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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.

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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.

1 **Abstract**

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

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

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

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

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

25 **Introduction**

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

32 Indeed, reducing meat consumption is advocated for both health and environmental reasons [6–
33 8]. However, in industrialized countries, meat plays an important cultural and structural role in
34 meals, which makes it relatively difficult to remove and replace [9–11]. In this context, meat
35 substitutes might be expected to be more acceptable than classic plant-based foods such as
36 pulses because they can be used in the same way as meat and do not require changes to the
37 meal structure [9].

38 From a nutritional standpoint, meat is an important contributor to micronutrient intake, and
39 especially of iron, zinc and some B-vitamins [12–15]. Therefore, when rearranging diets in order
40 to adopt more sustainable diets, attention should be paid to ensuring adequate nutrient intakes
41 [13, 16, 17]. However, the formulation of meat substitutes generally tends to be more driven by
42 attempts to imitate the organoleptic properties of meat (appearance, texture, flavor) than ensuring
43 an appropriate nutrient composition beyond the protein content [5]. The main ingredients
44 composing meat substitutes are generally soy, wheat, or pea proteins because of their
45 technological functional properties (such as a fibrous-like texture and emulsification) [4, 5, 18] but
46 many ingredients can be used, such as all kind of pulses, cereals, vegetables, herbs, and spices
47 [4, 18], leading to a multitude of possibilities of formulation. More specifically, pulses are currently
48 little consumed despite their nutritional and environmental benefits [7, 19] and meat substitute
49 could help to increase their consumption.

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

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

67 **Data and methods**

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

70 Input dietary data

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

79 Dietary data were collected by professional investigators assisted by a dietary software and using
80 three non-consecutive 24h-dietary recalls spread over a 3-week period [26]. Participants were not
81 aware beforehand of the days of recall. Portion sizes were estimated using validated photographs
82 [26]. The nutrient content of foods and beverages came from the 2016 food composition database
83 from the French Information Center on Food Quality (CIQUAL) [29]. Over all foods consumed,
84 meat or processed meat usually eaten in the main dish were identified as 'meat food items',
85 excluding composite dishes (e.g. lasagna) (Supplementary Table S1). Foods that were not
86 identified as meat food items are referred to hereinafter as 'other food items'. The mean nutrient
87 intakes from meat food items and other food items were then calculated for males and females
88 separately, using the weighted schemes proposed in INCA3 to account for the complex survey
89 design [26]. This resulted in average male and female individuals with mean nutrients intakes for
90 each sex.

91 Evaluation of diet quality

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

102 The probability of adequacy for each nutrient is calculated using the mean intake, the reference
103 value, the variability of the reference value and the intra-individual variability of intake, as
104 previously described [30]. However, during this study, probabilities of adequacy were calculated
105 for average male and female individuals, so intra-individual variability was considered to be equal
106 to zero. The reference values were extracted from the 2021 dietary guidelines released by ANSES
107 [31]. For iron and zinc, we considered the estimated requirement for the absorbed form and an
108 equation predicting absorption from dietary intakes [32–34]. Moreover, to take account of the high
109 requirement of iron for some females, the probability of adequacy of iron was calculated using two
110 different reference values: females with low to moderate menstrual losses and females with
111 elevated menstrual losses (about 20% of females) [31]. PANDiet was therefore calculated for the
112 average male (PANDiet-M) and for the average female using the reference values for iron for
113 female with normal (PANDiet-F) or high iron requirements (PANDiet-F+). An averaged PANDiet
114 was calculated as the mean of the PANDiet-M, the PANDiet-F and the PANDiet-F+ weighted by

115 their respective distributions in the study population (50.13% of males, 49.87% of females with a
116 weighting of 80% for PANDiet-F and 20% for PANDiet-F+).

117 Evaluation of the nutrient security of diet

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

128 Mathematical optimization of the meat substitute

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

135 *Optimized meat substitute*

136 The aim was to model a meat substitute that was entirely plant-based (i.e. containing no animal-
137 based ingredients) and composed of minimally processed ingredients. Thus only minimally
138 processed, common culinary ingredients of plant origin were included (e.g. tofu or textured soy

139 protein were not included as they are processed, but cooked pulses were included). A total of 159
140 ingredients for which a complete nutritional composition could be extracted from the CIQUAL 2020
141 food composition database [36] were categorized into groups and sub-groups (pulses, vegetables,
142 cereals, oil-rich foods, etc.) (Supplementary Table S4).

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

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

158 *Objective function*

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

161 *Nutritional constraints*

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

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

173 *Technological constraints*

174 Several technological constraints were applied:

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

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

189 *Sensitivity analysis and validation*

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

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

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

204 Effects of the optimized meat substitute on diet quality

205 *Comparison with existing meat substitutes*

206 Several modeled diets were designed to study the impacts of meat substitutes on diet quality
207 evaluated with the averaged PANDiet. For the average male and female, meat food items were
208 replaced by the same quantity of either the optimized meat substitute or each of 43 existing meat

209 substitutes available in the CIQUAL 2016 and 2020 databases and the NutriNet-Santé food
210 composition table [29, 36, 38] (Supplementary Table S6). We therefore modeled 44 diets: one
211 with the optimized meat substitute and 43 with existing meat substitutes. In addition, a modeled
212 diet was designed by simply deleting all meat food items. This modeled diet is highly unrealistic
213 but was not intended as a scenario. Rather, it was used to analyze the contribution of meat food
214 items to diet quality and disentangle the changes in nutrient adequacies that result from the
215 suppression of meat and those that result from the addition of meat substitutes.

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

220 *Inter-individual variability*

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

230 **Results**

231 Optimized meat substitute: composition and impacts on diet quality

232 The optimized meat substitute was composed of 13 ingredients (Table 1). It contained 8.5g/100g
233 protein (supplied mostly by navy bean, wheat germ, and flaxseed), was low in saturated fatty acids
234 (0.9g/100g) and rich in fiber (13g/100g). Ingredients contributed differently to the nutrient
235 composition of the meat substitute. Thyme, navy bean and wheat bran were the main contributors
236 to iron content, and dried shiitake mushroom to B-vitamins, whereas flaxseed contributed to 68%
237 of the alpha-linolenic acid (ALA) content and yellow sweet pepper to 91% of the vitamin C content
238 (Supplementary Table S7).

239 Compared to the observed diet at the average population level, replacing meat with the optimized
240 meat substitute resulted in a 5.7-point increase in the averaged PANDiet score, with energy
241 adjustment (or +5.5 points otherwise) (Table 2). This resulted from an increase in AS by +6.1
242 points and in MS by +5.3 points. In greater detail, the probabilities of adequacy mainly increased
243 for ALA, fiber, linoleic acid (LA), vitamin C, and folate with respect to AS, and sodium and SFA
244 with respect to MS. By contrast, some probabilities of adequacy decreased, notably for vitamin
245 B12, bioavailable zinc, bioavailable iron, and vitamin B6 with respect to AS. However, these
246 decreases were less marked when compared to a situation where meat was withdrawn and not
247 replaced by the meat substitute ("Modeled diet without meat"), except for zinc (-0.30) and vitamin
248 B12 (-0.33). On the contrary, for potassium, the decrease due to removing meat was totally
249 compensated by the meat substitute. Concerning nutrient security, the SecDiet score remained
250 stable, although the probability for iron slightly decreased (-0.01) but less than without meat.
251 Lastly, the PANDiet gain was more important in average male (+6.2) than in average female
252 (+5.2), because the MS increase was more pronounced for the average male (+6.3) than for the
253 average female (+4.3) while the increase in AS was similar (+6.1) (Supplementary Table S8). At
254 an individual level, in order to consider inter-individual variations, the PANDiet gain was less

255 marked when replacing meat with the optimized meat substitute and increased from 67.6 ± 5.8 to
256 71.2 ± 6.3 for females and from 67.7 ± 6.2 to 72.1 ± 7.3 for males (Supplementary Table S9).

257 At the average population level, the impact of the optimized meat substitute on diet quality was
258 compared to the impacts of existing meat substitutes (Fig. 1). In modeled diets adjusted for energy
259 intake, where meat was replaced by existing meat substitutes, the PANDiet score ranged from
260 70.6 to 75.1 (i.e. -3.1 to +1.5 compared to the initial PANDiet), depending on the meat substitute,
261 with a mean at 73.0. Only about a quarter of the meat substitutes (upper whisker of the boxplot)
262 increased the PANDiet score above its value in the observed diet (73.7). These increases were
263 much lower than that resulting from using the optimized meat substitute (79.4). AS from modeled
264 diets with existing meat substitutes were more spread out (72.4 to 80.7, with a mean at 77.2) but
265 always lower than the AS reached with the optimized meat substitute (84.6). Differences between
266 the optimized and existing meat substitutes were less marked for MS. The results were similar
267 when the modeled diets were not adjusted for energy intake (Supplementary Figure S2).

268

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

276

277 Sensitivity analysis and validation: influence of model constraints and overall stability of the
278 selected recipe.

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

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

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

299 Finally, while retaining all the initial technological constraints, we removed one by one each
300 ingredient composing the optimized meat substitute presented in Table 1, as well as other
301 ingredients in the database that were very similar (e.g., by concomitantly removing all sweet
302 peppers when removing yellow sweet pepper) (Table 4). The proportions of ingredients generally
303 varied but the main structure of the optimized meat substitute was mostly unchanged, since the

304 ingredient removed was usually replaced by another ingredient from the same sub-group (e.g.
305 navy bean was replaced with a mix of chick pea and blond lentil, or flaxseed was replaced with
306 chia seed). For most ingredients, the replacement led to a PANDiet decrease compared to its
307 value with the initial optimized meat substitute. This was mostly the case for rapeseed oil (-0.28),
308 yellow sweet pepper (-0.23), all sweet peppers (-0.28), dried mushrooms (-0.20), wheat bran (-
309 0.17), and thyme (-0.07). It was also apparent in the dual values calculated for eviction constraints,
310 which were higher for these ingredients. For some ingredients, the impact on the PANDiet was
311 low because there was a compensation between the loss of AS and the gain in MS. Replacement
312 of chick pea, flaxseed, and potato starch had the least impacts on PANDiet, AS and MS.

313 **Discussion**

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

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

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

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

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

357 The optimized meat substitute might appear low in protein compared to meat or other meat
358 substitutes on the market, but this was expected because we mainly used raw materials rather
359 than the protein isolates that are usually used to produce a high protein content in meat substitutes
360 [2, 18]. Moreover, the composition of the meat substitute resulted from the compromise made by
361 an optimization procedure based on the current set of nutrient adequacies, and protein adequacy
362 proved to be a secondary issue compared to other nutrients. We did not consider the amino acid

363 composition of the optimized meat substitute, but there should be no issue in this respect since
364 the protein sources comprised a mix of cereals, nuts and pulses that are known to have a
365 complementary composition in amino acids [42]. Moreover, it has been shown that when protein
366 intake is adequate in a varied diet, so is the intake of individual amino acids [43].

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

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

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

401 Our study had certain limitations. First, optimization was performed on an average individual,
402 which led to a somewhat crude evaluation of diet quality, since the variability of intake was not
403 taken into account. We believe that the impact of substitution is better evaluated at an individual
404 level rather than a population level because this takes more account of the heterogeneity of diets
405 [46], but our objective was to model a unique substitute that would best improve general diet
406 quality and not to find a personalized meat substitute for each individual. But we have shown that
407 replacing meat with the optimized meat substitute at the individual level led to similar conclusions,
408 although differences with observed diets were less marked. Further, the database of ingredients
409 was limited to those for which we had a complete nutritional composition, so despite our
410 considerable database (159 ingredients) we did not have an exhaustive list of potential
411 ingredients. While we tried to best describe the technological constraints associated with the

412 formulation of a plant-based patty, we might not have been sufficiently accurate and some
413 constraints were not considered, such as taste or consumer preferences. Furthermore, this study
414 focused on nutrition while including technological constraints, but further studies could
415 interestingly try to consider other criteria such as environmental impacts or cost.

416 In conclusion, we have shown that it is possible to identify the composition of a meat substitute
417 that would offer the best nutritional lever to replace meat in our population. As revealed by
418 optimization on a large set of nutrient adequacies, the optimized meat substitute could improve
419 diet quality by both increasing nutrient adequacy for nutrients not provided by meat and by
420 compensating for most of the nutrients conveyed by meat. Meat substitutes with an appropriate
421 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
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)					
<i>Protein</i>	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
<i>DHA</i>	0.25	+0.07	-0.06	-0.05	-0.03
<i>EPA+DHA</i>	0.09	+0.04	-0.03	-0.02	-0.02
Fiber	0.36	+0.17	-0.01	+0.63	+0.63
<i>Vitamin A</i>	0.96	+0.01	-0.07	-0.02	-0.01
<i>Thiamine</i>	1.00	0.00	0.00	0.00	0.00
<i>Riboflavin</i>	1.00	0.00	-0.03	-0.01	0.00
<i>Niacin</i>	1.00	0.00	0.00	0.00	0.00
<i>Pantothenic acid</i>	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
<i>Vitamin D</i>	0.00	0.00	0.00	0.00	0.00
<i>Vitamin E</i>	0.99	0.00	0.00	+0.01	+0.01
<i>Iodine</i>	0.98	+0.01	-0.01	0.00	0.00
<i>Magnesium</i>	0.99	0.00	-0.01	+0.01	+0.01
<i>Phosphorus</i>	1.00	0.00	0.00	0.00	0.00
Potassium	0.84	-0.02	-0.15	+0.04	+0.05
<i>Selenium</i>	1.00	0.00	0.00	0.00	0.00
Zinc	0.46	-0.42	-0.44	-0.30	-0.30
<i>Copper</i>	0.99	0.00	-0.01	+0.01	+0.01
<i>Manganese</i>	0.99	+0.01	0.00	+0.01	+0.01
<i>Calcium</i>	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)					
<i>Carbohydrates</i>	1.00	0.00	0.00	0.00	0.00
<i>Protein</i>	1.00	0.00	0.00	0.00	0.00
<i>Total fat</i>	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
<i>Sugars without lactose</i>	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)					
<i>Vitamin A</i>	1.00	0.00	0.00	0.00	0.00
<i>Thiamine</i>	1.00	0.00	0.00	0.00	0.00
<i>Riboflavin</i>	1.00	0.00	0.00	0.00	0.00
<i>Niacin</i>	1.00	0.00	0.00	0.00	0.00
<i>Folate</i>	1.00	0.00	0.00	0.00	0.00
<i>Vitamin B-12</i>	1.00	0.00	0.00	0.00	0.00
<i>Vitamin C</i>	1.00	0.00	0.00	0.00	0.00
<i>Iodine</i>	1.00	0.00	0.00	0.00	0.00
<i>Selenium</i>	1.00	0.00	0.00	0.00	0.00
<i>Zinc</i>	1.00	0.00	0.00	0.00	0.00
<i>Calcium</i>	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

^aDual 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

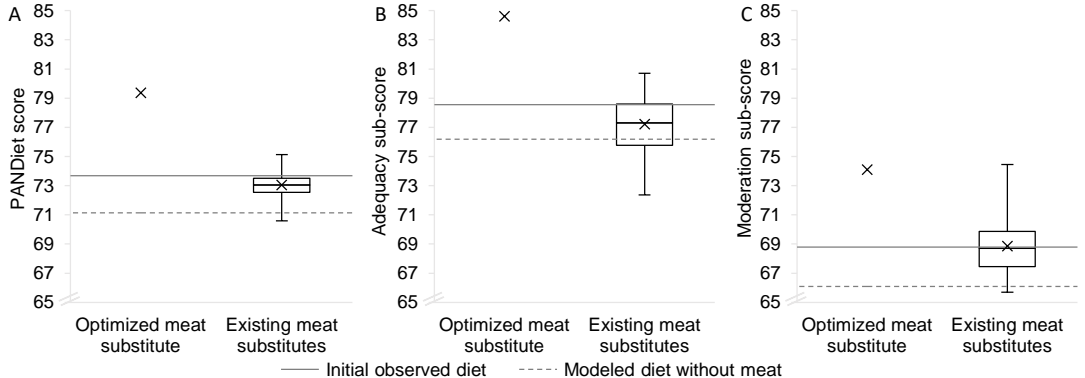
		Alternative composition when discarding an ingredient constituting the initial composition, by discarded ingredient ^{a, b}															
		Initial composition	Navy bean	Chick pea	Yellow sweet pepper	All sweet peppers ^c	Dried shiitake	Dried mushrooms ^d	Wheat bran	Wheat germ	Couscous	Rapeseed oil	Sunflower oil	Flaxseed	Sweet potato	Potato starch	Thyme
Pulses	Navy bean, cooked	41.59	32.06	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	47.40	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	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	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	5.00	4.39	5.00	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	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	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	5.00	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	-	4.63	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	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	1.00	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	3.60	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	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



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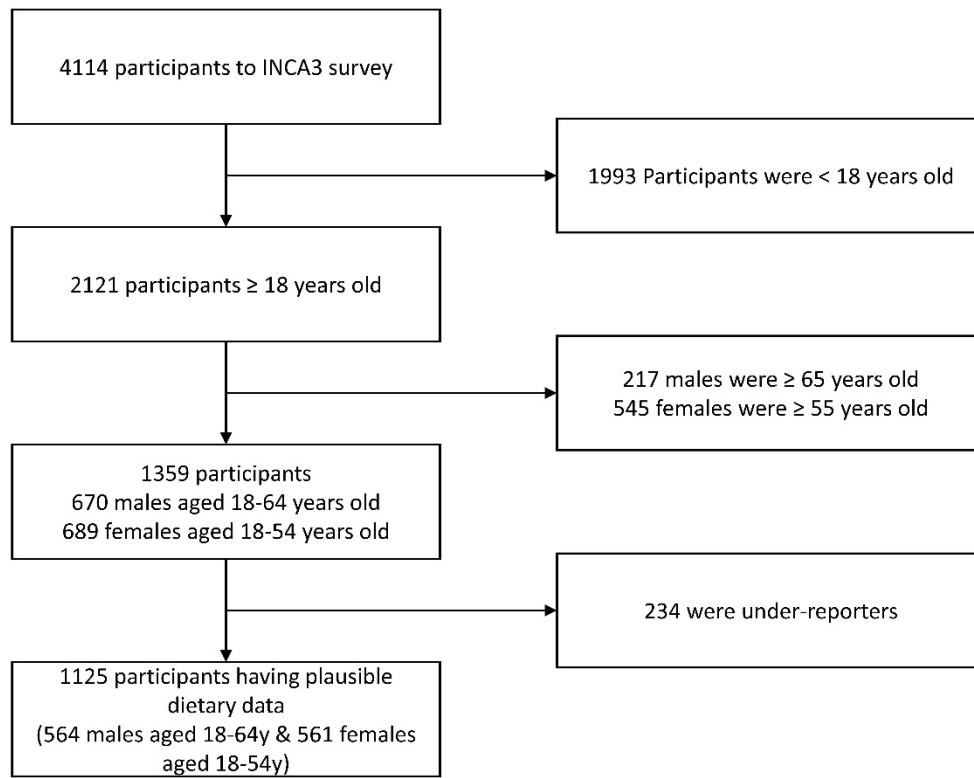
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Supplementary Figure S1 Flow chart explaining the sampling of French participants from the third Individual and National Study on Food Consumption Survey (INCA3) for the present study.

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, toumedos, 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)	Provençal-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, roasted/baked	Veal, loin, sautéed/pan-fried
Beef, rib steak, lean, grilled/pan-fried	Lamb, meat, cooked (average)	Veal, meat, cooked (average)
Beef, roast beef, roasted/baked	Lamb, neck, braised or boiled	Veal, minced steak, 15% fat, raw
Beef, round, cooked	Lamb, saddle, grilled/pan-fried	Veal, neck, braised or boiled
Beef, rump steak, grilled	Lamb, saddle, lean, roasted/baked	Veal, roast, cooked
Beef, short ribs, braised	Lamb, shoulder, lean, roasted/baked	Veal, shoulder, braised/boiled
Beef, sirloin steak, grilled/pan-fried	Lamb, shoulder, roasted/baked	Veal, shoulder, grilled/pan-fried
Beef, sirloin steak, roasted/baked	Liver, calf, cooked	Veal, tenderloin, grilled/pan-fried
Beef, steak or beef steak, grilled	Liver, lamb, cooked	Veal, tenderloin, roasted
Beef, steak or beef steak, raw	Liver, young cow, cooked	Venison (hart), roasted/baked
Beef, stewing meat, cooked	Meat balls, beef and lamb (kefta type), prepacked, raw	Venison (roebuck), roasted/baked
Beef, thin flank, grilled/pan-fried		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	
Deville 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			Moderation sub-score		
Nutrient	Reference value (/day)[3]	Variability	Nutrient	Reference value (/day)[3]	Variability
Protein	0.66 or 0.8 g/kg bw	12.5%	Protein	2.2 g/kg bw	12.5%
LA	3.08% EIEA	15%	Total fat	44% EIEA	5%
ALA	0.769% EIEA	15%	SFA	12% EIEA	15%
DHA	0.192 g	15%	Carbohydrates	60.5% EIEA	5%
EPA + DHA	0.385 g	15%	Sugars	100 g	15%
Fiber	23 g	15%	Sodium	3200 mg	15%
Vitamin A	580 or 490 µg	15%	Tolerable Upper Intake Limits ^d		
Thiamin	0.3 mg/1000 kcal	20%	Vitamin A	3000 µg	
Riboflavin	1.3 mg	10%	Niacin	900 mg	
Niacin	5.44 mg NE/1000kcal	10%	Vitamin B-6	25 mg	
Pantothenic acid	3.33 or 2.78 mg	40%	Vitamin D	100 µg	
Vitamin B-6	1.5 or 1.3 mg	10%	Calcium	2500 mg	
Folate	250 µg	15%	Copper	5 mg	
Vitamin B-12	3.33 µg	10%	Iodine	600 µg	
Vitamin C	90 mg	10%	Selenium	300 µg	
Vitamin D	10 µg	25%	Zinc	25 mg	
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%			

^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 were 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		
<i>Source of protein and fiber Texturizing and emulsifying ingredients</i>	<i>Source of fiber, vitamins and minerals</i>		<i>Taste enhancer</i>	
Broad bean, boiled/cooked in water Chick pea, boiled/cooked in water Navy bean, boiled/cooked in water Flageolet bean, boiled/cooked in water Flageolet bean, green, boiled/cooked in water Haricot bean, boiled/cooked in water Lentil, blond, boiled/cooked in water Lentil, green, boiled/cooked in water Lentil, pink or red, boiled/cooked in water Mung bean, boiled/cooked in water Red kidney bean, boiled/cooked in water Split pea, boiled/cooked in water	Artichoke, globe, cooked Beetroot, cooked Broccoli, cooked Brussels sprout, cooked Butter bean or yellow bean, boiled/cooked in water Button mushroom or cultivated mushroom, boiled/cooked in water Carrot, cooked Cauliflower, cooked Celeriac, cooked Celery stalk, cooked Chinese cabbage (nappa cabbage or bok choy), cooked Courgette or zucchini, pulp and peel, cooked Eggplant, cooked Fennel, boiled/cooked in water French bean, cooked Green cabbage, cooked Kohlrabi, boiled/cooked in water Leek, cooked Okra, cooked, without salt Olives, black, in brine Olives, green, in brine Onion, cooked	Parsnip, cooked Pepper, sweet, yellow, pan-fried, without fat Pumpkin (cucurbita moschata), pulp, cooked Pumpkin, cooked Red cabbage, boiled/cooked in water Red kuri squash, pulp, boiled/cooked in water Romanesco cauliflower or romanesco broccoli, cooked Rutabaga or Swede, cooked Salsify, cooked Shallot, cooked Shiitake mushroom, cooked Snow pea, cooked Spinach, cooked Squash, butternut, peeled, cooked Sweet corn, canned, drained Sweet pepper, green, cooked Sweet pepper, red, cooked Swiss chard, cooked Tomato paste, concentrated, canned Tomato, peeled, canned, drained Turnip, cooked White cabbage, boiled/cooked in water	Apricot, pitted, dried Chestnut, boiled/cooked in water Chinese black mushroom, dried Cranberry, dried, with sugar Date, pulp and peel, dried Fig, dried Onion, dried Prune Raisin Shiitake mushroom, dried Tomato, dried	Basil, dried Black pepper, powder Cardamom, powder Cloves Coriander, seed Fig, dried Cumin, seed Curry, powder Garlic, powder, dried Ginger, powder Laver (Porphyra sp.), dried or dehydrated Mint, dried Nutmeg Oregano, dried Paprika Parsley, dried Provence herbs, dried Rosemary, dried Saffron Sage, dried Salt, white (sea, igneous or rock), iodine added, no other enrichment Thyme, dried 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
<i>Source of carbohydrates, protein and fiber Plasto-elastic properties</i>		<i>Source of carbohydrates, protein and fiber</i>	<i>Source of carbohydrates, protein and fiber Contributors of a persistent texture in mouth</i>	
Buckwheat flour Millet flour Spelt flour Wheat flour, type 150	Barley flour Chestnut flour Maize/corn flour Rice flour Rye flour, type 130 Wheat flour, type 110 Wheat flour, type 55 (for bread)	Breadcrumbs Oat bran Oatmeal flakes Wheat bran Wheat germ	Durum wheat pre-cooked, whole grain, cooked, unsalted Millet, cooked, unsalted Quinoa, boiled/cooked in water, unsalted Rice, brown, cooked, unsalted Rice, cooked, unsalted Rice, red, cooked, unsalted Wild rice, cooked, unsalted	Couscous (precooked durum wheat semolina), cooked, unsalted Frik (crushed immature durum wheat), cooked, unsalted Pearled barley, boiled/cooked in water, unsalted Polenta or maize semolina, cooked, unsalted Semolina, cooked Wheat bulgur, 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
<i>Source of lipids</i> <i>Contributors of a soft texture</i>		<i>Source of lipids</i> <i>Contributors of a crunchy texture</i>		
		<i>Source of carbohydrates</i> <i>Thickening and binding ingredients</i>		
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]

¹Three 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)	Carbohydrate (g)	Fat (g)	Sugars (g)	Fiber (g)	SFA (g)	LA (g)	ALA (g)	Calcium (mg)	Copper (mg)	Iron (mg)	Iodine (µg)	Magnesium (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.

	Manganese (g)	Phosphorus (g)	Potassium (g)	Selenium (g)	Sodium (mg)	Zinc (mg)	Vitamin A (µg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)	Pantothenic 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				
	Observed initial diet	Modeled diets				Observed initial diet	Modeled diets			
		Without meat		With optimized meat substitute			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)										
<i>Protein</i>	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
<i>DHA</i>	0.02	-0.01	+0.01	-0.01	-0.01	0.49	-0.12	+0.14	-0.05	-0.08
<i>EPA+DHA</i>	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
<i>Vitamin A</i>	0.92	-0.08	+0.02	-0.01	-0.02	0.99	-0.05	0.00	-0.01	-0.02
<i>Thiamine</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Riboflavin</i>	1.00	-0.06	0.00	-0.01	-0.01	1.00	0.00	0.00	0.00	0.00
<i>Niacin</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Pantothenic acid</i>	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
<i>Vitamin D</i>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<i>Vitamin E</i>	0.99	0.00	0.00	+0.01	+0.01	0.99	0.00	0.00	+0.01	+0.01
<i>Iodine</i>	0.96	-0.02	+0.02	+0.01	0.00	1.00	0.00	0.00	0.00	0.00
<i>Magnesium</i>	0.99	-0.01	0.00	+0.01	+0.01	0.99	-0.02	0.00	+0.01	+0.01
<i>Phosphorus</i>	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
<i>Selenium</i>	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
<i>Copper</i>	0.99	-0.01	0.00	+0.01	+0.01	0.99	-0.01	0.00	+0.01	+0.01
<i>Manganese</i>	0.99	0.00	+0.01	+0.01	+0.01	0.99	0.00	+0.01	+0.01	+0.01
<i>Calcium</i>	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)										
<i>Carbohydrates</i>	1.00	0.00	0.00	0.00	0.00	1.00	-0.01	-0.01	0.00	0.00
<i>Protein</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Total fat</i>	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
<i>Sugars without lactose</i>	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)										
<i>Vitamin A</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Thiamine</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Riboflavin</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Niacin</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Folate</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Vitamin B-12</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Vitamin C</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Iodine</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Selenium</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Zinc</i>	1.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00
<i>Calcium</i>	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).

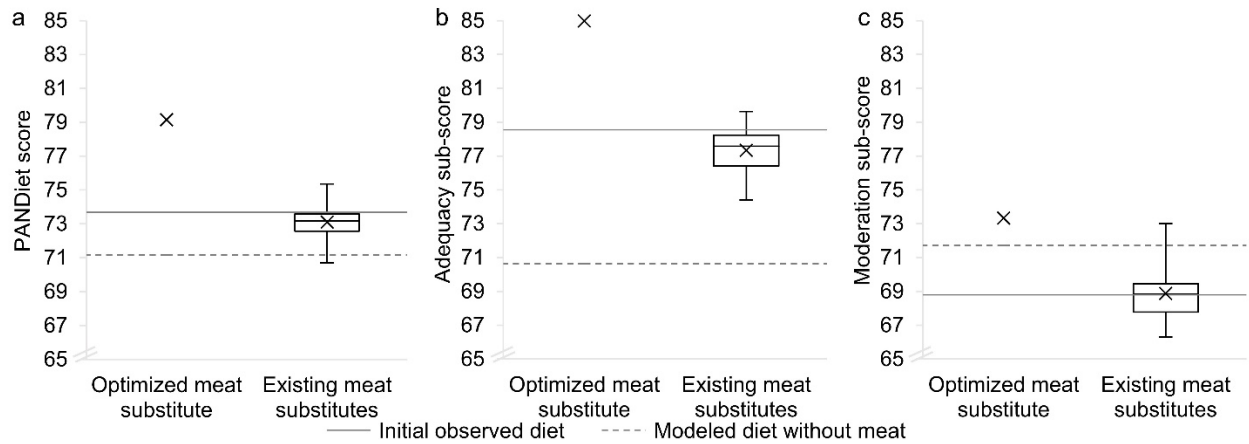
	Females (F) (n=561)			Males (M) (n=564)			Average Δ^b
	Initial diet	Modeled diet	Δ^a	Initial diet	Modeled diet	Δ	
PANDiet score (0-100)	67.64 ± 5.78 ^c	71.17 ± 6.25*	+3.54	67.72 ± 6.22	72.14 ± 7.27*	+4.43	+3.98
PANDiet (Female F+)^d	67.09 ± 5.75	70.58 ± 6.21*	+3.48				
Adequacy Sub-score (AS) (0-100)	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 $\Delta(F)$ and $\Delta(M)$ ($\Delta(F+)$ 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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