consumption, compared with that of meat products, may be due to the replacement of saturated fats with unsaturated fats and fiber, which might be further enhanced in the case of mycoprotein-based options.

Our meta-analyses were calculated using raw MD data, which provide information in clinical units for our findings despite the heterogeneity among the intervention and comparison groups. However, potential limitations of our review should be mentioned. First, few RCTs ($n = 7$) assessed PBMA with small sample sizes in each arm trial (from 8 to 58 participants). Second, the short-term length of the intervention (1–8 wk) delays us from determining chronic effects on cardiometabolic disease risk factors when PBMA replace meat intake. Therefore, it could be considered that studies could be not adequately powered to detect statistically significant differences in cardiometabolic disease risk factors. Moreover, the limited number of studies included in the meta-analyses of each cardiometabolic outcome ($n < 10$), no meta-regression or publication bias analyses were conducted [27,67]. Third, heterogeneity among nutrient profiles of current PBMA should be noted. Fourth, 7 of 8 publications were funded by the manufacturers of these PBMA, which could potentially bias the results obtained. Owing to the limited number of studies, it was not possible to perform a sensitivity analysis based on conflicts of interest. Finally, the scarcity of studies and assessments of other cardiometabolic disease risk factors such as inflammatory biomarkers or insulin made it impossible for us to conduct meta-analyses on these variables and draw more solid conclusions. Although some of them (e.g. blood C-peptide and IL-7) showed beneficial effects favoring PBMA, most did not change after comparing PBMA interventions and control conditions. However, with the increasing trend of people consuming plant-based diets [68], further trials are expected to address these gaps in knowledge.

In conclusion, overall, our study suggests that substituting meat consumption by PBMA could lower TC (−6.6%), LDL-cholesterol (12.1%), and body weight in people without CVDs but not modifying significantly other cardiometabolic risk factors such as TG, blood pressure, or blood glucose. A reduction in body weight of 1% was observed in favor of PBMA although this was not considered to be clinically significant (5%). It should be noted that the duration of the trials was relatively short. The use of meat alternatives could be recommended to facilitate the transition from meat consumption to a

higher intake of plant-based foods, because not only they provide a meat-eating experience, but also they do not have adverse cardiometabolic health effects compared with meat and have a lower environmental impact. However, further larger RCTs with longer follow-up periods assessing the effects of novel PBMA are needed, as well as prospective cohort studies, to unravel the long-term effects of PBMA consumption on risk of cardiometabolic diseases. Finally, in the coming years, the growing global market is expected to develop newly formulated PBMA that need to be assessed in future trials.

Acknowledgments

We thank María Inmaculada Infantes-López for her technical assistance and support with the graphical abstract and infographics.

Author contributions

The authors' responsibilities were as follows—RFR, MLM: conceived and supervised the study and wrote the original draft; RFR, VDG, MGM, GB, ARR: curated the data; RFR, GB: visualized the study; RFR: administered the project. BBP, VDG: were responsible for methodology; BBP: performed the software and formal analysis; BBP, VDG, MGM: performed the investigations; VDG, GB, ARR: validated the results; VDG: was responsible for funding acquisition; MLM: was responsible for resources; and all authors: read, reviewed, and approved the final manuscript.

Conflict of interest

The authors report no conflicts of interest.

Funding

RFR postdoctoral contract is supported by the Spanish Ministry of Science, Innovation and Universities, and cofinanced by the European Social Fund+ (JDC2023-050585-I, MCIU/AEI/10.13039/501100011033). BBP was supported by a grant from the University of Castilla-La Mancha, Spain, and cofinanced by the European Social Fund (2020-PREDUCLM-16746). VDG was supported by a grant from the National Agency for Research and Innovation, Uruguay (POS_EXT_2023_1_175630). The funders played no role in the study design, data collection or analysis, decision to publish, or preparation of the manuscript.

Data availability

This systematic review does not include original data. Data were extracted from the publicly available literature. The data set generated for this analyses are available upon request to the corresponding author.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ajcnut.2024.12.002>.

References

- [1] FAO, Food-based dietary guidelines [Internet]. Available from: <https://www.fao.org/nutrition/education/food-dietary-guidelines/regions/en/>.
- [2] Health Canada, Canada's dietary guidelines [Internet], Organisation Health Canada, 2019, p. 62. <https://food-guide.canada.ca/en/guidelines/>.
- [3] The World Economic Forum, Transforming the global food system for human health and resilience, World Economic Forum, 2023.
- [4] Biden-Harris Administration White House National Strategy on Hunger, Nutrition, and Health, The White House, 2022.
- [5] W. Willett, J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, et al., Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems, *Lancet* 393 (10170) (2019) 447–492, [https://doi.org/10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4).
- [6] J. Kennedy, P. Alexander, L.S. Taillie, L.M. Jaacks, Estimated effects of reductions in processed meat consumption and unprocessed red meat consumption on occurrences of type 2 diabetes, cardiovascular disease, colorectal cancer, and mortality in the USA: a microsimulation study, *Lancet Planet Health* 8 (7) (2024) e441–e451, [https://doi.org/10.1016/S2542-5196\(24\)00118-9](https://doi.org/10.1016/S2542-5196(24)00118-9).
- [7] M. Song, T.T. Fung, F.B. Hu, W.C. Willett, V.D. Longo, A.T. Chan, et al., Association of animal and plant protein intake with all-cause and cause-specific mortality, *JAMA Intern. Med.* 176 (10) (2016) 1453–1463, <https://doi.org/10.1001/jamainternmed.2016.4182>.
- [8] H.C.J. Godfray, P. Aveyard, T. Garnett, J.W. Hall, T.J. Key, J. Lorimer, et al., Meat consumption, health, and the environment, *Science* 361 (6399) (2018), <https://doi.org/10.1126/science.aam5324>.
- [9] V.I. Kraak, J. Aschemann-Witzel, The future of plant-based diets: aligning healthy marketplace choices with equitable, resilient, and sustainable food systems, *Annu. Rev. Public Health* 45 (1) (2024) 253–275, <https://doi.org/10.1146/annurev-publhealth-060722-032021>.
- [10] R. Micha, G. Michas, D. Mozaffarian, Unprocessed red and processed meats and risk of coronary artery disease and type 2 diabetes—an updated review of the evidence, *Curr. Atheroscler. Rep.* 14 (6) (2012) 515–524, <https://doi.org/10.1007/s11883-012-0282-8>.
- [11] A. Satija, S.N. Bhupathiraju, E.B. Rimm, D. Spiegelman, S.E. Chiuve, L. Borgi, et al., Plant-based dietary patterns and incidence of type 2 diabetes in US men and women: results from three prospective cohort studies, *PLoS Med* 13 (6) (2016) e1002039, <https://doi.org/10.1371/journal.pmed.1002039>.
- [12] S. Kuosmanen, M. Niva, A.M. Pajari, K. Korhonen, T. Muiilu, H. Kontinen, Barriers associated with pulse and plant-based meat alternative consumption across sociodemographic groups: a Capability, Opportunity, Motivation, Behaviour model approach, *Front. Nutr.* 10 (2023) 1186165, <https://doi.org/10.3389/fnut.2023.1186165>.
- [13] D. Fechner, B. Grün, S. Dolnicar, Identifying segment-specific barriers to ordering environmentally sustainable plant-based meat dishes in restaurants, *J. Sustain. Tour.* (2024) 1–24, <https://doi.org/10.1080/09669582.2024.2342982>.
- [14] F.B. Hu, B.O. Otis, G. McCarthy, Can plant-based meat alternatives be part of a healthy and sustainable diet? *JAMA* 322 (16) (2019) 1547–1548, <https://doi.org/10.1001/jama.2019.13187>.
- [15] J. He, N.M. Evans, H. Liu, S. Shao, A review of research on plant-based meat alternatives: driving forces, history, manufacturing, and consumer attitudes, *Compr. Rev. Food Sci. Food Saf.* 19 (5) (2020) 2639–2656, <https://doi.org/10.1111/1541-4337.12610>.
- [16] N. Abbaspour, R. Sanchez-Sabate, J. Sabaté, Non-animal-based options for animal-based foods- towards a systematic terminology, *Front. Nutr.* 10 (2023) 1208305, <https://doi.org/10.3389/fnut.2023.1208305>.
- [17] R. El Sadig, J. Wu, Are novel plant-based meat alternatives the healthier choice? *Food Res. Int.* 183 (2024) 114184, <https://doi.org/10.1016/j.foodres.2024.114184>.
- [18] D. Choudhury, S. Singh, J.S.H. Seah, D.C.L. Yeo, L.P. Tan, Commercialization of plant-based meat alternatives, *Trends Plant Sci* 25 (11) (2020) 1055–1058, <https://doi.org/10.1016/j.tplants.2020.08.006>.
- [19] B. Romão, R.B.A. Botelho, M.L. Torres, D.D.C. Maynard, M.E.M. de Holanda, V.R.P. Borges, et al., Nutritional profile of commercialized plant-based meat: an integrative review with a systematic approach, *Foods* 12 (3) (2023) 448, <https://doi.org/10.3390/foods12030448>.
- [20] M. Messina, A.M. Duncan, A.J. Glenn, F. Mariotti, Perspective: plant-based meat alternatives can help facilitate and maintain a lower animal to plant protein intake ratio, *Adv. Nutr.* 14 (3) (2023) 392–405, <https://doi.org/10.1016/j.advnut.2023.03.003>.
- [21] D.W.K. Toh, A. Srv, C.J. Henry, Unknown impacts of plant-based meat alternatives on long-term health, *Nat. Food* 3 (2) (2022) 90–91, <https://doi.org/10.1038/s43016-022-00463-5>.
- [22] R. Tso, C.G. Forde, Unintended consequences: nutritional impact and potential pitfalls of switching from animal- to plant-based foods, *Nutrients* 13 (8) (2021) 2527, <https://doi.org/10.3390/nu13082527>.
- [23] C.A. Monteiro, G. Cannon, M. Lawrence, M.L. da Costa Louzada, P.M. Pereira, Ultra-processed foods, diet quality, and health using the Nova classification system [Internet], Food and Agriculture Organisation of the United Nations, Rome, 2019. <https://www.fao.org/3/ca5644en/ca5644en.pdf>.
- [24] N.T. Locatelli, G.F.N. Chen, M.F. Batista, J.M. Furlan, R. Wagner, D.H. Bandoni, et al., Nutrition classification schemes for plant-based meat analogues: drivers to assess nutritional quality and identity profile, *Curr. Res. Food Sci.* 9 (2024) 100796, <https://doi.org/10.1016/j.crf.2024.100796>.

- [25] M. Nagra, F. Tsam, S. Ward, E. Ur, Animal vs plant-based meat: a hearty debate, *Can. J. Cardiol.* 40 (7) (2024) 1198–1209, <https://doi.org/10.1016/j.cjca.2023.11.005>.
- [26] J. Gibbs, G.-K. Leung, The effect of plant-based and mycoprotein-based meat substitute consumption on cardiometabolic risk factors: a systematic review and meta-analysis of controlled intervention trials, *Dietetics* 2 (1) (2023) 104–122, <https://doi.org/10.3390/dietetics2010009>.
- [27] J.P.T. Higgins, J. Thomas, J. Chandler, M. Cumpston, T. Li, M.J. Page, et al. (Eds.), *Cochrane handbook for systematic reviews of interventions*, version 6.4. Available from: www.training.cochrane.org/handbook (updated August 2023).
- [28] M.J. Page, J.E. McKenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, et al., The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, *BMJ* 372 (2021) n71, <https://doi.org/10.1136/bmj.n71>.
- [29] J.A.C. Sterne, J. Savović, M.J. Page, R.G. Elbers, N.S. Blencowe, I. Boutron, et al., RoB 2: a revised tool for assessing risk of bias in randomised trials, *BMJ* 366 (2019) 14898, <https://doi.org/10.1136/bmj.14898>.
- [30] L.A. McGuinness, J.P.T. Higgins, Risk-of-bias VISualization (robvis): an R package and Shiny web app for visualizing risk-of-bias assessments, *Res. Synth. Methods* 12 (1) (2021) 55–61, <https://doi.org/10.1002/jrsm.1411>.
- [31] D. Jackson, R. Turner, Power analysis for random-effects meta-analysis, *Res. Synth. Methods* 8 (3) (2017) 290–302, <https://doi.org/10.1002/jrsm.1240>.
- [32] R. DerSimonian, N. Laird, Meta-analysis in clinical trials, *Control Clin. Trials* 7 (3) (1986) 177–188, [https://doi.org/10.1016/0197-2456\(86\)90046-2](https://doi.org/10.1016/0197-2456(86)90046-2).
- [33] M.O.C. Coelho, A.J. Monteyne, M.L. Dirks, T.J.A. Finnigan, F.B. Stephens, B.T. Wall, Daily mycoprotein consumption for 1 week does not affect insulin sensitivity or glycaemic control but modulates the plasma lipidome in healthy adults: a randomised controlled trial, *Br. J. Nutr.* 125 (2) (2021) 147–160, <https://doi.org/10.1017/S0007114520002524>.
- [34] G.F. Pavis, R.R. Iñiesta, H. Roper, H.E. Theobald, E.J. Derbyshire, T.J.A. Finnigan, et al., A four-week dietary intervention with mycoprotein-containing food products reduces serum cholesterol concentrations in community-dwelling, overweight adults: a randomised controlled trial, *Clin. Nutr.* 43 (3) (2024) 649–659, <https://doi.org/10.1016/j.clnu.2024.01.023>.
- [35] D.W.K. Toh, A.S. Fu, K.A. Mehta, N.Y.L. Lam, S. Haldar, C.J. Henry, Plant-based meat analogs and their effects on cardiometabolic health: an 8-week randomized controlled trial comparing plant-based meat analogs with their corresponding animal-based foods, *Am. J. Clin. Nutr.* 119 (6) (2024) 1405–1416, <https://doi.org/10.1016/j.ajcnut.2024.04.006>.
- [36] W.H. Turnbull, A.R. Leeds, G.D. Edwards, Effect of mycoprotein on blood lipids, *Am. J. Clin. Nutr.* 52 (4) (1990) 646–650.
- [37] F. Bianchi, C. Stewart, N.M. Astbury, B. Cook, P. Aveyard, S.A. Jebb, Replacing meat with alternative plant-based products (RE-MAP): a randomized controlled trial of a multicomponent behavioral intervention to reduce meat consumption, *Am. J. Clin. Nutr.* 115 (5) (2022) 1357–1366, <https://doi.org/10.1093/ajcn/nqab414>.
- [38] A. Crimmarco, S. Springfield, C. Petlura, T. Streaty, K. Cunanan, J. Lee, et al., A randomized crossover trial on the effect of plant-based compared with animal-based meat on trimethylamine-N-oxide and cardiovascular disease risk factors in generally healthy adults: Study with Appetizing Plantfood—Meat Eating Alternative Trial (SWAP-MEAT), *Am. J. Clin. Nutr.* 112 (5) (2020) 1188–1199, <https://doi.org/10.1093/ajcn/nqaa203>.
- [39] D.N. Farsi, J.L. Gallegos, T.J.A. Finnigan, W. Cheung, J.M. Munoz, D.M. Commane, The effects of substituting red and processed meat for mycoprotein on biomarkers of cardiovascular risk in healthy volunteers: an analysis of secondary endpoints from Mycomeat, *Eur. J. Nutr.* 62 (8) (2023) 3349–3359, <https://doi.org/10.1007/s00394-023-03238-1>.
- [40] S. McGrath, X. Zhao, R. Steele, B.D. Thombs, A. Benedetti, Estimating the sample mean and standard deviation from commonly reported quantiles in meta-analysis, *Stat. Methods Med. Res.* 29 (9) (2020) 2520–2537, <https://doi.org/10.1177/0962280219889080>.
- [41] M. Koperska, B. Szyk, J. Bowater, A. Benn, Omnicalculator [Internet]. Available from: <https://www.omnicalculator.com/es/salud/glucemia>.
- [42] UnitsLab [Internet]. Available from: https://unitslab.com/es/node/60#google_vignette.
- [43] V. Wolfgang, Conducting meta-Analyses in R with the metafor package, *J. Stat. Softw.* 36 (2010) 1–48.
- [44] A. Crimmarco, M.J. Landry, M.M. Carter, C.D. Gardner, Assessing the effects of alternative plant-based meats v. animal meats on biomarkers of inflammation: a secondary analysis of the SWAP-MEAT randomized crossover trial, *J. Nutr. Sci.* 11 (2022) e82, <https://doi.org/10.1017/jns.2022.84>.
- [45] D.N. Farsi, J.L. Gallegos, G. Koutsidis, A. Nelson, T.J.A. Finnigan, W. Cheung, et al., Substituting meat for mycoprotein reduces genotoxicity and increases the abundance of beneficial microbes in the gut: Mycomeat, a randomised crossover control trial, *Eur. J. Nutr.* 62 (3) (2023) 1479–1492, <https://doi.org/10.1007/s00394-023-03088-x>.
- [46] A.S. Thompson, A. Tresserra-Rimbau, N. Karavasiloglou, A. Jennings, M. Cantwell, C. Hill, et al., Association of healthful plant-based diet adherence with risk of mortality and major chronic diseases among adults in the UK, *JAMA Netw. Open* 6 (3) (2023) e234714, <https://doi.org/10.1001/jamanetworkopen.2023.4714>.
- [47] Y. Li, D.D. Wang, X.T. Nguyen, R.J. Song, Y.L. Ho, F.B. Hu, et al., Plant-based diets and the incidence of cardiovascular disease: the Million Veteran Program, *BMJ Nutr. Prev. Health.* 6 (2) (2023) 212–220, <https://doi.org/10.1136/bmjnp-2021-000401>.
- [48] C.A. Monteiro, G. Cannon, R.B. Levy, J.C. Moubarac, M.L. Louzada, F. Rauber, et al., Ultra-processed foods: what they are and how to identify them, *Public Health Nutr* 22 (5) (2019) 936–941, <https://doi.org/10.1017/S1368980018003762>.
- [49] F. Rauber, M. Laura da Costa Louzada, K. Chang, I. Huybrechts, M.J. Gunter, C.A. Monteiro, et al., Implications of food ultra-processing on cardiovascular risk considering plant origin foods: an analysis of the UK Biobank cohort, *Lancet Reg. Health Eur.* 43 (2024) 100948, <https://doi.org/10.1016/j.lanepe.2024.100948>.
- [50] S. Hosseinpour-Niazi, P. Mirmiran, M. Hedayati, F. Azizi, Substitution of red meat with legumes in the therapeutic lifestyle change diet based on dietary advice improves cardiometabolic risk factors in overweight type 2 diabetes patients: a cross-over randomized clinical trial, *Eur. J. Clin. Nutr.* 69 (5) (2015) 592–597, <https://doi.org/10.1038/ejcn.2014.228>.
- [51] M.L. Chamberlin, S.M.G. Wilson, M.E. Gaston, W.Y. Kuo, M.P. Miles, Twelve weeks of daily lentil consumption improves fasting cholesterol and postprandial glucose and inflammatory responses—a randomized clinical trial, *Nutrients* 16 (3) (2024) 419, <https://doi.org/10.3390/nu16030419>.
- [52] D.K. Gupta, C.E. Lewis, K.A. Varady, Y.R. Su, M.S. Madhur, D.T. Lackland, et al., Effect of dietary sodium on blood pressure: a crossover trial, *JAMA* 330 (23) (2023) 2258–2266, <https://doi.org/10.1001/jama.2023.23651>.
- [53] R. Alessandrini, M.K. Brown, S. Pombo-Rodrigues, S. Bhageerutti, F.J. He, G.A. MacGregor, Nutritional quality of plant-based meat products available in the UK: a cross-sectional survey, *Nutrients* 13 (12) (2021) 4225, <https://doi.org/10.3390/nu13124225>.
- [54] V.N. Tejani, S.S. Dhillon, N. Damarlapally, N.U.B. Usman, T. Winson, P. Basu Roy, et al., The relationship between dietary fiber intake and blood pressure worldwide: a systematic review, *Cureus* 15 (9) (2023) e46116, <https://doi.org/10.7759/cureus.46116>.
- [55] T. Pham, S. Knowles, E. Bermingham, J. Brown, R. Hannaford, D. Cameron-Smith, et al., Plasma amino acid appearance and status of appetite following a single meal of red meat or a plant-based meat analog: a randomized crossover clinical trial, *Curr. Dev. Nutr.* 6 (5) (2022) nzac082, <https://doi.org/10.1093/cdn/nzac082>.
- [56] J.P. Goode, K.J. Smith, M. Breslin, M. Kilpatrick, T. Dwyer, A.J. Venn, et al., Modelling the replacement of red and processed meat with plant-based alternatives and the estimated effect on insulin sensitivity in a cohort of Australian adults, *Br. J. Nutr.* 131 (6) (2024) 1084–1094, <https://doi.org/10.1017/S0007114523002659>.
- [57] M. Messina, J.L. Sievenpiper, P. Williamson, J. Kiel, J.W. Erdman, Perspective: soy-based meat and dairy alternatives, despite classification as ultra-processed foods, deliver high-quality nutrition on par with unprocessed or minimally processed animal-based counterparts, *Adv. Nutr.* 13 (3) (2022) 726–738, <https://doi.org/10.1093/advances/nmac026>.
- [58] T. Petersen, M. Hartmann, S. Hirsch, Which meat (substitute) to buy? Is front of package information reliable to identify the healthier and more natural choice? *Food Qual. Prefer.* 94 (2021) 104298, <https://doi.org/10.1016/j.foodqual.2021.104298>.
- [59] R.P. Mensink, World Health Organization, Effects of saturated fatty acids on serum lipids and lipoproteins: a systematic review and regression analysis, World Health Organization, Geneva, 2016.
- [60] M.J. Vincent, B. Allen, O.M. Palacios, L.T. Haber, K.C. Maki, Meta-regression analysis of the effects of dietary cholesterol intake on LDL and HDL cholesterol, *Am. J. Clin. Nutr.* 109 (1) (2019) 7–16, <https://doi.org/10.1093/ajcn/nqy273>.
- [61] L. Rizzolo-Brime, A. Orta-Ramirez, Y. Puyol Martin, P. Jakszyn, Nutritional assessment of plant-based meat alternatives: a comparison of nutritional information of plant-based meat alternatives in Spanish supermarkets, *Nutrients* 15 (6) (2023) 1325, <https://doi.org/10.3390/nu15061325>.
- [62] L. Fu, G. Zhang, S. Qian, Q. Zhang, M. Tan, Associations between dietary fiber intake and cardiovascular risk factors: an umbrella review of meta-analyses of randomized controlled trials, *Front. Nutr.* 9 (2022) 972399, <https://doi.org/10.3389/fnut.2022.972399>.
- [63] E.D. Jesch, T.P. Carr, Food ingredients that inhibit cholesterol absorption, *Prev. Nutr. Food Sci.* 22 (2) (2017) 67–80, <https://doi.org/10.3746/pnf.2017.22.2.67>.

- [64] G. den Besten, K. van Eunen, A.K. Groen, K. Venema, D.J. Reijngoud, B.M. Bakker, The role of short-chain fatty acids in the interplay between diet, gut microbiota, and host energy metabolism, *J. Lipid Res.* 54 (9) (2013) 2325–2340, <https://doi.org/10.1194/jlr.R036012>.
- [65] M.A. Toribio-Mateas, A. Bester, N. Klimenko, Impact of plant-based meat alternatives on the gut microbiota of consumers: a real-world study, *Foods* 10 (9) (2021) 2040, <https://doi.org/10.3390/foods10092040>.
- [66] T.J.A. Finnigan, B.T. Wall, P.J. Wilde, F.B. Stephens, S.L. Taylor, M.R. Freedman, Mycoprotein: the future of nutritious nonmeat protein, a symposium review, *Curr. Dev. Nutr.* 3 (6) (2019) nzz021, <https://doi.org/10.1093/cdn/nzz021>.
- [67] J.A. Sterne, A.J. Sutton, J.P. Ioannidis, N. Terrin, D.R. Jones, J. Lau, et al., Recommendations for examining and interpreting funnel plot asymmetry in meta-analyses of randomised controlled trials, *BMJ* 343 (2011) d4002, <https://doi.org/10.1136/bmj.d4002>.
- [68] V.K. Sullivan, E. Martinez-Steele, V. Garcia-Larsen, C.M. Rebholz, Trends in plant-based diets among U.S. adults, 1999–March 2020, *J. Nutr.* 154 (12) (2024) 3575–3584, <https://doi.org/10.1016/j.tjnut.2024.08.004>.