The potential effects of meat substitution on diet quality could be high if meat substitutes are optimized for nutritional composition - a modeling study in French adults (INCA3)

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List of abbreviations

ALA, alpha-linolenic acid; ANSES, French Agency for Food, Environmental and Occupational Health and Safety; AS, Adequacy Sub-score; CIQUAL, French Information Centre on Food Quality; INCA3, Third Individual and National Study on Food Consumption Survey; LA, linoleic acid; MS, Moderation Sub-score; PANDiet, Probability of Adequate Nutrient Intake; SFA; saturated fatty acids.

Declaration

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Conflicts of interest/Competing interests
The authors declare that they have no competing interests.

Ethics approval
The INCA3 study was carried out in accordance with the Declaration of Helsinki guidelines and was approved by the 'Comité Consultatif sur le Traitement de l'Information en matière de Recherche dans le domaine de la Santé' (Advisory Committee on Information Processing in Health Research).

Consent to participate
For the data collection of the INCA3 survey, oral consent was obtained, witnessed and formally recorded from participants.

Consent for publication
Not applicable

Availability of data and material
The datasets of the INCA3 survey are available at data.gouv.fr.

Code availability
Not applicable

Authors' contributions
Marion Salomé, Hélène Fouillet and François Mariotti designed the research; Marion Salomé, Hélène Fouillet et Marie-Charlotte Nicaud conducted the research; Marion Salomé, Hélène Fouillet et François Mariotti analyzed data; Alison Dussiot, Emmanuelle Kesse-Guyot, Marie-Noëlle Maillard and Jean-François Huneau provided methodological support; Marion Salomé wrote the first draft of the manuscript and all authors provided critical comments on the manuscript. Marion Salomé, François Mariotti and Hélène Fouillet had primary responsibility for the final content and all authors have read and approved the final manuscript.

Abstract

Purpose. While consumer demand for meat substitutes is growing, their varied composition raises questions regarding their nutritional value. We aimed to identify and characterize the optimal composition of a meat substitute that would best improve diet quality after complete meat replacement.

Methods. From an average individual representing the dietary intake of French adults (INCA3, n=1125), meat was replaced with an equivalent amount of a mostly pulse-based substitute, whose composition was based on a list of 159 possible plant ingredients and optimized non-linearly to maximize diet quality assessed with the PANDiet score (considering adequacy for 32 nutrients), while taking account of technological constraints and applying nutritional constraints to limit the risk of overt deficiency in 12 key nutrients.

Results. The optimized meat substitute contained 13 minimally processed ingredients. When used to substitute meat, the PANDiet score increased by 5.7 points above its initial value before substitution (versus -3.1 to +1.5 points when using other substitutes on the market), mainly because of higher intakes of nutrients that are currently insufficiently consumed (e.g. alpha-linolenic acid, fiber, linoleic acid) and a lower SFA intake. The meat substitute also mostly compensated for the lower provision of some indispensable nutrients to which meat greatly contributed (e.g. vitamin B6, potassium, bioavailable iron), but it could not compensate for bioavailable zinc and vitamin B12.

Conclusion. Choosing the correct ingredients can result in a nutritionally highly effective meat substitute that could compensate for reductions in many nutrients supplied by meat while providing key nutrients that are currently insufficiently consumed.

Keywords: Plant-based substitutes; Nutrient composition; Mathematical optimization; Nonlinear programming; Diet quality.

Introduction

Meat substitutes, also called meat analogues or meat replacers, are designed to mimic the appearance and practical uses of meat products [1]. While some meat alternatives, such as tofu or tempeh formed part of the traditional diet in Asia [2, 3], more recent products are emerging and seeing rapid market growth [4, 5]. These products, such as plant-based sausages or patties, are not just intended for vegetarians but for all consumers who are willing to reduce their meat consumption [4, 5].

Indeed, reducing meat consumption is advocated for both health and environmental reasons [6–8]. However, in industrialized countries, meat plays an important cultural and structural role in meals, which makes it relatively difficult to remove and replace [9–11]. In this context, meat substitutes might be expected to be more acceptable than classic plant-based foods such as pulses because they can be used in the same way as meat and do not require changes to the meal structure [9].

From a nutritional standpoint, meat is an important contributor to micronutrient intake, and especially of iron, zinc and some B-vitamins [12–15]. Therefore, when rearranging diets in order to adopt more sustainable diets, attention should be paid to ensuring adequate nutrient intakes [13, 16, 17]. However, the formulation of meat substitutes generally tends to be more driven by attempts to imitate the organoleptic properties of meat (appearance, texture, flavor) than ensuring an appropriate nutrient composition beyond the protein content [5]. The main ingredients composing meat substitutes are generally soy, wheat, or pea proteins because of their technological functional properties (such as a fibrous-like texture and emulsification) [4, 5, 18] but many ingredients can be used, such as all kind of pulses, cereals, vegetables, herbs, and spices [4, 18], leading to a multitude of possibilities of formulation. More specifically, pulses are currently little consumed despite their nutritional and environmental benefits [7, 19] and meat substitute could help to increase their consumption.

The nutritional composition of meat substitutes has been previously studied and compared to that of meat [20, 21], and mathematical optimization has been used to identify a meat substitute formulation with the closest nutritional composition to that of meat [22]. However, assessing the nutritional quality of a meat substitute requires to go beyond its intrinsic nutrient composition and to fully characterize the impact of its integration into the diet at a given expected level of consumption [23, 24]. To our knowledge, no information is available regarding possible optimization of the nutritional composition of a meat substitute in order to maximize overall diet quality.

Our aim during this study was therefore to evaluate to what extent a meat substitute with optimum nutritional design could improve diet quality when fully replacing meat. We used mathematical optimization to determine the best ingredients for a meat substitute that would maximally improve the overall nutrient adequacy of the diet of French adults but without jeopardizing nutrient security for a subset of critical nutrients. The aim was to design a meat substitute mainly pulse-based and using minimally processed ingredients, given growing concerns with respect to ultra-processed foods [25]. We then analyzed the impact of this optimized meat substitute, and the role of the selected ingredients, on the diet quality and compared it with a large market sample of meat substitutes currently available.

Data and methods

In this study, the composition of a meat substitute intended to completely replace meat was optimized in order to best improve the diet quality of French adults.

Input dietary data

The data used in this study came from the third Individual and National Study on Food Consumption Survey 3 (INCA3), performed in mainland France in 2014-2015. The INCA3 survey is a French nationwide and representative cross-sectional survey and its design has been fully described elsewhere [26]. Male participants aged 18-64y and premenopausal female participants aged 18-54y were included in the study. Elderly and postmenopausal females were excluded because of different nutrient requirements. Under-reporters for energy intake were excluded using Henry's equations [27] and the cutoffs proposed by Black [28]. The final sample contained 1125 adults (564 males and 561 females) (Supplementary Figure S1).

Dietary data were collected by professional investigators assisted by a dietary software and using three non-consecutive 24h-dietary recalls spread over a 3-week period [26]. Participants were not aware beforehand of the days of recall. Portion sizes were estimated using validated photographs [26]. The nutrient content of foods and beverages came from the 2016 food composition database from the French Information Center on Food Quality (CIQUAL) [29]. Over all foods consumed, meat or processed meat usually eaten in the main dish were identified as 'meat food items', excluding composite dishes (e.g. lasagna) (Supplementary Table S1). Foods that were not identified as meat food items are referred to hereinafter as 'other food items'. The mean nutrient intakes from meat food items and other food items were then calculated for males and females separately, using the weighted schemes proposed in INCA3 to account for the complex survey design [26]. This resulted in average male and female individuals with mean nutrients intakes for each sex.

<u>Evaluation of diet quality</u>

Diet quality was evaluated using the Probability of Adequate Nutrient Intake (PANDiet) scoring system [30], which reflects the probability for an individual of having an adequate nutrient intake (Supplementary Table S2). The PANDiet is the mean of two sub-scores: the Adequacy Sub-score (AS), which measures the probability of adequacy of intake, and the Moderation Sub-score (MS), which measures the probability of not having an excessive intake of nutrients that need to be limited. The AS is the mean of probabilities for 27 nutrients whose intakes need to be above the nutrient reference value, multiplied by 100. The MS is the mean of probabilities of 6 nutrients whose intakes should be below an upper bound reference value, multiplied by 100. The overall PANDiet score ranges from 0 to 100, with a higher score indicating better nutritional quality of the diet.

The probability of adequacy for each nutrient is calculated using the mean intake, the reference value, the variability of the reference value and the intra-individual variability of intake, as previously described [30]. However, during this study, probabilities of adequacy were calculated for average male and female individuals, so intra-individual variability was considered to be equal to zero. The reference values were extracted from the 2021 dietary guidelines released by ANSES [31]. For iron and zinc, we considered the estimated requirement for the absorbed form and an equation predicting absorption from dietary intakes [32–34]. Moreover, to take account of the high requirement of iron for some females, the probability of adequacy of iron was calculated using two different reference values: females with low to moderate menstrual losses and females with elevated menstrual losses (about 20% of females) [31]. PANDiet was therefore calculated for the average male (PANDiet-M) and for the average female using the reference values for iron for female with normal (PANDiet-F) or high iron requirements (PANDiet-F+). An averaged PANDiet was calculated as the mean of the PANDiet-M, the PANDiet-F and the PANDiet-F+ weighted by their respective distributions in the study population (50.13% of males, 49.87% of females with a weighting of 80% for PANDiet-F and 20% for PANDiet-F+).

Evaluation of the nutrient security of diet

The nutrient security of the diet was estimated using the SecDiet score, which measures the risk of having an overt nutrient deficiency [35]. The SecDiet is composed of 12 nutrients for which clinical signs of deficiency due to insufficient dietary intake have been documented: vitamin A, thiamin, riboflavin, niacin, folate, vitamin B12, vitamin C, iodine, selenium, iron, zinc, and calcium. A deficiency threshold was defined for each nutrient and corresponded to the minimal intake below which clinical signs of deficiency may appear (Supplementary Table S3). The SecDiet is the mean of the squares of the 12 probabilities and ranges from 0 to 1 with a higher score reflecting a lower risk of nutrient deficiency. In the same way as the PANDiet, probabilities for each nutrient were calculated using the mean intake, the reference value (defined as the deficiency threshold) and the variability of the reference value.

Mathematical optimization of the meat substitute

The optimization problem was to find the ingredient composition of a meat substitute, intended to replace meat consumption in the average male and female individuals, so as to maximize the non-linear PANDiet score under nutritional and technological constraints (see below) in order to ensure both nutrient security and formulation feasibility. The problem was solved using a non-linear optimization algorithm (NLP, with multistart to avoid local minima) under the OPTMODEL procedure (SAS 9.4, SAS Institute Inc., Cary, NC, USA.).

Optimized meat substitute

The aim was to model a meat substitute that was entirely plant-based (i.e. containing no animal-based ingredients) and composed of minimally processed ingredients. Thus only minimally processed, common culinary ingredients of plant origin were included (e.g. tofu or textured soy protein were not included as they are processed, but cooked pulses were included). A total of 159 ingredients for which a complete nutritional composition could be extracted from the CIQUAL 2020 food composition database [36] were categorized into groups and sub-groups (pulses, vegetables, cereals, oil-rich foods, etc.) (Supplementary Table S4).

The nutrient contents of the ingredients were given for their cooked form when available (e.g. for pulses or vegetables) or raw form for other ingredients (e.g. oils, flours, etc.). Although the nutrient content of a cooked ingredient already takes account of possible losses during cooking, we applied a retention factor (i.e. the percentage of nutrient content retained after cooking) to the nutrient composition of the optimized meat substitute by considering cooking using dry heat to reproduce an industrial process [37]. Nutrients for which significant losses were expected during cooking were riboflavin (retention factor=98%), niacin (98%), vitamin B6 (95%), vitamin A (93%), pantothenic acid (88%), thiamin (78%), vitamin C (78%), and folate (68%).

The meat substitute was designed to replace by the same quantity the mean quantity of all meat food items consumed by each sex (125.3g for average male and 79.7g for average female), while the intake of other food items was kept constant. We chose to replace by the same quantity rather than by the same energy because meat substitutes generally have the same portion size than meat products. The optimization results (i.e., decision variables) were the proportions of each ingredient (from the 159 possible) used to compose the optimized meat substitute (under the obvious constraint that the sum of the proportions equaled 100%).

Objective function

The objective was to maximize overall adequacy in nutrient intake using the averaged PANDiet score, as described above, as the objective function.

Nutritional constraints

Nutritional constraints were applied to the 12 critical nutrients included in the SecDiet, in order to limit any increased risk of deficiency in the diet after meat substitution for the average male and average female. For these nutrients, the probability of sufficient intake in the modeled diet (with meat replaced with the optimized meat substitute) had to be ≥99% of the corresponding probability in the observed diet. Constraints were also applied to nine nutrients (retinol, niacin, vitamin B6, vitamin D, calcium, copper, iodine, selenium, zinc) to maintain their intakes in the modeled diet below their tolerable upper intake levels, as defined by ANSES [31] (Supplementary Table S2).

In order to minimize effects on the energy intake of subjects, the energy content of the optimized meat substitute was also limited to ±20% of the energy intake supplied by meat food items to each sex. This resulted in a change in the total energy intake of the average diet limited to ±1.9% for the average male and ±1.5% for the average female.

Technological constraints

Several technological constraints were applied:

- Water content constraint: the range of the water arising from ingredients in the optimized meat substitute had to be between 50 and 65g water per 100g, and was defined to ensure a water content similar to that of other meat substitutes available [36].
- Ingredient groups constraints: several constraints were applied to specify the acceptable proportions of ingredients from the same group or sub-group in order to obtain the composition of a meat substitute that could be easily formulated (Supplementary Table S5). These constraints were based on the ingredient lists of meat substitutes available in supermarkets and on the nutritional properties (sources of lipids, protein, fiber, etc.) and technological properties (binding, texturizing ingredients, etc.) of the different ingredient groups and sub-groups (Supplementary Table S4). The aim was to model a meat substitute that could be a pulse-based patty (40% to 60% of pulses among all ingredients).

- Ingredient number constraints: the number of ingredients from each sub-group was restricted to two in order to limit the total number of ingredients while allowing some flexibility.

Sensitivity analysis and validation

After running the optimization procedure and obtaining the composition of the meat substitute, we tested the degree to which the selected recipe had a nutritional advantage over its possible alternatives. This was done by discarding each of the selected ingredients one by one, by adding a new constraint so that the proportion of the ingredient would be equal to zero, in order to assess the impact of any alternative on PANDiet. We also evaluated the influence of the technological constraints on the composition and nutritional efficiency of the optimized meat substitute.

Moreover, to identify the active constraints that influenced the solution, we estimated the dual values associated with each of the nutritional and technological constraints. Dual values were estimated using the optimization algorithm in order to represent the potential gain in objective function (PANDiet) for the relaxation by one unit of the limiting bound of the constraint being considered.

Finally, as an *a posteriori* partial validation of the technological constraints, the recipe of the optimized meat substitute was tested at a kitchen scale to check if a realistic plant-based patty could be obtained from the optimized ingredient composition.

Effects of the optimized meat substitute on diet quality

Comparison with existing meat substitutes

Several modeled diets were designed to study the impacts of meat substitutes on diet quality evaluated with the averaged PANDiet. For the average male and female, meat food items were replaced by the same quantity of either the optimized meat substitute or each of 43 existing meat substitutes available in the CIQUAL 2016 and 2020 databases and the NutriNet-Santé food composition table [29, 36, 38] (Supplementary Table S6). We therefore modeled 44 diets: one with the optimized meat substitute and 43 with existing meat substitutes. In addition, a modeled diet was designed by simply deleting all meat food items. This modeled diet is highly unrealistic but was not intended as a scenario. Rather, it was used to analyze the contribution of meat food items to diet quality and disentangle the changes in nutrient adequacies that result from the suppression of meat and those that result from the addition of meat substitutes.

These modeled diets were adjusted for energy, by reporting the difference of energy between meat food items and the meat substitute into changes in the amounts of other food items. For the no-meat scenario, the quantities of other food items were increased to maintain the same energy intake. The results are presented with and without energy adjustments.

Inter-individual variability

The composition of the optimized meat substitute was obtained with an optimization procedure performed at the population level, using average individuals. In order to obtain a more accurate estimate of the effects of the optimized meat substitute on the diet quality of the population, we simulated the substitution of meat food items with the optimized meat substitute in the diet of each participant (n=564 males, 561 females). The meat food items consumed were identified for each participant and replaced with the same quantity of the optimized meat substitute. The difference of energy was adjusted using the rest of the diet. The SecDiet and PANDiet scores and sub-scores were calculated, taking account of intra-individual variability between the days of recall. Differences between the observed and modeled diets were evaluated using Student’s t-test.

Results

Optimized meat substitute: composition and impacts on diet quality

The optimized meat substitute was composed of 13 ingredients (Table 1). It contained 8.5g/100g protein (supplied mostly by navy bean, wheat germ, and flaxseed), was low in saturated fatty acids (0.9g/100g) and rich in fiber (13g/100g). Ingredients contributed differently to the nutrient composition of the meat substitute. Thyme, navy bean and wheat bran were the main contributors to iron content, and dried shiitake mushroom to B-vitamins, whereas flaxseed contributed to 68% of the alpha-linolenic acid (ALA) content and yellow sweet pepper to 91% of the vitamin C content (Supplementary Table S7).

Compared to the observed diet at the average population level, replacing meat with the optimized meat substitute resulted in a 5.7-point increase in the averaged PANDiet score, with energy adjustment (or +5.5 points otherwise) (Table 2). This resulted from an increase in AS by +6.1 points and in MS by +5.3 points. In greater detail, the probabilities of adequacy mainly increased for ALA, fiber, linoleic acid (LA), vitamin C, and folate with respect to AS, and sodium and SFA with respect to MS. By contrast, some probabilities of adequacy decreased, notably for vitamin B12, bioavailable zinc, bioavailable iron, and vitamin B6 with respect to AS. However, these decreases were less marked when compared to a situation where meat was withdrawn and not replaced by the meat substitute ("Modeled diet without meat"), except for zinc (-0.30) and vitamin B12 (-0.33). On the contrary, for potassium, the decrease due to removing meat was totally compensated by the meat substitute. Concerning nutrient security, the SecDiet score remained stable, although the probability for iron slightly decreased (-0.01) but less than without meat. Lastly, the PANDiet gain was more important in average male (+6.2) than in average female (+5.2), because the MS increase was more pronounced for the average male (+6.3) than for the average female (+4.3) while the increase in AS was similar (+6.1) (Supplementary Table S8). At an individual level, in order to consider inter-individual variations, the PANDiet gain was less marked when replacing meat with the optimized meat substitute and increased from 67.6 ± 5.8 to 71.2 ± 6.3 for females and from 67.7 ± 6.2 to 72.1 ± 7.3 for males (Supplementary Table S9).

At the average population level, the impact of the optimized meat substitute on diet quality was compared to the impacts of existing meat substitutes (Fig. 1). In modeled diets adjusted for energy intake, where meat was replaced by existing meat substitutes, the PANDiet score ranged from 70.6 to 75.1 (i.e. -3.1 to +1.5 compared to the initial PANDiet), depending on the meat substitute, with a mean at 73.0. Only about a quarter of the meat substitutes (upper whisker of the boxplot) increased the PANDiet score above its value in the observed diet (73.7). These increases were much lower than that resulting from using the optimized meat substitute (79.4). AS from modeled diets with existing meat substitutes were more spread out (72.4 to 80.7, with a mean at 77.2) but always lower than the AS reached with the optimized meat substitute (84.6). Differences between the optimized and existing meat substitutes were less marked for MS. The results were similar when the modeled diets were not adjusted for energy intake (Supplementary Figure S2).

Fig. 1 a. PANDiet, b. AS and c. MS scores in modeled average diets where meat food items were replaced with the optimized meat substitute or with existing meat substitutes (n=43). Modeled diets were adjusted for energy intake to maintain the same energy as the initial observed diet. Whiskers of the boxplot represent min and max of scores obtained in modeled diets with currently available meat substitutes. Horizontal lines represent scores in the initial diet (full line) or in a modeled diet without meat where meat food items were removed and adjusted for energy intake in the rest of the diet (dashed line)

<u>Sensitivity analysis and validation: influence of model constraints and overall stability of the selected recipe.</u>

Among the active constraints that influenced the solution some were more binding than others, as shown by their dual values indicating a potential gain in the averaged PANDiet score for a release by one unit in their binding bound. Among the nutritional constraints, only the constraint limiting the decrease in the probability of adequacy for iron (as regards the SecDiet) in female individual was active. However, the effect of this constraint was limited; if the constraint was deleted, this probability dropped from 99% of its initial value to 98.7%, with a negligible PANDiet gain (+0.02) (data not shown). Several technological constraints were active (Table 3), the three most active being the upper bounds of herbs, spices and salt, oil-rich foods and nuts and seeds, with PANDiet increases between +0.10 and +0.24 per 1% increase in their upper binding bounds.

When the recipe was tested at a kitchen scale, it proved to be feasible, although a little dry and crumbly, with an overpowering thyme flavor.

Consistent with this, we determined whether releasing some or all of the technological constraints might have led to a markedly different composition of the optimized meat substitute (Supplementary Table S10). If the six constraints on pulses and cereals were released, the optimized meat substitute would contain broad bean instead of navy bean and at a lower proportion (28%), together with much more wheat germ (23%). However, cereals or pulses were not selected when releasing all the constraints on the ingredient groups, but only vegetables, oil-rich foods, and herbs. If all technological constraints were released, the optimized meat substitutes would be difficult to formulate since it would contain mostly dried ingredients and oil (39% dried shiitake mushroom, 24% dried Chinese black mushroom, 14% rapeseed oil, 13% thyme, etc.).

Finally, while retaining all the initial technological constraints, we removed one by one each ingredient composing the optimized meat substitute presented in Table 1, as well as other ingredients in the database that were very similar (e.g., by concomitantly removing all sweet peppers when removing yellow sweet pepper) (Table 4). The proportions of ingredients generally varied but the main structure of the optimized meat substitute was mostly unchanged, since the ingredient removed was usually replaced by another ingredient from the same sub-group (e.g. navy bean was replaced with a mix of chick pea and blond lentil, or flaxseed was replaced with chia seed). For most ingredients, the replacement led to a PANDiet decrease compared to its value with the initial optimized meat substitute. This was mostly the case for rapeseed oil (-0.28), yellow sweet pepper (-0.23), all sweet peppers (-0.28), dried mushrooms (-0.20), wheat bran (-0.17), and thyme (-0.07). It was also apparent in the dual values calculated for eviction constraints, which were higher for these ingredients. For some ingredients, the impact on the PANDiet was low because there was a compensation between the loss of AS and the gain in MS. Replacement of chick pea, flaxseed, and potato starch had the least impacts on PANDiet, AS and MS.

Discussion

In this study, we identified what would be the “best” composition for a plant-based meat substitute to improve the quality of the diet of French adults when completely substituting meat. The approach we used was original and innovative because it went beyond a simple comparison of the nutrient contents of the meat being replaced and considered the nutritional impact of the new food item on overall diet quality. Indeed, when considering the substitution of meat by another food, nutritional advantages depend on addressing all nutrient inadequacies, whether or not they are related to the removal of meat. We thus identified an optimal composition for a meat substitute that could be seen as a good lever to replace meat in the diet.

The optimized meat substitute supplied some nutrients that are currently insufficiently consumed in the population, such as LA, ALA, fiber, folate, and vitamin C, and it also enabled less excessive intakes of SFA and sodium, as had also been shown in several studies that simulated the substitution of meat with plant-based substitutes [24, 39, 40]. Indeed, a higher content of fiber, several minerals, and polyunsaturated fatty acids has been found in plant-based substitutes than in meat [20, 21], but the optimized meat substitute proved to be much more efficient than existing meat substitutes. The benefits of meat substitutes might therefore be much greater if appropriate consideration were given to a large number of nutrients consumed insufficiently or in excess, and if the sourcing of a large number of ingredients were more finely tuned. These beneficial effects were also greater than those elicited by simply removing meat without providing a specific replacement.

The optimized meat substitute also compensated totally or partially the loss of nutrients previously supplied by meat, and particularly potassium, vitamin B6, bioavailable iron, and, to a lesser extent, bioavailable zinc. Except for potassium, the probabilities of adequacy for these nutrients still decreased with the optimized meat substitute, but less than if meat had simply been replaced by increases in the rest of the diet. The decrease was however still important for bioavailable zinc.

The only exception was vitamin B12 where the optimized meat substitute had no effect on the probability of adequacy, which was expected since all plant ingredients in the substitute are considered as non-reliable sources of vitamin B12 (and we considered no vitamin B12 in our composition table). Zinc, iron, and vitamin B12 are generally nutrients of concern when reducing meat consumption since meat, and animal-based foods in general, are important contributors of these nutrients [41]. We were however able to show that through the choice of appropriate ingredients, the iron content in the optimized meat substitute was sufficient to maintain adequacy, even with our fine assessment of iron bioavailability. The optimized meat substitute also supplied zinc, although the bioavailable amount was not sufficient to maintain the same probability of adequacy as in the observed diet.

As shown by Van Mierlo et al., zinc and iron fortification was necessary when seeking to match the nutritional composition of beef, alongside vitamin B12 fortification to match that of beef and chicken [22]. In a study modeling diets using meat substitutes that were fortified or not with iron and vitamin B12, fortification was shown to allow a more efficient use in the context of meat reduction [23]. Therefore, fortifying meat substitutes could help to maintain adequate intakes of vitamin B12, zinc, and iron. Some plant-based substitutes are indeed already fortified; for example, it has been reported in Australia that 24% of products are fortified with vitamin B12, 20% with iron and 18% with zinc [20]. These nutrients could also be supplied by other foods of the diet, and diet optimization could help to target the consumption of appropriate food groups [23].

The optimized meat substitute might appear low in protein compared to meat or other meat substitutes on the market, but this was expected because we mainly used raw materials rather than the protein isolates that are usually used to produce a high protein content in meat substitutes [2, 18]. Moreover, the composition of the meat substitute resulted from the compromise made by an optimization procedure based on the current set of nutrient adequacies, and protein adequacy proved to be a secondary issue compared to other nutrients. We did not consider the amino acid composition of the optimized meat substitute, but there should be no issue in this respect since the protein sources comprised a mix of cereals, nuts and pulses that are known to have a complementary composition in amino acids [42]. Moreover, it has been shown that when protein intake is adequate in a varied diet, so is the intake of individual amino acids [43].

Along with the potential impacts on diet quality of meat substitutes, this study offers interesting perspectives in terms of their formulation and composition. We showed that some ingredients proved to offer interesting levers to improve the nutrient composition of meat substitutes, such as flax or chia seeds which are rich in ALA, black mushrooms which conveys B-vitamins and wheat germ and bran which are important sources of zinc and iron. By removing each ingredient successively from the optimized meat substitute, we found that the initial recipe was very robust inasmuch as it was not compromised by the removal of one ingredient. The gain in the PANDiet score offered by the optimized meat substitute was therefore the result of the complex assembly of its different ingredients supplying different nutrients at optimal proportions, as identified by our optimization approach.

One of our objectives was to model a meat substitute containing ingredients obtained by minimal processing steps. Indeed, most meat substitutes are ultra-processed (according to the NOVA classification [44]) and use ingredients that are refined, extracted and purified (e.g. protein isolates), additives, or involve processing techniques that enhance a meat-like fibrous texture, in order to mimic the texture, taste, and flavor of meat [4, 5]. However, given the importance placed on naturalness by consumers [45] and concerns regarding the health effects of an excessive consumption of ultra-processed foods [25], we chose to limit the set of possible ingredients to those minimally processed. Our results have also implications in everyday practice as they show that simple ingredients can be used to formulate a meat substitute that would be very nutritionally efficient, and can be translated at home with simple recipes for plant-based patties.

The final recipe for the optimized meat substitute still contains quite a lot of ingredients but we have shown that they do not have the same nutritional importance, so some could be replaced or removed. Some ingredient groups were imposed for technological reasons rather than for their nutritional properties and experimental formulations could interestingly determine the extent to which these ingredients are indeed necessary at these proportions. Modifying some of the technological constraints would have increased the PANDiet gain, as shown by their dual values. Early tests showed us that with a ±5% change in the upper or lower bounds of some constraints, the same ingredients were almost always chosen, although in slightly different proportions (data not shown). Therefore, the composition and proportions of ingredients described here might vary as a function of technological issues. One challenge of our study was to define the technological constraints that could make the theoretical optimized meat substitute recipe being realistic, i.e. that it could be used to produce a meat substitute that would look like a plant-based patty. The constraints as defined proved to be appropriate inasmuch as the meat substitute was made possible at a kitchen scale, but adjustments would still be necessary to achieve a final product.

Our study had certain limitations. First, optimization was performed on an average individual, which led to a somewhat crude evaluation of diet quality, since the variability of intake was not taken into account. We believe that the impact of substitution is better evaluated at an individual level rather than a population level because this takes more account of the heterogeneity of diets [46], but our objective was to model a unique substitute that would best improve general diet quality and not to find a personalized meat substitute for each individual. But we have shown that replacing meat with the optimized meat substitute at the individual level led to similar conclusions, although differences with observed diets were less marked. Further, the database of ingredients was limited to those for which we had a complete nutritional composition, so despite our considerable database (159 ingredients) we did not have an exhaustive list of potential ingredients. While we tried to best describe the technological constraints associated with the formulation of a plant-based patty, we might not have been sufficiently accurate and some constraints were not considered, such as taste or consumer preferences. Furthermore, this study focused on nutrition while including technological constraints, but further studies could interestingly try to consider other criteria such as environmental impacts or cost.

In conclusion, we have shown that it is possible to identify the composition of a meat substitute that would offer the best nutritional lever to replace meat in our population. As revealed by optimization on a large set of nutrient adequacies, the optimized meat substitute could improve diet quality by both increasing nutrient adequacy for nutrients not provided by meat and by compensating for most of the nutrients conveyed by meat. Meat substitutes with an appropriate composition could therefore be adapted nutritionally to replace meat.

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Table 1. Ingredient composition of the optimized meat substitute

Ingredient groups and sub-groups		Ingredient	Proportion (%) in the optimized meat substitute
Pulses		Navy bean, boiled/cooked in water	41.6
		Chick pea, boiled/cooked in water	5.8
Vegetables, cooked		Pepper, sweet, yellow, pan-fried, without fat	15.0
Fragmented cereals	>10g/100g of protein	Wheat bran	5.6
		Wheat germ	4.4
	<10g/100g of protein	Couscous (precooked durum wheat semolina), cooked, unsalted	5.0
Nuts and seeds		Flaxseed	5.0
Vegetables and fruits, dried		Shiitake mushroom, dried	5.0
Vegetable oils		Rapeseed oil	3.6
		Sunflower oil	1.4
Starch		Potato starch	3.9
Tubers and garden peas		Sweet potato, cooked	2.7
Herbs, spices and salt		Thyme, dried	1.0

Table 2. PANDiet, AS, MS, SecDiet and probabilities of adequacies in the observed average diet, in modeled diets without meat and in modeled diets where meat was substituted by the optimized meat substitute

	Observed initial diet	Modeled diet without meat		Modeled diet with the optimized meat substitute	
		With energy adjustment [a]	Without energy adjustment	With energy adjustment [a]	Without energy adjustment
		Difference from observed initial diet			
PANDiet score (0-100)	73.68	**-2.53[b]**	**-2.50**	**+5.68**	**+5.48**
Adequacy Sub-score (AS) (0-100)	78.55	**-2.36**	**-7.91**	**+6.06**	**+6.43**
Probabilities of adequacy for AS components (0-1)					
Protein	1.00	0.00	0.00	0.00	0.00
LA	0.50	**-0.07**	**-0.07**	**+0.38**	**+0.38**
ALA	0.00	**0.00**	**0.00**	**+0.88**	**+0.87**
DHA	0.25	+0.07	-0.06	-0.05	-0.03
EPA+DHA	0.09	+0.04	-0.03	-0.02	-0.02
Fiber	0.36	**+0.17**	**-0.01**	**+0.63**	**+0.63**
Vitamin A	0.96	+0.01	-0.07	-0.02	-0.01
Thiamine	1.00	0.00	0.00	0.00	0.00
Riboflavin	1.00	0.00	-0.03	-0.01	0.00
Niacin	1.00	0.00	0.00	0.00	0.00
Pantothenic acid	0.99	-0.01	-0.03	+0.01	+0.01
Vitamin B-6	0.98	**-0.19**	**-0.42**	**-0.05**	**-0.04**
Folate	0.89	**+0.05**	**-0.04**	**+0.08**	**+0.08**
Vitamin B-12	1.00	**-0.16**	**-0.31**	**-0.33**	**-0.31**
Vitamin C	0.50	**+0.21**	**-0.04**	**+0.34**	**+0.36**
Vitamin D	0.00	0.00	0.00	0.00	0.00
Vitamin E	0.99	0.00	0.00	+0.01	+0.01
Iodine	0.98	+0.01	-0.01	0.00	0.00
Magnesium	0.99	0.00	-0.01	+0.01	+0.01
Phosphorus	1.00	0.00	0.00	0.00	0.00
Potassium	0.84	**-0.02**	**-0.15**	**+0.04**	**+0.05**
Selenium	1.00	0.00	0.00	0.00	0.00
Zinc	0.46	**-0.42**	**-0.44**	**-0.30**	**-0.30**
Copper	0.99	0.00	-0.01	+0.01	+0.01
Manganese	0.99	+0.01	0.00	+0.01	+0.01
Calcium	0.97	0.02	-0.01	+0.02	+0.02
Iron	0.85	**-0.29**	**-0.35**	**-0.08**	**-0.08**
Moderation Sub-score (MS) (0-100)	68.80	**-2.71**	**+2.91**	**+5.30**	**+4.53**
Probabilities of adequacy for MS components (0-1)					
Carbohydrates	1.00	0.00	0.00	0.00	0.00
Protein	1.00	0.00	0.00	0.00	0.00
Total fat	1.00	0.00	0.00	0.00	0.00
SFA	0.08	**+0.04**	**+0.04**	**+0.19**	**+0.19**
Sodium	0.38	**-0.04**	**+0.13**	**+0.15**	**+0.12**
Sugars without lactose	0.66	-0.16	+0.01	-0.02	-0.04
SecDiet (0-1)	1.00	-0.01	-0.01	0.00	0.00
Probabilities of adequacy of the SecDiet (0-1)					
Vitamin A	1.00	0.00	0.00	0.00	0.00
Thiamine	1.00	0.00	0.00	0.00	0.00
Riboflavin	1.00	0.00	0.00	0.00	0.00
Niacin	1.00	0.00	0.00	0.00	0.00
Folate	1.00	0.00	0.00	0.00	0.00
Vitamin B-12	1.00	0.00	0.00	0.00	0.00
Vitamin C	1.00	0.00	0.00	0.00	0.00
Iodine	1.00	0.00	0.00	0.00	0.00
Selenium	1.00	0.00	0.00	0.00	0.00
Zinc	1.00	0.00	0.00	0.00	0.00
Calcium	1.00	0.00	0.00	0.00	0.00
Iron	0.99	**-0.03**	**-0.05**	**-0.01**	**0.00**

[a] Energy adjustment was done by adjusting the quantity consumed of other food items in order to keep the same total energy intake as the observed initial diet.

[b] Values are differences between the modeled diet and the observed initial diet. Values in bold are those most affected by the removal and/or replacement of meat.

Table 3. Dual values associated with active technological constraints [a]

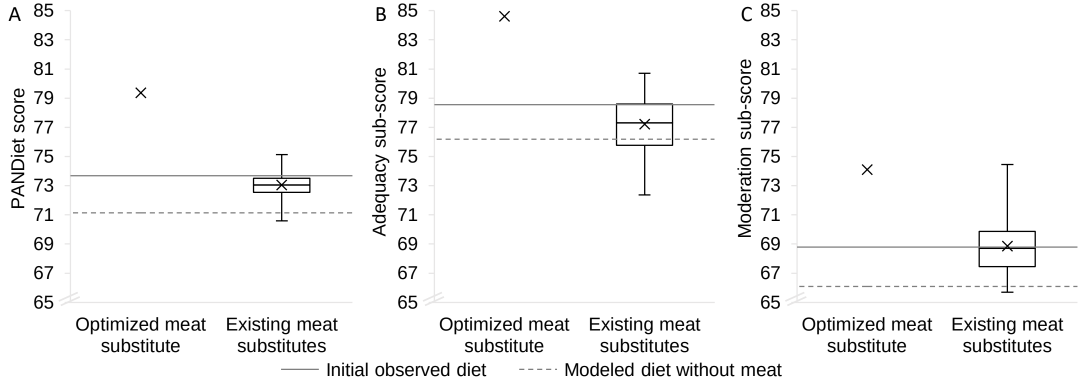
Constraint	Bounds of the constraint	Binding bound	Dual value
Herbs, spices and salt (group)	0-1%	Upper bound	2.4E-01
Oil-rich foods (group)	5-10%	Upper bound	1.6E-01
Nuts and seeds (sub-group)	0.5-5%	Upper bound	1.0E-01
Fragmented cereals, >10g/100g of protein (sub-group)	0-10%	Upper bound	4.6E-02
Vegetables and fruits, dried (sub-group)	0.5-5%	Upper bound	2.7E-02
Whole & fragmented cereals, <10g/100g of protein (sub-group)	5-15%	Lower bound	-2.1E-02
Cereals (group)	5-15%	Upper bound	1.5E-02
Vegetables and fruits (group)	5-20%	Upper bound	1.3E-02
Water content	50-65%	Lower bound	-4.7E-03

[a] Dual values represent the potential PANDiet gain for a relaxation by one unit of the binding bound of the constraint, i.e., for an absolute increase (decrease) of 1% in the upper (lower) binding bound of the constraint. Active constraints have a positive (negative) value if the upper (lower) bound is binding. Dual values of constraints not presented in this table are equal to zero.

Table 4. Alternative compositions of the meat substitute when one ingredient of the optimized composition is removed and impacts on the PANDiet, AS and MS scores and on the dual values of the constraints

			Alternative composition when discarding an ingredient constituting the initial composition, by discarded ingredient [a, b]														
		Initial compo-sition	Navy bean	Chick pea	Yellow sweet pepper	All sweet peppers[c]	Dried shiitake	Dried mushrooms[d]	Wheat bran	Wheat germ	Couscous	Rapeseed oil	Sunflower oil	Flaxseed	Sweet potato	Potato starch	Thyme
Pulses	Navy bean, cooked	41.59		47.40	32.36	31.57	21.62	28.34	52.50	25.16	22.53	47.27	18.24	32.99	39.81	40.43	48.84
	Chick pea, cooked	5.77	32.06		12.64	14.38	25.43	18.34	-	21.56	24.01	-	29.43	13.51	9.99	7.48	-
	Lentil, blond, cooked	-	14.93	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Vegetables, cooked	Pepper, sweet, yellow, cooked	15.00	15.00	15.00			15.00	19.50	13.40	15.00	15.00	15.00	15.00	15.00	15.00	15.00	15.00
	Sweet pepper, green, cooked	-	-	-	15.00		-	-	-	-	-	-	-	-	-	-	-
	Brussel sprouts, cooked	-	-	-	-	15.00	-	-	-	-	-	-	-	-	-	-	-
	Olives, black	-	-	-	-	-	-	-	1.60	-	-	-	-	-	-	-	-
Vegetables and fruits, dried	Shiitake mushroom, dried	5.00	5.00	5.00	3.27	2.38			4.39	5.00	5.00	5.00	5.00	5.00	5.00	5.00	3.52
	Chinese black mushroom, dried	-	-	-	1.73	2.62	5.00		0.61	-	-	-	-	-	-	-	1.48
	Chestnut, cooked	-	-	-	-	-	-	0.50	-	-	-	-	-	-	-	-	-
Fragmented cereals >10g/100g of protein	Wheat bran	5.63	10.00	4.53	10.00	10.00	10.00	10.00		10.00	10.00	7.30	10.00	10.00	5.92	6.33	10.00
	Wheat germ	4.37	-	5.47	-	-	-	-	10.00		-	2.70	-	-	4.08	3.67	-
Whole & fragmented cereals, <10g/100g of protein	Couscous, cooked, unsalted	5.00	0.60	5.00	5.00	5.00	5.00	5.00	5.00	5.00		5.00	5.00	5.00	5.00	5.00	5.00
	Durum wheat, cooked, unsalted	-	4.40	-	-	-	-	-	-	-	5.00	-	-	-	-	-	-
Vegetable oils	Rapeseed oil	3.60	4.33	3.47	3.64	3.74	3.95	3.80	3.83	3.87	3.94		4.63	3.57	3.70	3.64	3.34
	Sunflower oil	1.40	0.67	1.53	1.36	1.26	1.05	1.20	1.17	1.13	1.06	-		1.43	1.30	1.36	1.66
	Combined oil	-	-	-	-	-	-	-	-	-	-	5.00	0.37	-	-	-	-
Nuts and seeds	Flaxseed	5.00	5.00	5.00	1.74	3.67	2.31	3.48	4.67	2.68	3.23	-	5.00		5.00	5.00	5.00
	Seeds, chia, dried	-	-	-	3.26	1.33	2.69	1.52	-	2.32	1.77	5.00	-	5.00	-	-	-
	Fenugreek, seed	-	-	-	-	-	-	-	0.33	-	-	-	-	-	-	-	-
Tubers and garden peas	Sweet potato, cooked	2.74	2.01	2.80	4.15	4.49	3.09	2.32	1.00	2.95	2.96	2.84	2.16	3.21		2.49	1.70
	Yam or Indian potato, cooked	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00	-	-
Starch	Potato starch	3.89	5.00	3.80	4.84	3.56	3.85	5.00	0.50	4.33	4.50	3.89	4.17	4.29	3.20		3.46
	Maize/corn starch	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3.60	-
Herbs, spices and salt	Thyme, dried	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
	Basil, dried	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1.00
			Dual of the constraint: proportion (discarded ingredient)=0														
			0.00	0.00	0.02	0.02	0.01	0.06	0.05	0.00	0.00	0.12	0.05	0.00	0.01	0.00	0.15
			Δ with the initial optimized meat substitute														
		Δ(PANDiet)	-0.06	0.00	-0.23	-0.28	-0.04	-0.20	-0.17	0.00	-0.01	-0.28	-0.03	0.00	-0.02	-0.01	-0.07
		Δ(AS)	-0.38	+0.04	-0.62	-0.79	-0.20	-0.27	-0.05	-0.09	-0.14	-0.36	-0.26	-0.01	-0.11	-0.05	-0.24
		Δ(MS)	+0.26	-0.04	+0.16	+0.24	+0.12	-0.12	-0.29	+0.09	+0.13	-0.19	+0.20	0.00	+0.07	+0.04	+0.11

[a] The crossed box indicates that the constraint of the proportion equal to zero was applied to this ingredient.
[b] Names of ingredients have been shortened for more clarity. The full names of ingredients can be found in Supplementary Table S2.
[c] Pepper, sweet, yellow, pan-fried, without fat; Sweet pepper, green, cooked; Sweet pepper, red, cooked.
[d] Shiitake mushroom, dried; Chinese black mushroom, dried



A
PANDiet score
85
83
81
79
77
75
73
71
69
67
65
Optimized meat substitute
Existing meat substitutes
B
Adequacy sub-score
C
Moderation sub-score
Initial observed diet
Modeled diet without meat

European Journal of Nutrition

The potential effects of meat substitution on diet quality could be high if meat substitutes are optimized for nutritional composition – a modeling study in French adults (INCA3).

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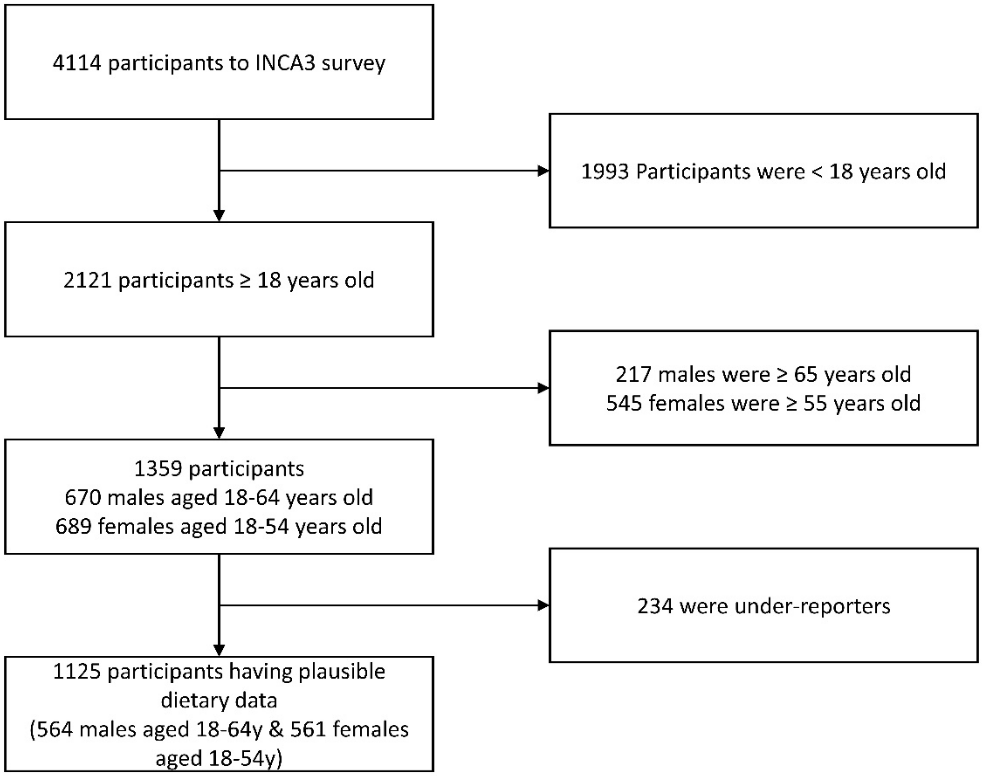


Supplementary Figure S1 Flow chart explaining the sampling of French participants from the third Individual and National Study on Food Consumption Survey (INCA3) for the present study.

Supplementary Table S1 Meat food items identified in INCA3 diets as substitutable by a plant-based meat substitute in modeled scenarios.

Meat food items (n=166)		
Beef, lamb and horse meat food items (n=93)		
Beef on skewer	Beef, tournedos, Rossini-style	Meat balls, pork and beef, (Swedish-style), prepacked
Beef stew with carrots	Brain, lamb, cooked	Meat, cooked (average)
Beef tongue with Madeira wine sauce, prepacked	Burgundy-style beef stew	Merguez sausage, beef and mutton, cooked
Beef, bolar-blade, grilled/pan-fried	Caen-style tripe	Mixed meat on skewer
Beef, braised	Caen-style tripe, prepacked	Ox muzzle
Beef, cheek, braised or boiled	Calf, head, boiled/cooked in water	Pheasant, meat, roasted/baked
Beef, chuck, braised or boiled	Feathered game, meat, cooked (average)	Provencal-type tripe (with tomato)
Beef, flank steak, grilled/pan-fried	Heart, beef, cooked	Red meat, cooked (average)
Beef, ground, cooked (average)	Horse, meat, raw	Sauté of lamb w curry, prepacked
Beef, hanger steak, grilled	Horse, meat, roasted/baked	Stewed lamb garnished with potatoes and other vegetables
Beef, knuckle, boiled/cooked in water	Horse, rib steak, grilled/pan-fried	Sweetbread, calf, sautéed/pan-fried
Beef, meat balls, cooked	Horse, topside, grilled/pan-fried	Tongue, beef, cooked
Beef, minced steak, 10% fat, cooked	Kidney, beef, cooked	Veal fillet, roasted/baked
Beef, minced steak, 15% fat, cooked	Kidney, lamb, braised	Veal olive or veal paupiette
Beef, minced steak, 15% fat, raw	Kidney, veal, sautéed/pan-fried	Veal stew in white sauce
Beef, minced steak, 20% fat, cooked	Lamb on skewer	Veal, breast, raw
Beef, minced steak, 20% fat, raw	Lamb, chop fillet, grilled/pan-fried	Veal, chop, grilled/pan-fried
Beef, minced steak, 5% fat, cooked	Lamb, chop, grilled (average)	Veal, escalope, cooked
Beef, minced steak, 5% fat, raw	Lamb, leg, braised	Veal, knuckle or shank, braised or boiled
Beef, oxtail, boiled/cooked in water	Lamb, leg, grilled/pan-fried	Veal, loin, sautéed/pan-fried
Beef, rib steak, lean, grilled/pan-fried	Lamb, leg, roasted/baked	Veal, meat, cooked (average)
Beef, roast beef, roasted/baked	Lamb, meat, cooked (average)	Veal, minced steak, 15% fat, raw
Beef, round, cooked	Lamb, neck, braised or boiled	Veal, neck, braised or boiled
Beef, rump steak, grilled	Lamb, saddle, grilled/pan-fried	Veal, roast, cooked
Beef, short ribs, braised	Lamb, saddle, lean, roasted/baked	Veal, shoulder, braised/boiled
Beef, sirloin steak, grilled/pan-fried	Lamb, shoulder, lean, roasted/baked	Veal, shoulder, grilled/pan-fried
Beef, sirloin steak, roasted/baked	Lamb, shoulder, roasted/baked	Veal, tenderloin, grilled/pan-fried
Beef, steak or beef steak, grilled	Liver, calf, cooked	Veal, tenderloin, roasted
Beef, steak or beef steak, raw	Liver, lamb, cooked	Venison (hart), roasted/baked
Beef, stewing meat, cooked	Liver, young cow, cooked	Venison (roebuck), roasted/baked
Beef, thin flank, grilled/pan-fried	Meat balls, beef and lamb (kefta type), prepacked, raw	Wild boar, roasted/baked
Poultry meat food items (n=39)		
Capon, meat and skin, roasted/baked	Heart, chicken, cooked	
Chicken leg, meat, boiled/cooked in water	Liver, chicken, cooked	
Chicken leg, meat, roasted/baked	Milanese-style turkey escalope or breaded veal escalope	
Chicken with curry and coconut milk sauce	Pigeon, meat, roasted/baked	
Chicken, Basque style, prepacked	Poultry on skewer	
Chicken, breast, without skin, cooked	Poultry paupiette	
Chicken, leg, meat and skin, boiled/cooked in water	Poultry sausage	
Chicken, leg, meat and skin, roasted/baked	Poultry sausage, delicatessen style	
Chicken, marinated wing, roasted/baked	Poultry, cooked (average)	
Chicken, meat and skin, roasted/baked	Preserved duck	
Chicken, wing, meat and skin, roasted/baked	Preserved gizzards, duck, canned	
Cockerel in red wine sauce	Quail, meat and skin, cooked	
Duck breast fillet, smoked	Rabbit with mustard sauce, prepacked	
Duck with sauce (green pepper sauce, hunter-style sauce, etc.), prepacked	Rabbit, meat, braised	
Duck, breast, cooked in pan	Rabbit, meat, cooked	
Duck, breast, Rossini-style	Rabbit, wild, meat, cooked	
Duck, meat and skin, roasted/baked	Turkey, escalope, sautéed/pan-fried, with salt	
Duck, meat, roasted/baked	Turkey, leg, meat only, raw	
Guinea fowl, raw	Turkey, meat, roasted/baked	
	white meat, cooked (average)	
Pork meat food items (n=34)		
Black or white pudding (blood sausage), sautéed (average)	Pork with caramel sauce, prepacked	
Black pudding (blood sausage), sautéed/pan-fried	Pork, belly, raw	
Chipolata sausage, cooked	Pork, chop, grilled	
Chitterling sausage, raw	Pork, knuckle or shank, raw	
Devilled pork shoulder in mustard sauce, prepacked	Pork, loin, roasted/baked	
Frankfurter sausage	Pork, meat, cooked (average)	
Kidney, pork, cooked	Pork, rack, cooked	
Liver sausage	Pork, roast, cooked	
Liver, pork, cooked	Pork, round steak, cooked	
Montbeliard sausage	Pork, shoulder, cooked	
Morteau sausage	Pork, spare-ribs, braised	
Morteau sausage, boiled/cooked in water	Sausage (average)	
Pork belly, smoked, raw	Saveloy or cervelat	
Pork filet mignon, cooked	Smoked Alsatian sausage or Landjäger	
Pork loin, cooked	Strasbourg sausage	
Pork tenderloin roast, cooked	Toulouse sausage, cooked	
Pork trotters salt-cured		

Supplementary Table S2 Reference values of the PANDiet scoring system version 3.2 [1, 2].

PANDiet score
Average of Adequacy and Moderation sub-scores

Adequacy sub-score		
Nutrient	**Reference value (/day)[3]**	**Variability**
Protein	0.66 or 0.8 g/kg bw	12.5%
LA	3.08% EIEA	15%
ALA	0.769% EIEA	15%
DHA	0.192 g	15%
EPA + DHA	0.385 g	15%
Fiber	23 g	15%
Vitamin A	580 or 490 µg	15%
Thiamin	0.3 mg/1000 kcal	20%
Riboflavin	1.3 mg	10%
Niacin	5.44 mg NE/1000kcal	10%
Pantothenic acid	3.33 or 2.78 mg	40%
Vitamin B-6	1.5 or 1.3 mg	10%
Folate	250 µg	15%
Vitamin B-12	3.33 µg	10%
Vitamin C	90 mg	10%
Vitamin D	10 µg	25%
Vitamin E	5.26 or 4.74 mg	45%
Calcium	860 (<= 24 y.o) or 750 mg (>24 y.o.)	15% or 13%
Copper	0.86 or 0.68 mg	60%
Iodine	107 µg	20%
Bioavailable iron [a]	0.95 mg	40%
Magnesium	224 or 176 mg	35%
Manganese	1.89 or 1.56 mg	40%
Phosphorus [b]	Calcium (mmol) / 1.65	7.5% + CV Calcium (mg)
Potassium	2692 mg	15%
Selenium	54 µg	15%
Bioavailable zinc [c]	0.642 + 0.038 x bw	10%

Moderation sub-score		
Nutrient	**Reference value (/day)[3]**	**Variability**
Protein	2.2 g/kg bw	12.5%
Total fat	44% EIEA	5%
SFA	12% EIEA	15%
Carbohydrates	60.5% EIEA	5%
Sugars	100 g	15%
Sodium	3200 mg	15%

Tolerable Upper Intake Limits [d]	
Vitamin A	3000 µg
Niacin	900 mg
Vitamin B-6	25 mg
Vitamin D	100 µg
Calcium	2500 mg
Copper	5 mg
Iodine	600 µg
Selenium	300 µg
Zinc	25 mg

[a] See supplemental method 1 in de Gavelle et al. [4] for the calculation of bioavailable iron and requirements for females. Iron requirements for females were adapted to consider females with normal and high requirements [3].
[b] See supplemental method 1 in de Gavelle et al. [4]
[c] See Supplemental file in Salomé et al. [2] for the calculation of bioavailable zinc.
[d] Penalty are usually applied when intakes of some nutrients are higher than tolerable upper intake limits in the calculation of the PANDiet [1]. Here, when calculating the PANDiet at the average individual level, penalties were not taken into account but tolerable upper intake limits where defined as upper bound constraints in the optimization procedure.
ALA, alpha-linolenic acid; bw, body weight; CV, coefficient of variation; DHA, docosahexaenoic acid; EIEA, energy intake excluding alcohol; EPA, eicosapentaenoic acid; LA, linoleic acid; NE, niacin equivalent; SFA, saturated fatty acids.

Supplementary Table S3 Nutrients included as components in the SecDiet score and associated deficiency and threshold values.

Nutrients were included in the SecDiet score if clinical signs of deficiency might appear because of insufficient intakes. The threshold value (DT) was defined as the minimal intake below which there is a risk of onset of a deficiency. The reference value was used to calculate the probability of adequacy of the average deficiency threshold (aDT), which corresponds to the intake at which 50% of the population is at risk of nutritional deficiency. The complete construction of the score has been fully described elsewhere [5].

Nutrient	Deficiency	Threshold (DT)	CV	50% of risk (aDT)
Vitamin A[6]	Xerophtalmia	300 µg RE or 270 µg RE	15%	231 µg RE or 208 µg RE
Thiamin[7]	Beriberi	0.18 mg/1000kcal	20%	0.13 mg/1000kcal
Riboflavin[7]	Ariboflavinosis	1.0 mg	10%	0.83 mg
Niacin[7]	Pellagra	4.35 mg NE/1000kcal	10%	3.63 NE/1000kcal
Folate[7]	Megaloblastic anemia	175 µg	15%	135 µg
Vitamin B-12[8]	Megaloblastic anemia	1 µg	15%	0.77 µg
Vitamin C[6]	Scurvy	10 mg	10%	8.3 mg
Iodine [a] [7]	Goiter	129 µg	20%	92.4 µg
Selenium[9]	Keshan disease	21 µg or 16 µg	15%	16.2 µg or 12.3 µg
Bioavailable iron [a] [10]	Anemia	0.83 or 1.08 mg	40%	0.45 or 0.55 mg
Bioavailable zinc[11]	Zinc deficiency	1.6 mg or 1.3 mg	15%	1.23mg or 1.0 mg
Calcium[12–14]	Fracture risk (long-term)	500 mg	15%	385 mg

DT, deficiency threshold; CV, coefficient of variation of the individual threshold; aDT, average deficiency threshold; RE, retinol equivalent; NE, niacin equivalent.

[a] These thresholds were calibrated in order to match the prevalence of inadequacy with the actual prevalence of goiter (10%)[15] and iron-deficiency anemia in the population (0.2% in males, 3.9% in females)[16]. The prevalence of inadequacy of the study population was estimated using the Nusser method [17], to extract intra-individual variations and using a probabilistic approach [18].

Supplementary Table S4 Classification of ingredients available for composition of the meat substitute. Ingredients were categorized in groups and sub-groups according to their nutritional or technological properties.

Pulses	Vegetables and fruits			Herbs, spices and salt
	Vegetables, cooked		Vegetables and fruits, dried	
Source of protein and fiber Texturizing and emulsifying ingredients	*Source of fiber, vitamins and minerals*			*Taste enhancer*
Broad bean, boiled/cooked in water	Artichoke, globe, cooked	Parsnip, cooked	Apricot, pitted, dried	Basil, dried
Chick pea, boiled/cooked in water	Beetroot, cooked	Pepper, sweet, yellow, pan-fried, without fat	Chestnut, boiled/cooked in water	Black pepper, powder
Navy bean, boiled/cooked in water	Broccoli, cooked	Pumpkin (cucurbita moschata), pulp, cooked	Chinese black mushroom, dried	Cardamom, powder
Flageolet bean, boiled/cooked in water	Brussels sprout, cooked	Pumpkin, cooked	Cranberry, dried, with sugar	Cloves
Flageolet bean, green, boiled/cooked in water	Butter bean or yellow bean, boiled/cooked in water	Red cabbage, boiled/cooked in water	Date, pulp and peel, dried	Coriander, seed
Haricot bean, boiled/cooked in water	Button mushroom or cultivated mushroom, boiled/cooked in water	Red kuri squash, pulp, boiled/cooked in water	Fig, dried	Cumin, seed
Lentil, blond, boiled/cooked in water	Carrot, cooked	Romanesco cauliflower or romanesco broccoli, cooked	Onion, dried	Curry, powder
Lentil, green, boiled/cooked in water	Cauliflower, cooked	Rutabaga or Swede, cooked	Prune	Garlic, powder, dried
Lentil, pink or red, boiled/cooked in water	Celeriac, cooked	Salsify, cooked	Raisin	Ginger, powder
Mung bean, boiled/cooked in water	Celery stalk, cooked	Shallot, cooked	Shiitake mushroom, dried	Laver (Porphyra sp.), dried or dehydrated
Red kidney bean, boiled/cooked in water	Chinese cabbage (nappa cabbage or bok choy), cooked	Shiitake mushroom, cooked	Tomato, dried	Mint, dried
Split pea, boiled/cooked in water	Courgette or zucchini, pulp and peel, cooked	Snow pea, cooked		Nutmeg
	Eggplant, cooked	Spinach, cooked		Oregano, dried
	Fennel, boiled/cooked in water	Squash, butternut, peeled, cooked		Paprika
	French bean, cooked	Sweet corn, canned, drained		Parsley, dried
	Green cabbage, cooked	Sweet pepper, green, cooked		Provence herbs, dried
	Kohlrabi, boiled/cooked in water	Sweet pepper, red, cooked		Rosemary, dried
	Leek, cooked	Swiss chard, cooked		Saffron
	Okra, cooked, without salt	Tomato paste, concentrated, canned		Sage, dried
	Olives, black, in brine	Tomato, peeled, canned, drained		Salt, white (sea, igneous or rock), iodine added, no other enrichment
	Olives, green, in brine	Turnip, cooked		Thyme, dried
	Onion, cooked	White cabbage, boiled/cooked in water		Turmeric, powder

Cereals				
Flours, >10g/100g of protein	Flours, <10g/100g of protein	Fragmented cereals, >10g/100g of protein	Whole cereals	Fragmented cereals, <10g/100g of protein
Source of carbohydrates, protein and fiber Plasto-elastic properties		*Source of carbohydrates, protein and fiber*	*Source of carbohydrates, protein and fiber Contributors of a persistent texture in mouth*	
Buckwheat flour	Barley flour	Breadcrumbs	Durum wheat pre-cooked, whole grain, cooked, unsalted	Couscous (precooked durum wheat semolina), cooked, unsalted
Millet flour	Chestnut flour	Oat bran	Millet, cooked, unsalted	Frik (crushed immature durum wheat), cooked, unsalted
Spelt flour	Maize/corn flour	Oatmeal flakes	Quinoa, boiled/cooked in water, unsalted	Pearled barley, boiled/cooked in water, unsalted
Wheat flour, type 150	Rice flour	Wheat bran	Rice, brown, cooked, unsalted	Polenta or maize semolina, cooked, unsalted
	Rye flour, type 130	Wheat germ	Rice, cooked, unsalted	Semolina, cooked
	Wheat flour, type 110		Rice, red, cooked, unsalted	Wheat bulgur, cooked, unsalted
	Wheat flour, type 55 (for bread)		Wild rice, cooked, unsalted	

Supplementary Table S4 (continued) Classification of ingredients available for composition of the meat substitute. Ingredients were categorized in groups and sub-groups according to their nutritional or technological properties.

Oil-rich foods			Tubers and starch	
Vegetable oils	**Nuts/seeds paste**	**Nuts and seeds**	**Tubers and garden peas**	**Starch**
Source of lipids *Contributors of a soft texture*		*Source of lipids* *Contributors of a crunchy texture*	*Source of carbohydrates* *Thickening and binding ingredients*	
Avocado oil Combined oil (blended vegetable oils) Grapeseed oil Hazelnut oil Linseed oil Olive oil, extra virgin Peanut oil Rapeseed oil Sunflower oil Walnut oil	Peanut butter or peanut paste Tahini (sesame paste)	Almond, (with peel) Almond, peeled, unpeeled or blanched Brazil nut Cashew nut, grilled, unsalted Coconut, kernel, dried Cucurbitacea, seed Fennel, seed Fenugreek, seed Flaxseed Hazelnut Macadamia nut Peanut Pecan nut Pine nuts Pistachio nut, grilled Poppy, seed Seeds, chia, dried Sesame seed Sunflower seed Walnut, dried, husked	Cassava or manioc, roots, cooked Garden peas, cooked Jerusalem artichoke, cooked Potato, boiled/cooked in water Sweet potato, cooked Taro, tuber, cooked Yam or Indian potato, peeled, boiled/cooked in water	Maize/corn starch Potato starch

Supplementary Table S5 Technological constraints applied during optimization of the meat substitute: ingredient categories and proportions.

Ingredient groups and sub-groups		Proportion range	
Pulses		40-60%	
Vegetables and fruits	Vegetables, cooked	5-20%	5-20%
	Vegetables and fruits, dried		0.5-5%
Cereals	Flours, >10g/100g of protein	5-15%	0-5%
	Flours, <10g/100g of protein		0-10%
	Fragmented cereals, >10g/100g of protein		0-10%
	Whole & fragmented cereals, <10g/100g of protein		5-15%
Oil-rich foods	Vegetable oils	5-10%	5-10%
	Nuts and seeds		0.5-5%
	Nuts/seeds paste		no constraint
Tubers and starch	Tubers and garden peas	1-10%	1-10%
	Starch		0.5-5%
Herbs, spices and salt		0-1%	

Supplementary Table S6 List of existing meat substitutes used for modeled diets.

Substitute name	Data-base of origin[1]
Tofu, plain	[19]
Tempeh	[19]
Soy protein, textured, rehydrated	[19]
Soy burger or vegetable escalope	[20]
Cereal burger with cheese (without soybean)	[19]
Cereal burger with vegetables (without soybean)	[19]
Plant-based burger or steak from wheat (seitan) and vegetables	[19]
Plant-based burger or steak from lentil, soybean and vegetables	[19]
Plant-based burger from red kidney bean	[21]
Plant-based burger from lentil	[21]
Plant-based burger or steak from soybean and cheese	[19]
Plant-based burger or steak from soybean and vegetables	[19]
Plant-based burger or steak from soybean, cheese and vegetables	[19]
Plant-based burger from soybean	[21]
Plant-based burger from soybean with curry #1	[21]
Plant-based burger from soybean with curry #2	[21]
Plant-based burger from soybean with tomatoes and sweet pepper #1	[21]
Plant-based burger from soybean with tomatoes and sweet pepper #2	[21]
Plant-based burger from soybean with herbs #1	[21]
Plant-based burger from soybean with herbs #2	[21]
Plant-based burger from soybean with vegetables #1	[21]
Plant-based burger from soybean with vegetables #2	[21]
Plant-based burger from soybean with tomatoes and basil #1	[21]
Plant-based burger from soybean with tomatoes and basil #2	[21]
Plant-based burger or steak from wheat and soybean (vegan)	[19]
Plant-based burger or steak from wheat and soybean (not vegan)	[19]
Plant-based burger from cereals and soybean	[21]
Plant-based sausage with wheat or seitan	[19]
Plant-based sausage with wheat	[21]
Plant-based sausage with tofu (vegan)	[19]
Plant-based sausage with tofu (not vegan)	[19]
Plant-based sausage with tofu	[21]
Falafel	[20]
Falafel, prepacked	[19]
Soy and wheat burger or bite (vegan)	[19]
Soy and wheat burger or bite (not vegan)	[19]
Plant-based ball with wheat and/or soybean	[19]
Wheat-based nuggets (wo soybean)	[19]
Soybean and wheat-based nuggets (not vegan)	[19]
Soybean and wheat-based nuggets (vegan)	[19]
Schnitzel, soybean and wheat-based (not vegan)	[19]
Schnitzel, soybean and wheat-based (vegan)	[19]
Schnitzel, soybean, wheat and cheese-based, cordon bleu-style	[19]

[1]Three nutritional composition databases were used: CIQUAL French composition table version 2016 [20], version 2020 [19] and the NutriNet-Santé Study Food composition database [21]

Supplementary Table S7 Nutritional composition per 100g of the optimized meat substitute and contribution of each ingredient to its nutrient content.

	Weight (g)	Energy (kcal)	Water (g)	Protein (g)	Carbo-hydrate (g)	Fat (g)	Sugars (g)	Fiber (g)	SFA (g)	LA (g)	ALA (g)	Calcium (mg)	Copper (mg)	Iron (mg)	Iodine (µg)	Magne-sium (g)
Nutrient content (per 100g)	**100**	**211**	**50.0**	**8.5**	**19.4**	**8.1**	**2.3**	**13.0**	**0.9**	**2.3**	**1.2**	**75.3**	**0.6**	**4.4**	**7.7**	**97.1**
Contribution of each ingredient to nutrient content (%)																
Navy bean, boiled/cooked in water	41.6[a]	**25.8**	**51.0**	**46.9**	**29.3**	2.6	**20.0**	**50.6**	5.3	2.2	**5.4**	**39.8**	**19.0**	**25.7**	**53.8**	**22.7**
Pepper, sweet, yellow, pan-fried, without fat	15.0	2.5	**27.2**	1.8	4.1	1.1	**32.1**	2.5	3.3	1.3	1.2	1.5	1.6	0.8	**19.4**	1.7
Chick pea, boiled/cooked in water	5.8	4.0	**7.2**	5.6	5.3	2.1	0.8	3.6	3.1	3.8	0.4	5.5	2.4	1.7	**7.5**	2.6
Wheat bran	5.6	7.4	1.0	10.1	6.8	3.0	6.0	**18.2**	5.5	5.8	0.7	5.5	10.4	**19.0**	1.7	**31.6**
Flaxseed	5.0	**11.6**	0.6	**11.8**	1.7	**22.5**	3.4	**10.5**	**18.5**	9.5	**67.5**	**15.1**	**10.7**	11.7	0.3	**19.2**
Couscous (precooked durum wheat semolina), cooked, unsalted	5.0	3.7	6.1	2.7	8.0	0.6	3.5	0.9	1.5	0.9	0.1	1.0	1.4	0.6	6.5	1.0
Shiitake mushroom, dried	5.0	7.5	0.9	5.6	**16.5**	0.6	4.8	4.4	1.3	0.3	0.0	0.7	**45.5**	2.0	0.0	6.8
Wheat germ	4.4	7.6	0.7	**13.9**	7.9	5.1	**19.1**	5.5	9.3	**9.8**	2.3	3.1	6.0	8.9	5.7	11.3
Potato starch	3.9	6.4	1.0	0.0	**17.3**	0.1	2.2	0.2	0.2	0.1	0.2	1.4	0.7	0.7	0.2	0.2
Rapeseed oil	3.6	**15.3**	0.0	0.0	0.0	**44.2**	0.0	0.0	**30.5**	**31.0**	**22.0**	0.1	0.0	0.0	0.0	0.0
Sweet potato, cooked	2.7	0.8	4.3	0.5	1.7	0.1	7.3	0.6	0.1	0.0	0.0	1.2	0.6	0.4	1.1	0.6
Sunflower oil	1.4	6.0	0.0	0.0	0.0	**17.1**	0.0	0.0	**18.1**	**34.9**	0.1	0.0	0.0	0.0	1.8	0.0
Thyme, dried	1.0	1.3	0.2	1.1	1.4	0.9	0.7	2.9	3.2	0.4	0.3	**25.1**	1.5	**28.4**	1.9	2.3

[a] Values are percentages calculated from the quantity of nutrient provided by the ingredient in the optimized meat substitute divided by the total nutrient content in the optimized meat substitute. Bold values represent the 3 main ingredients contributing to the content of each nutrient (e.g. navy bean, rapeseed oil and flaxseed are the three main contributors of energy in the optimized meat substitute). Vitamin B12 content is not presented as the optimized meat substitute is entirely plant-based and did not contain any vitamin B12.
ALA, alpha-linolenic acid; LA, linoleic acid.

Supplementary Table S7 (continued) Nutritional composition per 100g of the optimized meat substitute and contribution of each ingredient to its nutrient content.

	Manga-nese (g)	Phos-phorus (g)	Potas-sium (g)	Sele-nium (g)	Sodium (mg)	Zinc (mg)	Vitamin A (µg)	Thiamin (mg)	Ribo-flavin (mg)	Niacin (mg)	Panto-thenic acid (mg)	Vitamin B6 (mg)	Folate (µg)	Vitamin C (mg)	Vitamin D (µg)	Vitamin E (mg)
Nutrient content (per 100g)	**2.1**	**241**	**490**	**9.7**	**9.3**	**2.4**	**37.1**	**0.3**	**0.1**	**2.7**	**1.5**	**0.3**	**75.1**	**20.8**	**0.3**	**2.9**
Contribution of each ingredient to nutrient content (%)																
Navy bean, boiled/cooked in water	**11.7**	**31.1**	**40.8**	**42.7**	**40.1**	**20.7**	1.5	**26.9**	6.4	**13.3**	3.9	9.2	**39.5**	**3.2**	**19.9**	1.4
Pepper, sweet, yellow, pan-fried, without fat	0.6	1.4	6.7	**15.4**	4.0	0.9	**28.2**	1.7	5.4	3.1	1.6	12.3	**11.4**	**91.0**	0.0	11.1
Chick pea, boiled/cooked in water	2.4	3.4	2.0	5.9	6.7	2.6	0.2	1.3	1.2	0.4	0.5	1.8	6.5	0.1	**2.8**	2.4
Wheat bran	**35.8**	**24.1**	**14.5**	3.9	8.0	**17.5**	0.1	15.2	**20.4**	**45.1**	**8.6**	**25.7**	8.2	0.0	0.0	3.0
Flaxseed	5.9	12.4	6.5	**14.4**	**11.0**	12.6	0.0	**23.2**	**7.7**	5.7	3.3	10.7	6.2	0.1	0.0	0.5
Couscous (precooked durum wheat semolina), cooked, unsalted	0.7	1.5	1.1	5.1	1.3	1.2	0.2	1.2	0.2	0.4	1.1	7.3	0.8	0.1	0.0	0.1
Shiitake mushroom, dried	2.8	6.1	**15.6**	2.8	7.0	15.9	0.0	5.7	**49.0**	**26.2**	**73.2**	**16.5**	**10.8**	0.8	**74.5**	0.0
Wheat germ	**35.6**	**18.2**	8.8	4.5	3.4	**25.4**	0.2	**21.9**	4.7	2.7	**3.9**	**12.4**	8.3	0.1	2.2	**15.5**
Potato starch	0.2	0.6	0.3	0.2	1.6	0.3	0.0	0.1	0.2	0.2	2.5	0.1	4.2	0.0	0.0	0.0
Rapeseed oil	0.0	0.0	0.0	1.8	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**34.7**
Sweet potato, cooked	0.5	0.5	2.0	1.4	**9.3**	0.3	**64.6**	0.9	1.6	1.0	1.3	2.1	0.2	2.1	0.0	0.8
Sunflower oil	0.0	0.0	0.0	1.4	1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	**27.8**
Thyme, dried	3.8	0.8	1.7	0.5	5.9	2.6	**5.1**	1.9	3.1	1.8	0.0	1.9	3.6	**2.4**	0.0	2.6

Supplementary Table S8 PANDiet, AS, MS, SecDiet scores and probabilities of adequacies in the observed average diet, in modeled diets without meat and with the optimized meat substitute replacing meat in average male and female.

	Average female					Average male				
		Modeled diets					Modeled diets			
	Observed initial diet	Without meat		With optimized meat substitute		Observed initial diet	Without meat		With optimized meat substitute	
		Without E.A.[a]	With E.A	Without E.A.	With E.A		Without E.A.	With E.A	Without E.A.	With E.A
		Difference from observed initial diet					Difference from observed initial diet			
PANDiet score (0-100)	76.17	**-4.15**[b]	**-2.88**	**+5.25**	**+5.20**	71.35	**-0.88**	**-2.20**	**+5.71**	**+6.16**
PANDiet (Female F+)[c]	75.39	**-4.05**	**-2.83**	**+5.21**	**+5.16**					
Adequacy Sub-score (AS) (0-100)	75.09	**-10.63**	**-3.75**	**+6.72**	**+6.08**	82.31	**-5.24**	**-1.00**	**+6.15**	**+6.05**
AS (Female F+)[c]	73.54	**-10.43**	**-3.65**	**+6.64**	**+6.01**					
Probability of adequacy for AS components (0-1)										
Protein	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
LA	0.59	-0.06	-0.06	**+0.30**	**+0.31**	0.40	-0.08	-0.08	**+0.45**	**+0.46**
ALA	0.00	0.00	0.00	**+0.83**	**+0.84**	0.00	0.00	0.00	**+0.90**	**+0.91**
DHA	0.02	-0.01	+0.01	-0.01	-0.01	0.49	-0.12	+0.14	-0.05	-0.08
EPA+DHA	0.00	0.00	0.00	0.00	0.00	0.17	-0.06	+0.08	-0.03	-0.04
Fiber	0.15	-0.01	**+0.12**	**+0.83**	**+0.82**	0.56	-0.02	**+0.23**	**+0.44**	**+0.44**
Vitamin A	0.92	-0.08	+0.02	-0.01	-0.02	0.99	-0.05	0.00	-0.01	-0.02
Thiamine	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Riboflavin	1.00	-0.06	0.00	-0.01	-0.01	1.00	0.00	0.00	0.00	0.00
Niacin	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Pantothenic acid	0.99	-0.04	-0.01	+0.01	+0.01	1.00	-0.03	-0.01	0.00	0.00
Vitamin B-6	0.96	**-0.65**	**-0.35**	**-0.07**	**-0.10**	1.00	**-0.18**	-0.02	0.00	0.00
Folate	0.79	-0.07	+0.09	**+0.16**	**+0.15**	1.00	-0.01	0.00	0.00	0.00
Vitamin B-12	1.00	**-0.62**	**-0.31**	**-0.62**	**-0.66**	1.00	0.00	0.00	0.00	-0.01
Vitamin C	0.23	-0.02	**+0.24**	**+0.50**	**+0.47**	0.78	-0.05	**+0.18**	**+0.22**	**+0.22**
Vitamin D	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vitamin E	0.99	0.00	0.00	+0.01	+0.01	0.99	0.00	0.00	+0.01	+0.01
Iodine	0.96	-0.02	+0.02	+0.01	0.00	1.00	0.00	0.00	0.00	0.00
Magnesium	0.99	-0.01	0.00	+0.01	+0.01	0.99	-0.02	0.00	+0.01	+0.01
Phosphorus	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Potassium	0.69	**-0.25**	-0.04	**+0.10**	**+0.08**	0.99	-0.06	0.00	0.00	0.00
Selenium	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Zinc	0.51	**-0.48**	**-0.45**	**-0.29**	**-0.29**	0.41	**-0.40**	**-0.39**	**-0.30**	**-0.31**
Copper	0.99	-0.01	0.00	+0.01	+0.01	0.99	-0.01	0.00	+0.01	+0.01
Manganese	0.99	0.00	+0.01	+0.01	+0.01	0.99	0.00	+0.01	+0.01	+0.01
Calcium	0.94	-0.01	+0.05	+0.04	+0.03	1.00	0.00	0.00	0.00	0.00
Iron	0.81	**-0.35**	**-0.29**	**-0.07**	**-0.08**	0.97	**-0.37**	**-0.30**	**-0.09**	**-0.09**
Iron (Female F+)[c]	0.41	**-0.30**	**-0.27**	**-0.09**	**-0.10**					
Moderation Sub-score (MS) (0-100)	77.25	**+2.34**	**-2.01**	**+3.78**	**+4.32**	60.40	**+3.47**	**-3.40**	**+5.27**	**+6.28**
Probability of adequacy for MS components (0-1)										
Carbohydrates	1.00	0.00	0.00	0.00	0.00	1.00	-0.01	-0.01	0.00	0.00
Protein	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Total fat	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
SFA	0.07	+0.02	+0.02	**+0.13**	**+0.13**	0.10	+0.06	+0.06	**+0.24**	**+0.25**
Sodium	0.66	**+0.12**	**-0.05**	**+0.11**	**+0.13**	0.10	**+0.14**	-0.03	**+0.14**	**+0.16**
Sugars without lactose	0.90	0.00	-0.09	-0.02	-0.01	0.42	+0.01	-0.23	-0.06	-0.03
SecDiet (0-1)	1.00	-0.01	-0.01	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Probability of adequacy of the SecDiet (0-1)										
Vitamin A	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Thiamine	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Riboflavin	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Niacin	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Folate	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Vitamin B-12	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Vitamin C	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Iodine	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Selenium	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Zinc	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Calcium	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Iron	0.99	**-0.09**	**-0.07**	-0.01	-0.01	1.00	0.00	0.00	0.00	0.00

[a] E.A. means "energy adjustment". For modeled diets with energy adjustment, the difference of energy between the observed initial diet and the modeled diet without energy adjustment was reported on other food items in order to maintain the same energy intake between the observed initial diet and the modeled diet with energy adjustment.

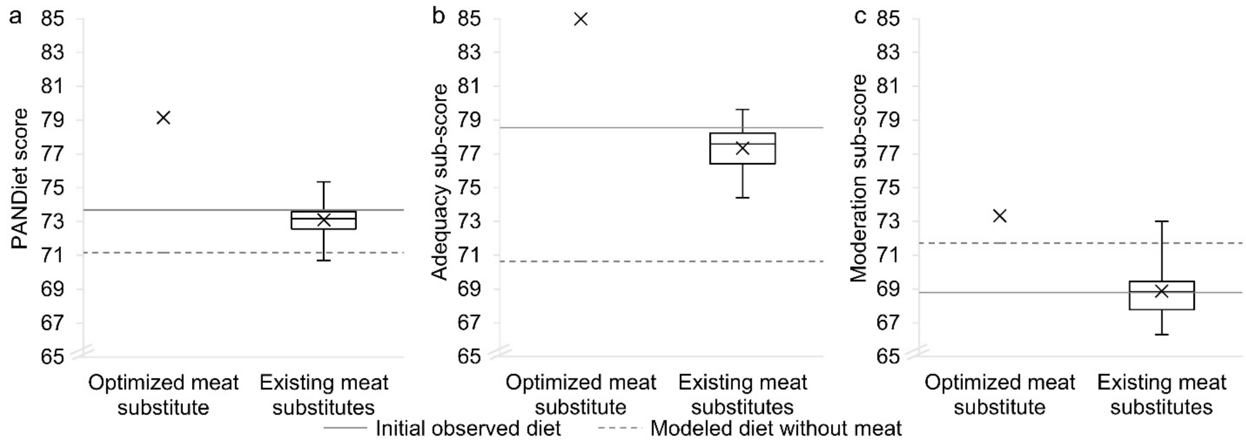
[b] Values are differences between the modeled diet and the observed initial diet. Values in bold are those most affected by removing and/or replacing the meat.

[c] Values when considering iron requirements for female with high iron requirements (Female F+). The modification of the reference value impacts the probability of adequacy of iron, the AS and the PANDiet scores.

Supplementary Table S9 PANDiet, AS, MS, SecDiet scores and probabilities of adequacies in initial diets and modeled diets with the optimized meat substitute in individual substitutions in the INCA3 population (n=1125).

	Females (F) (n=561)			Males (M) (n=564)			Average
	Initial diet	Modeled diet	Δ[a]	Initial diet	Modeled diet	Δ	Δ[b]
PANDiet score (0-100)	67.64 ± 5.78[c]	71.17 ± 6.25*	**+3.54**	67.72 ± 6.22	72.14 ± 7.27*	**+4.43**	**+3.98**
PANDiet (Female F+)[d]	67.09 ± 5.75	70.58 ± 6.21*	**+3.48**				
Adequacy Sub-score (AS) (0-100)	61.63 ± 12.65	65.64 ± 12.06*	**+4.01**	68.89 ± 13.25	73.14 ± 13.10*	**+4.25**	**+4.12**
AS (Female F+)[d]	60.54 ± 12.59	64.45 ± 11.95*	**+3.91**				
Probability of adequacy for AS components (0-1)							
Protein	0.89 ± 0.17	0.78 ± 0.27*	**-0.11**	0.93 ± 0.18	0.86 ± 0.25*	**-0.07**	**-0.09**
LA	0.47 ± 0.31	0.64 ± 0.30*	**+0.17**	0.40 ± 0.35	0.60 ± 0.35*	**+0.21**	**+0.19**
ALA	0.12 ± 0.21	0.57 ± 0.33*	**+0.45**	0.09 ± 0.20	0.58 ± 0.38*	**+0.49**	**+0.47**
DHA	0.16 ± 0.29	0.16 ± 0.28	-0.01	0.25 ± 0.38	0.25 ± 0.38	-0.01	-0.01
EPA+DHA	0.14 ± 0.27	0.14 ± 0.27	0.00	0.23 ± 0.37	0.22 ± 0.36	-0.01	-0.01
Fiber	0.30 ± 0.31	0.68 ± 0.27*	**+0.37**	0.49 ± 0.36	0.83 ± 0.27*	**+0.34**	**+0.36**
Vitamin A	0.49 ± 0.35	0.50 ± 0.35	+0.01	0.50 ± 0.40	0.52 ± 0.39	+0.02	+0.02
Thiamine	0.95 ± 0.09	0.97 ± 0.08*	**+0.01**	0.97 ± 0.07	0.98 ± 0.05*	**+0.01**	**+0.01**
Riboflavin	0.68 ± 0.31	0.63 ± 0.32*	**-0.04**	0.84 ± 0.26	0.81 ± 0.29	-0.03	**-0.04**
Niacin	1.00 ± 0.02	1.00 ± 0.02	0.00	1.00 ± 0.01	1.00 ± 0.01	0.00	0.00
Pantothenic acid	0.86 ± 0.14	0.89 ± 0.13*	**+0.03**	0.89 ± 0.16	0.92 ± 0.14*	**+0.03**	**+0.03**
Vitamin B-6	0.61 ± 0.30	0.55 ± 0.32*	**-0.06**	0.75 ± 0.32	0.72 ± 0.34	-0.03	**-0.05**
Folate	0.55 ± 0.33	0.65 ± 0.29*	**+0.11**	0.75 ± 0.30	0.84 ± 0.24*	**+0.10**	**+0.10**
Vitamin B-12	0.53 ± 0.33	0.31 ± 0.33*	**-0.22**	0.74 ± 0.32	0.47 ± 0.42*	**-0.27**	**-0.24**
Vitamin C	0.37 ± 0.36	0.44 ± 0.37*	**+0.07**	0.45 ± 0.43	0.57 ± 0.41*	**+0.13**	**+0.10**
Vitamin D	0.02 ± 0.06	0.02 ± 0.06	0.00	0.04 ± 0.11	0.04 ± 0.11	0.00	0.00
Vitamin E	0.83 ± 0.18	0.91 ± 0.11*	**+0.08**	0.86 ± 0.20	0.93 ± 0.13*	**+0.07**	**+0.07**
Iodine	0.64 ± 0.30	0.64 ± 0.30	0.00	0.79 ± 0.27	0.79 ± 0.27	0.00	0.00
Magnesium	0.88 ± 0.14	0.93 ± 0.10*	**+0.05**	0.89 ± 0.15	0.94 ± 0.11*	**+0.05**	**+0.05**
Phosphorus	0.96 ± 0.08	0.96 ± 0.08	0.00	0.97 ± 0.08	0.97 ± 0.08	0.00	0.00
Potassium	0.53 ± 0.32	0.57 ± 0.30*	**+0.04**	0.78 ± 0.28	0.81 ± 0.26*	**+0.03**	**+0.03**
Selenium	0.93 ± 0.13	0.92 ± 0.13	0.00	0.97 ± 0.09	0.97 ± 0.09	0.00	0.00
Zinc	0.36 ± 0.32	0.26 ± 0.28*	**-0.10**	0.36 ± 0.37	0.21 ± 0.30*	**-0.14**	**-0.12**
Copper	0.88 ± 0.12	0.94 ± 0.09*	**+0.06**	0.90 ± 0.14	0.95 ± 0.09*	**+0.05**	**+0.05**
Manganese	0.84 ± 0.17	0.94 ± 0.10*	**+0.10**	0.87 ± 0.18	0.96 ± 0.09*	**+0.09**	**+0.10**
Calcium	0.57 ± 0.34	0.62 ± 0.33*	**+0.05**	0.72 ± 0.34	0.78 ± 0.30*	**+0.06**	**+0.05**
Iron	0.63 ± 0.23	0.61 ± 0.21	-0.02	0.77 ± 0.23	0.74 ± 0.24*	**-0.03**	-0.02
Iron (Female F+)[d]	0.35 ± 0.22	0.31 ± 0.19*	**-0.04**				
Moderation Sub-score (MS) (0-100)	73.64 ± 10.53	76.70 ± 10.53*	**+3.06**	66.54 ± 13.35	71.15 ± 13.23*	**+4.61**	**+3.84**
Probability of adequacy for MS components (0-1)							
Carbohydrates	0.94 ± 0.12	0.91 ± 0.16*	**-0.03**	0.94 ± 0.15	0.89 ± 0.19*	**-0.04**	**-0.04**
Protein	0.95 ± 0.13	0.98 ± 0.07*	**+0.03**	0.91 ± 0.21	0.97 ± 0.12*	**+0.06**	**+0.04**
Total fat	0.90 ± 0.18	0.92 ± 0.15*	**+0.02**	0.94 ± 0.15	0.96 ± 0.12*	**+0.02**	**+0.02**
SFA	0.28 ± 0.28	0.39 ± 0.31*	**+0.11**	0.31 ± 0.32	0.47 ± 0.36*	**+0.15**	**+0.13**
Sodium	0.64 ± 0.30	0.69 ± 0.30*	**+0.05**	0.38 ± 0.36	0.46 ± 0.37*	**+0.08**	**+0.06**
Sugars without lactose	0.71 ± 0.31	0.71 ± 0.31	0.00	0.55 ± 0.38	0.54 ± 0.38	-0.01	-0.01
SecDiet	0.91 ± 0.09	0.91 ± 0.09	0.00	0.94 ± 0.09	0.95 ± 0.09	0.00	0.00
Probability of adequacy of the SecDiet (0-1)							
Vitamin A	0.88 ± 0.18	0.90 ± 0.16	+0.02	0.88 ± 0.24	0.91 ± 0.20*	**+0.03**	+0.02
Thiamine	1.00 ± 0.01	1.00 ± 0.01*	**0.00**	1.00 ± 0.01	1.00 ± 0.01	0.00	0.00
Riboflavin	0.92 ± 0.12	0.91 ± 0.14	-0.01	0.96 ± 0.12	0.95 ± 0.14	-0.01	-0.01
Niacin	1.00 ± 0.02	1.00 ± 0.02	0.00	1.00 ± 0.01	1.00 ± 0.01	0.00	0.00
Folate	0.91 ± 0.15	0.95 ± 0.11*	**+0.03**	0.96 ± 0.13	0.97 ± 0.10*	**+0.01**	**+0.02**
Vitamin B-12	0.97 ± 0.05	0.93 ± 0.11*	**-0.04**	0.98 ± 0.06	0.94 ± 0.16*	**-0.04**	**-0.04**
Vitamin C	0.97 ± 0.06	0.98 ± 0.04*	**+0.01**	0.98 ± 0.06	0.98 ± 0.05*	**+0.01**	**+0.01**
Iodine	0.87 ± 0.16	0.87 ± 0.16	0.00	0.93 ± 0.16	0.93 ± 0.16	0.00	0.00
Selenium	0.99 ± 0.03	0.99 ± 0.03	0.00	0.99 ± 0.02	0.99 ± 0.02	0.00	0.00
Zinc	0.99 ± 0.03	0.99 ± 0.03	0.00	0.99 ± 0.04	0.99 ± 0.05	0.00	0.00
Calcium	0.92 ± 0.14	0.94 ± 0.12*	**+0.02**	0.95 ± 0.14	0.97 ± 0.10*	**+0.02**	**+0.02**
Iron	0.94 ± 0.10	0.95 ± 0.11	0.00	0.98 ± 0.05	0.98 ± 0.05	0.00	0.00

[a] Δ is the difference between the mean of "Modeled diet" and the mean of "Initial diet".
[b] Average Δ is the mean of Δ(F) and Δ(M) (Δ(F+) for PANDiet, AS and probability of adequacy of iron) and weighted by their respective distributions in the study population.
[c] Values are means ± SD weighted for the survey design. *Significantly different from the mean of "Initial diet" assessed by t-test. P<0.05. Values in bold are those significantly affected by replacing meat.
[d] Values when considering iron requirements for females with high iron requirements (Female F+). The modification of the reference value impacts the probability of adequacy of iron, the AS and the PANDiet scores.



Supplementary Figure S2 a. PANDiet, b. AS and c. MS scores in modeled average diets where meat food items were replaced with the optimized meat substitute or with existing meat substitutes (n=43). Modeled diets were not adjusted for energy intake. Whiskers of the boxplot represent min and max of scores obtained in the modeled diet with available meat substitutes. Horizontal lines represent scores in the initial diet (full line) or in a modeled diet where meat food items were removed (dashed line).

Supplementary Table S10 List of ingredients in the different optimized meat substitutes obtained after releasing several technological constraints.

Ingredient sub-group	Ingredient	Optimized meat substitute	Releasing of technological constraints: Pulses and cereals constraints only [a]	Ingredients category constraints only [b]	All technological constraints [c]
		g/100g			
Pulses	Navy bean, boiled/cooked in water	41.59	-	-	-
	Chick pea, boiled/cooked in water	5.77	-	-	-
	Broad bean, boiled/cooked in water	-	27.94	-	-
Vegetables, cooked	Pepper, sweet, yellow, pan-fried, without fat	15.00	19.50	19.18	-
	Chinese cabbage (nappa cabbage or bok choy), cooked	-	-	30.00	-
Fragmented cereals, >10g/100g of protein	Wheat bran	5.63	7.64	-	-
	Wheat germ	4.37	23.42	-	-
Fragmented cereals, <10g/100g of protein	Couscous (precooked durum wheat semolina), cooked, unsalted	5.00	-	-	-
Nuts and seeds	Flaxseed	5.00	5.00	9.11	4.43
	Poppy, seed	-	-	11.54	6.12
Vegetables and fruits, dried	Shiitake mushroom, dried	5.00	0.50	18.00	38.49
	Chinese black mushroom, dried	-	-	-	23.58
Vegetable oils	Rapeseed oil	3.60	4.90	-	14.14
	Sunflower oil	1.40	0.10	-	-
Starch	Potato starch	3.89	0.50	-	-
Tubers and garden peas	Sweet potato, cooked	2.74	4.47	-	-
	Garden peas, cooked	-	5.03	-	-
Herbs, spices and salt	Thyme, dried	1.00	1.00	3.21	13.06
	Basil, dried	-	-	8.90	-
	Laver (Porphyra sp.), dried or dehydrated	-	-	0.07	0.19
	Δ(PANDiet) with the optimized meat substitute		+0.73	+1.63	+3.53
	Δ(AS) with the optimized meat substitute		+2.26	+3.89	+4.50
	Δ(AS) with the optimized meat substitute		-0.81	-0.63	+2.56

[a] Constraints on cereals (n=5) and on pulses (n=1) were deleted. All other constraints were kept similar.
[b] All technological constraints were deleted except the water content and the limits on energy content for average male and female.
[c] All technological constraints were deleted.

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