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The nature of protein intake as a discriminating factor of diet sustainability: a multi-criteria approach

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Abbreviations:

IPCC: Intergovernmental Panel on Climate Change
GBD: Global Burden of Diseases
INSEE: National Institute of Statistics and Economic Studies
Org-FFQ: Organic Food Frequency Questionnaire
GHG: greenhouse gas
CED: Cumulative energy demand
pReCiPe: partial ReCiPe
PANDiet: Diet Quality Index based on the Probability of Adequate Nutrient Intake
PNNS: Programme National Nutrition Santé
PNNS-GS2: Program National Nutrition Health Guidelines Score
cDQI: Comprehensive Diet Quality Index
AS: Adequation sub-score of PANDiet
MS: Moderation sub-score of PANDiet
TMREL: Theoretical Minimum-Risk Exposure Level
HRS: Health Risk Score
SD: Standard Deviation
SEM: Standard Error of the Mean
AHC: Ascending Hierarchical Classification
PCA: Principal Component Analysis
SFF: sweetened and fatty foods

1 **Abstract**

2 Animal production is responsible for 56-58% of the GHG emissions and limiting meat consumption
3 would strongly contribute to reducing human health risks in Western countries. This study aimed to
4 investigate the nature of protein intake as a discriminating factor for diets' sustainability.

5 Using data from 29,210 French adults involved in the NutriNet-Santé cohort, we identified clusters
6 according to 23 protein sources. A multicriteria (environmental, economic, nutritional and health)
7 sustainability analysis was then conducted on the identified clusters. The economic analysis focused
8 on both food and protein expenditure structures, using a budget coefficient approach. Relative
9 values of clusters compared to the whole sample were calculated.

10 We identified five clusters: milk-based, meat-based, fast food-based, healthy-fish-based, and
11 healthy-plant-based. We found that the healthy-plant-based and healthy-fish-based clusters were
12 the most sustainable, conciliating the compromise between human health (0.25 and 0.53
13 respectively for the Health Risk Score) and the protection of the environment (-62% and -19%
14 respectively for the pReCiPe indicator). Conversely, the highest environmental impacts (+33% for the
15 pReCiPe indicator) and the highest health risk (0.95 for the HRS) were observed for the meat-based
16 cluster, which was associated with the lowest nutritional scores (-61% for the PNNS-GS2 score). The
17 economic analysis showed that the healthy-plant-based cluster was the one with the highest food
18 budget coefficient (+46%), followed by the healthy-fish-based cluster (+8%), partly explained by a
19 strong share of organic food in the diet. However, the meat-based cluster spent more of their food
20 budget on their protein intake (+13%), while the healthy-plant-based cluster exhibited the lowest
21 expenditure for this intake (-41%).

22 Our results demonstrate that the nature of protein intake is a discriminating factor in diet
23 sustainability. Also, reducing animal protein consumption would generate co-benefits beyond
24 environmental impacts, by being favorable for health, while reducing the monetary cost associated
25 with protein intake.

26 **Keywords**

27 Sustainable, dietary patterns, protein sources, environmental pressures, health risk, food
28 expenditure, protein expenditure.

29 **Highlights Results**

30 Five clusters were extracted based on the contributions of protein sources: milk-based,
31 meat-based, fast-food-based, healthy-fish-based, and healthy-plant-based.

32 **Sustainability assessment of the identified diets:** the healthy-plant-based and healthy-fish-
33 based clusters were the most sustainable with the lowest environmental impacts, the
34 highest nutritional quality and the best adherence to the French dietary guidelines, and the
35 lowest health risk score. In contrast, the meat-based cluster displayed the highest
36 environmental impacts and health risk score. The fast-food-based cluster was associated
37 with the lowest nutritional scores.

38 **Economic analysis:** we put a specific emphasis on the economic dimensions: the healthy-
39 plant-based cluster showed the largest share of income allocated to food, followed by the
40 healthy-fish-based cluster. In addition, the meat-based cluster had the largest share of food
41 budget allocated to protein intake while the healthy-plant-based cluster had the lowest.

42

43 **Introduction**

44 Some planetary boundaries being officially crossed (1–3), recent efforts to limit global warming to
45 1.5°C, as stipulated in the Paris Climate Agreement, remain insufficient according to the 2021
46 Intergovernmental Panel on Climate Change (IPCC) report (4). Moreover, The 2023 Sustainable
47 Development Goals Report not only confirms this assessment but also sounds the alarm, urgently
48 calling for a doubling of efforts to get these objectives back on track (5). Actually, current food
49 systems are responsible for one third of global GHG emissions (6), one third to 80% of which
50 originates from the production stage (6,7). Besides, as populations become more urbanized and
51 affluent, their dietary patterns are shifting towards calorie-rich diets with more animal-based and
52 protein-dense foods (8). These dietary patterns have been largely influenced by the “protein”
53 debate, which has been evolving for decades. It was in the 1930s that particular attention was paid
54 to this nutrient, with the widespread incidence of kwashiorkor, and its association with protein
55 deficiency (9). A special Protein Advisory Group was then created by the United Nations, whose
56 mission was to “fight to close the protein gap”, while dietary guidelines encouraged the consumption
57 of protein-rich foods, namely meat and milk (10). Furthermore, the “protein” debate has been largely
58 influenced by animal production industry, given the great market opportunities offered by this
59 sector, whose trade balance reached 28 billion euros in 2018 in the EU (11). However, the debate has
60 gone off in another direction, and it is now beyond doubt that the reduction of meat consumption
61 would contribute to strongly reducing human health risks in Western countries according to the
62 Global Burden of Diseases (GBD) analysis (12). Moreover, animal food production is responsible for
63 56-58% of the emissions generated by food production while providing only 37% of the protein
64 supply (13). In that regard, the IPCC has strongly recommended to reduce meat consumption by two-
65 thirds (4), as red meat and processed meat production have been shown to have the highest impact
66 on all dimensions (GHG emissions, land use, water use, acidification and eutrophication) (13,14).
67 Note that these emissions are double those generated by plant-based foods (15). Although it has
68 been proven that there is no longer protein gap in Western countries, as protein intake exceeding

69 needs (16), the protein debate persists and has shifted towards new trends of “protein transitions”.
70 The new markets of plant-based meat and dairy substitutes are growing exponentially (17),
71 contributing to collapse the global dietary issues into a single nutrient. That being said, the
72 individuals’ dietary patterns seem to be strongly influenced by this debate. Indeed, it has been
73 shown that the overall diet of meat eaters is less healthy than the one of plant-based foods eaters
74 (18–20).

75 Thus, as we assume that the nature of protein intake might be indicative of the overall dietary
76 patterns of individuals, we hypothesized that it could be a discriminating factor for diet sustainability,
77 as defined by FAO in 2012 (21). We identified a previous study comparing diets defined by protein
78 sources in relation to sustainability (22) but the economic dimension was not assessed. However, we
79 believe that this aspect holds considerable importance regarding individual dietary choices,
80 particularly given the established literature linking healthier and acceptable diets to increased
81 expenses (23). Our objective was to identify clusters in the population of French adults participating
82 in the NutriNet-Santé cohort, according to the sources of protein intake, and then to characterize, in
83 a multi-criteria approach, the level of sustainability of these clusters according to environmental,
84 economic, nutritional and health aspects. We specifically conducted an economic analysis to
85 investigate the expenditure structure of both food and protein intake across the identified clusters as
86 this dimension of diets’ sustainability is often omitted.

87 **Methods and Data**

88 **Study population**

89 The present study used observational data from the NutriNet-Santé study. The NutriNet-Santé study
90 is an Internet-based cohort launched in May 2009 (24). Its purpose is to study the determinants of
91 diets, nutritional status, and physical activity as well as their associations with health. The
92 participants, recruited on a voluntary basis, are adults living in France with an access to internet.
93 Participants have to complete annual or biannual questionnaires on socioeconomic status, lifestyle,
94 anthropometry, dietary intake and physical activity. Regularly, specific questionnaires are proposed.

95 Gender, occupational status, income, place of residence, physical activity, and smoking habits are
96 self-reported using validated questionnaires (25). The NutriNet- Santé study is in line with the
97 principles of the Helsinki Declaration (26) and validated by both the INSERM Ethical Evaluation
98 Committee (CEEI) (no. 0000388FWA00005831) and the National Committee for Information
99 Technology and Freedom (CNIL) (nos. 908450 and 909216). The study is registered in
100 ClinicalTrials.gov (NCT03335644).

101 **Assessment of food consumption and protein intake in total and by food groups**

102 Food consumption data were collected via an Organic Food Frequency Questionnaire (Org-FFQ)
103 developed in 2014, including 264 organic and conventional food items (27). In the present study, a
104 total of 23 food groups were defined based on their protein content as follows: meat (including red
105 meat and pork), processed meat, poultry, seafood, eggs, milk, dairy (including all dairy products
106 except for milk), fast food, sweetened and fatty foods (SFF), fat (including animal fat and margarine),
107 dressing, potatoes, legumes, whole-grain products, cereals (including all cereals products), nuts,
108 soya-based products (including also substitutes), vegetables, fruits, fruit juice, beverages (including
109 non-alcoholic beverages), oil (including vegetable oils) and alcohol (including all alcoholic beverages).
110 Nutrient values were derived from the food composition table developed for the NutriNet-Santé
111 study (28). Detailed information on the composition of the food groups is provided in the legend of
112 Figure 1.

113 **Environmental data**

114 Environmental pressures, greenhouse gas (GHG) emissions (CO₂-eq), Cumulative Energy Demand
115 (MJ), Land use (m²), were assessed using the DIALECTE tool (29). Developed by Solagro, this French
116 diagnostic tool aims to evaluate the environmental performance of French farms using a
117 comprehensive approach. The Life Cycle Assessment method was used on 60 raw agricultural
118 products. The scope of the analysis was limited to the agricultural production stage but organic and
119 conventional products were distinguished. Details are provided in **Supplemental Material 1**. In
120 addition, the pReCiPe score, a synthetic impact indicator including the three indicators above, has

121 been calculated (30). To balance conflicting environmental indicators, the ReCiPe method considers
 122 both midpoint and endpoint measures. Developed in the Netherlands, this LCA method aligns the
 123 indicators to provide a comprehensive view (30). It focuses on 18 indicators, three of which are
 124 oriented towards final impacts, including resource availability, human health and ecosystem
 125 diversity. In practice, some authors have found that the environmental impact of food products and
 126 diets can be assessed by measuring greenhouse gas emissions, primary energy consumption, and
 127 land occupation. These factors make up about 90% of the total environmental dimension of the
 128 ReCiPe model. To calculate the environmental impact of a food product or diet, one can use the
 129 partial ReCiPe score (pReCiPe), with normalization and weighting factors (31).

130 The pReCiPe score is computed as follows:

$$pReCiPe = 0.0459 \times GHGe + 0.0025 \times CED + 0.0439 \times LO$$

131
 132 with GHGe, in kg of CO₂eq/d, CED, in MJ/d and LO, in m²/d. The highest the pReCiPe, the highest the
 133 environmental impact.

134 **Nutritional quality data**

135 Three dietary indexes were computed. The PANDiet (Diet Quality Index based on the Probability of
 136 Adequate Nutrient Intake) is a nutritional adequacy score based on the nutritional references values
 137 (32,33). The PNNS-GS2 (Program National Nutrition Health Guidelines Score) measures the
 138 adherence of individuals to the French dietary guidelines established by the High Council of Public
 139 Health in 2017 (34). The cDQI (Comprehensive Diet Quality Index) aims to assess the quality of plant
 140 and animal foods consumed (35). Further details are provided in **Supplemental Material 2**.

141 **Health risk data**

142 Health risk was assessed using a “*Health Risk Score*” (HRS) of the diet, computed using the distance
 143 to the Theoretical Minimum-Risk Exposure Level (TMREL), provided in the GBD study in 2019 (12). It
 144 reflects the overall risk of death associated with the individual dietary pattern, resulted from a

145 suboptimal consumption of each food group. The computation of the HRS, ranging from 0 to 1, is
146 provided in the **Supplemental Material 3**.

147 **Economic data**

148 The economic data used were participants' monthly income, and their estimated food expenditures
149 for their whole diet and each food group.

150 Participants' income was collected as part of the socio-economic status questionnaire, where each
151 participant provided the income class corresponding to his/her monthly income. Income per
152 consumption unit (C.U) were estimated using household composition and age of family members
153 according to the INSEE procedure (36). In the NutriNet-Santé study, the monetary cost of the diet
154 (€/d) was calculated for each participant using prices (€/g) from several databases. Further details
155 are provided in **Supplemental Material 4**.

156 **Statistical Analysis**

157 Among the participants in the cohort NutriNet-Santé, 29, 210 individuals were selected for this study,
158 with Org-FFQ data, no missing data for sociodemographic aspects (except for monthly income which
159 is a non-mandatory question) and with available information on place of purchase. Those considered
160 as under- or over-reporters for energy intake were excluded as previously published (27). A flowchart
161 is provided in **Supplemental Figure 1**.

162 **Construction of the protein-source-typology and description of clusters**

163 The contribution (in %) to total protein intake of the 23 food groups was calculated for each
164 individual, to focus on the sources independently of the total intake. The typology aiming to identify
165 groups of individuals with similar protein sources was built using a two-step procedure. First, a
166 Principal Component Analysis (37) was applied on the 23 protein contributing food groups (the list is
167 available on **Figure 1**). This multivariate data analysis method allowed to reduce the initial range of
168 information by maximizing the variance. Nine dimensions were retained according to Kaiser criterion
169 (eigenvalues >1). Then, on the basis of the retained dimensions, an Ascending Hierarchical
170 Classification (AHC) was performed with data preprocessing using the K-means algorithm reiterated

171 100 times. As this study used a large database, the complementary use of the k-means and AHC
 172 methods allowed to stabilize the solution. Further details are provided in **Supplemental Material 5**.

173 **Description and comparison of clusters**

174 The clusters were named according to the food groups contributing the most to the protein intake of
 175 each cluster compared to the whole sample. First, means (SD) of protein contribution of each food
 176 group were computed (%/day) for the whole sample. Then, as cluster potentially exhibits a different
 177 energy intake than the whole sample, energy-adjusted means of protein contributions of the 23 food
 178 groups (SEM) were calculated for each cluster, using ANCOVA models.

179 The identified clusters were described according to the socio-demographic characteristics reporting
 180 mean (SD) or % for continuous and categorical variables respectively. Means comparison across
 181 clusters was performed using Pearson's Chi-square test for categorical variables and ANOVA test for
 182 continuous variables. For food groups consumption, mean (SD) were presented for the whole
 183 sample, and for each cluster, energy-adjusted mean of food group intakes (g/day) and standard error
 184 of the mean (SEM) were calculated, using ANCOVA models.

185 Percentages of total energy intake were calculated for macronutrients. For vitamins, minerals and
 186 fiber, each nutrient energy-adjusted intake was calculated based on the "residual method" (38).

187 Prevalence of adequate protein intake is computed as defined in the PANDiet score (33).

188 To allow comparison of clusters to the whole sample in relative values for all indicators, standardized
 189 means were computed for the whole sample, corresponding to the mean that the whole sample
 190 would have if its energy intake was that of the cluster (*overall_i*). Relative values as regards energy-
 191 adjusted indicator, were then calculated with the following formula:

$$\text{Relative value of indicator } i(\%) = \frac{\text{Energy adjusted mean}_i - \text{Standardized mean}_{\text{overall}_i}}{\text{Standardized mean}_{\text{overall}_i}} \times 100$$

192 Where i denotes clusters.

193 **Multicriteria analysis**

194 For each sustainability indicator considered, we calculated the mean (SD), and for each cluster,
 195 energy-adjusted means (SEM) were calculated via ANCOVA models. Comparison between clusters

196 was based on relative values computed as defined above. A comparison of means across clusters was
 197 performed using ANCOVA models.

198 **Economic analysis**

199 The objective was to analyze both food and protein expenditure structure across clusters. The
 200 economic analysis included 27,244 of the 29,210 participants, for whom there were no missing
 201 income data (since the question was optional). The monthly income variable, modelled, as category
 202 was transformed into a numeric variable by considering the class center of the daily income category
 203 for each individual as previously done (39) and converted as euros per day.

204 The expenditure structure analysis across clusters was conducted using a budget coefficient
 205 approach (40). This approach makes comparable the share of food expenditure between individuals
 206 with different incomes and different diets (40).

207 To do so, we first computed for each participant, the budget coefficients of both the overall diet and
 208 the food groups, using the following formulas:

$$\text{Budget coefficient of the overall diet}_i = \frac{\text{Overall diet expenditure}_i}{\text{Income}_i} \times 100$$

$$\text{Budget coefficient of food group}_{i,j} = \frac{\text{Food group expenditure}_{i,j}}{\text{Overall diet expenditure}_i} \times 100$$

209 *Where i denotes individuals and j denotes food groups.*

210 Insofar as we assume that the production mode (organic/conventional) affects food expenditure, the
 211 analysis was detailed by distinguishing expenditures allocated to organic products from those
 212 allocated to conventional products. To do so, budget coefficients of organic and conventional foods,
 213 for the overall diet and for each food group were computed for each individual. For the overall diet,
 214 budget coefficients of the overall diet by production mode were computed with respect to the
 215 overall diet budget. The budget coefficients of the food groups by production mode were calculated
 216 in relation to the overall diet budget allocated to foods from the corresponding production mode.

217 We defined the protein expenditure as the share of the food group expenditure allocated to the daily
 218 protein intake. It was calculated, for each food group and for each participant, using the following
 219 formula:

$$\text{Protein expenditure}_{i,j} (\text{€}) = \frac{\text{Food expenditure}_{i,j} (\text{€}) \times \text{Protein intake}_{i,j} (\text{g})}{\text{Quantity consumed}_{i,j} (\text{g})}$$

220 Where i denotes individuals and j denotes food groups.

221 Then, the “**Total protein expenditure**” was calculated for each participant by summing the protein
222 expenditures for all food groups.

223 The budget coefficients of protein intake were then computed, using the following formulas:

$$\text{Budget coefficient of protein intake per food group}_{i,j} = \frac{\text{Protein expenditure}_{i,j}}{\text{Overall diet expenditure}_i} \times 100$$

$$\text{Budget coefficient of the total protein intake}_i = \frac{\text{Total Protein expenditure}_i}{\text{Overall diet expenditure}_i} \times 100$$

224 Where i denotes individuals and j denotes food groups.

225 Afterwards, non-adjusted means (SD) were computed for all the calculated budget coefficients for
226 the whole sample, and for each cluster, means and standard error of the mean (SEM) adjusted for
227 energy intake were estimated using ANCOVA models. Comparison between clusters was based on
228 relative percentage values computed using standardized means as defined above. Comparison of
229 means across clusters was performed using the ANCOVA test.

230 Data management and statistical analyses were performed using RStudio software (RStudio, Version
231 1.4.1717, © 2009-2021 RStudio, PBC).

232 **Results**

233 The study population was predominantly female (75%), with a mean age of 54 (SD=14) years
234 **(Supplemental Table 1).**

235 **Description of the protein-source typology**

236 Based on food group contribution to protein intake, we identified 5 clusters (**Figure 1 and Table 1**):
237 **Milk-based** cluster (17% of the population), characterized by high contributions of milk (+336%
238 higher than the whole sample) and beverages (coffee, tea (including with milk), all sweetened
239 beverages except fruit juice 100% ; **Meat-based** cluster (26% of the population) with high
240 contributions of red meat to proteins (+54%) , poultry and processed meat; **Fast-food-based** cluster
241 (29% of the population) showing a higher protein intake derived from fast food to proteins (+37%) ,

242 refined or wholegrain cereals, fatty and sweet products; **Healthy-fish-based** cluster (25% of the
243 population), characterized by high protein intake from seafood (+49%), wholegrain cereal products,
244 fruit and vegetables; and finally the **Healthy-plant-based** cluster (3% of the population) for which the
245 most of protein intake is derived from the consumption of soy (+909%), legumes, nuts, fruit and
246 vegetables. The detailed values are presented in **Table 1**, and **figure 1**.

247 The characteristics of the participants in the 5 clusters are shown in **Supplemental Table 1**. Food
248 group consumptions across clusters are presented in **Supplemental figure 2**, and computed nutrient
249 intakes across clusters are presented in **Supplemental Table 2**. Total Protein intakes range from
250 67g/d in the healthy-plant-based cluster to 99g/d in the meat-based cluster, while plant-based
251 protein intakes vary from 25g/d in the meat-based cluster to 53g/d in the healthy-plant-based
252 cluster.

253 **Multi-criteria analysis of clusters**

254 Results of the multicriteria analysis of clusters are presented in **Table 2** and **figure 2**.

255 **Nutritional quality**

256 **Table 2** shows that the healthy-plant-based had the highest PNNS-GS2 score (+144% compared to
257 the whole sample), reflecting a better adherence to the PNNS guidelines and the highest PANDiet
258 score (+12% compared to the whole sample) based on nutritional reference values, followed by the
259 healthy-fish-based cluster. This latter cluster, though, showed the highest cDQI score (+15%
260 compared to the whole sample), indicating the highest quality of both animal and plant foods
261 consumed. Inversely, the meat-based cluster had the lowest nutritional scores for all computed
262 indicators (-61%, -5% and -8% respectively for the PNNS-GS2, the PANDiet, and the cDQI indicators).

263 **Health risk score**

264 The health risk analysis (**Table 2**) showed that the structure of the healthy-plant-based cluster was
265 the most beneficial compared to the other clusters (0.25 for the HRS score), followed by the healthy-
266 fish-based cluster (0.53 for the HRS score). Yet, the health risk score associated with the meat-based
267 cluster was the highest among the five clusters (0.95 for the HRS score). Furthermore, the analysis of

268 the contribution of food groups to the health risk score shows that for all clusters, a low consumption
269 of wholegrain products and legumes and a high consumption of red meat contribute the most to the
270 value of the HRS.

271 **Environmental impacts**

272 **Table 2** shows that for all observed indicators, the healthy-plant-based cluster had the least impact
273 on the environment (pReCIpe: - 62% compared to the whole sample), while the meat-based cluster
274 showed the highest impact (pReCIpe: + 33% compared to the whole sample) among the five
275 identified diets. The environmental impacts of healthy-fish-based and fast-food-based clusters were
276 lower than the whole sample means for all indicators. The milk-based diet showed similar
277 environmental impacts to the whole sample means.

278 **Organic food consumption across clusters**

279 **Table 2** shows that participants of the healthy-plant-based cluster had the highest share of organic
280 consumption (+127% compared to the whole sample), followed by the participants of the healthy-
281 fish-based cluster showing a 40% higher share than the average of the population. However, the
282 participants of the meat-based and milk-based clusters showed the lowest share of organic food (-
283 30% compared to the whole sample) among the five identified clusters.

284 **Economic analysis**

285 The healthy-plant-based cluster had the largest share of income allocated to food (+46% compared
286 to the whole sample) (**Figure 3**). On the opposite, consumers of milk-based and fast-food-based
287 clusters spent the smallest share of their income for food (-10% and -6% compared to the whole
288 sample), while the food budget coefficient of the meat-based cluster is similar to the mean of the
289 population studied. Comparison of clusters by food groups revealed that budget coefficients
290 followed the same trend as food intake across the clusters. Furthermore, analysis of food
291 expenditure structure by cluster showed that vegetables are the food group for which all clusters
292 spent the largest share of their overall diet expenditure, with the exception of the meat-based
293 cluster, who spent the most for meat.

294 After vegetables, the milk-based cluster spent more for meat and non-alcoholic beverages, the fast-
295 food-based cluster for dairy products, the healthy-fish-based cluster for fruit and seafood, and the
296 healthy-plant-based cluster for fruits and soy-based foods. The detailed values are presented in
297 **Supplemental table 3.**

298 Analysis of the overall diet budget coefficients according to the production mode (**Supplemental**
299 **Table 4**) showed that 70% of the food expenditure of the healthy-plant-based cluster was allocated
300 to organic products, which contributes to the higher diet expenditure. Conversely, the meat-based
301 cluster had the lowest share of the budget allocated to organic food (20%).

302 In terms of budget coefficients of protein intake (**Figure 3**), meat-based cluster participants were
303 those spending the most of their overall diet expenditure for their protein intake (+13% compared to
304 the whole sample). The healthy-plant-based cluster exhibited
305 the lowest protein expenditure (-41% compared to the whole sample), followed by the fast-food-
306 based and milk-based clusters (-5% and -3% respectively, compared to the whole sample). Analysis of
307 protein expenditure structure by cluster showed that meat-based, milk-based and fast-food-based
308 clusters spent the largest share of their overall diet expenditure on meat proteins. The healthy-fish-
309 based cluster allocated the largest share of their overall diet expenditure to seafood proteins, while
310 the healthy-plant-based cluster spent more on nuts proteins.

311 The detailed values are presented in **Supplemental Table 5.**

312 **Discussion**

313 We extracted five clusters based according to food-group contribution to protein intake (all analyses
314 are adjusted for energy intake). The healthy-plant-based cluster (3%) and the healthy-fish-based
315 cluster (25%) were the most sustainable for the environmental, nutritional and health dimensions.
316 Conversely, the meat-based cluster (26%) exhibited the highest environmental pressures, the lowest
317 nutritional scores and a high health risk. Furthermore, based on an economic analysis, we observed
318 that although the healthy-plant-based cluster had the highest food budget coefficient, its
319 expenditure for protein intake was the lowest. Conversely, expenditure on protein intake was high

320 for the meat-based cluster eaters. This study therefore argues that the protein sources of a diet are a
321 good factor in the sustainability of diets.

322 **Nutritional quality and health risk across diets**

323 The healthy-plant-based cluster exhibited the highest PANDiet score, and a better adherence to the
324 PNNS guidelines. In fact, while the choice of protein sources in individuals' diets often raises the
325 question of protein adequacy (including protein and amino acid intakes) (16), previous studies
326 documented that balanced diets in accordance with public health goals and with low meat intake,
327 provide an adequate intake for most nutrients (41). Indeed, the amounts and quality of plant-based
328 proteins are frequently underestimated or misunderstood (42). Moreover, maintaining protein
329 adequacy in spite of the decrease in the consumed quantity of animal protein could be explained by
330 the great excess above the needs in terms of protein intake in Western countries (16). But this issue
331 is still being debated and for example, a Canadian cohort study stated that the transition to plant-
332 based protein might be nutritionally challenging since animal protein contributes overwhelmingly to
333 total protein intake, particularly for the elderly (43).

334 The health risk analysis showed that the dietary structure of the healthy-plant-based cluster eaters is
335 the most protective in terms of health benefits, as reflected using the HRS, while the health risk
336 associated with the meat-based cluster is much higher. Similar results were found using another
337 health risk estimator, the HiDiet score, aiming to evaluate the effect of diet on long-term morbidity
338 and mortality (22). Thus, plant-based protein consumption was proven to be associated with nutrient
339 intakes and dietary profiles that are supportive of cardiometabolic health (44). Moreover, the
340 reduction in premature mortality associated with the adoption of balanced low-meat diets, was
341 estimated at 19% for the flexitarian diet and 22% for the vegan diet (41). Furthermore, the
342 association between animal sourced food consumption and the risk of chronic diseases has been
343 established by literature (45–47). For instance, it has been demonstrated that a 5% substitution of
344 animal protein with plant protein would reduce the risk of incidence of type 2 diabetes by 23% (48).

345 Indeed, red and processed meat were proved to be risk factors for type 2 diabetes, while soy and
346 dairy products provide protection (49).

347 **Environmental impacts across the diets**

348 As the literature on the environmental impacts of protein consumption has not been sufficiently
349 developed, we situated our results in relation to existing studies comparing predominantly animal-
350 based diets to more plant-based diets. In our study, the healthy plant-based cluster had less
351 environmental impact than the meat-based cluster, which exhibited the highest environmental
352 pressures. This is in accordance with the available literature regarding the lowest impact of plant-
353 based dietary patterns (8,22,50,51). Moreover, it has been demonstrated, in a comprehensive review
354 (52), that the decrease of the environmental footprint is generally proportional to the extent to
355 which animal-based food consumption is restricted (41). Furthermore, we reported that belonging to
356 the healthy-plant-based cluster was concomitant with a higher consumption of organic products, as
357 shown before (53), which could contribute to the lower environmental impacts, especially for energy
358 demand. A previous study also based on the NutriNet-Santé cohort (54), showed that organic food
359 consumption could partly explain the inverse link between plant-based diet and some environmental
360 impacts (GHG emissions and energy demand), specifying that this link is only established for
361 individuals with diets rich in plant-based foods.

362 **Economic analysis**

363 We showed that, at constant energy intake, the overall diet expenditure of the healthy-plant-based
364 cluster was the highest among the five clusters, followed by the healthy-fish-based cluster, and to a
365 lesser extent the meat-based cluster. In that regard, a previous study based on a representative
366 sample of 1,719 French adults (INCA2), showed that meeting with nutritional reference values
367 systematically increased the cost of food (55), which is consistent with our previous findings
368 regarding the superiority of the nutritional quality of healthy-plant-based and healthy-fish-based
369 clusters. Nevertheless, improving diet quality by optimization on nutritional constraints without
370 increasing food expenditure, regardless of the initially observed cost, has been shown to be possible

371 (55). However, for food budgets below 3.85€/day, significant diet changes were needed.
372 Furthermore, the high food budget coefficients associated with the healthy-plant-based and healthy-
373 fish-based clusters might also be explained by the much higher share of organic food consumption of
374 these two clusters. Similarly, another study also based on the NutriNet-Santé cohort (56)
375 demonstrated that high consumers of organic food displayed a high consumption of plant-based
376 foods and a healthier diet. Thus, the monetary cost of their diet was higher (+26%) compared to that
377 of low consumers due to the higher prices of organic products as shown by a decomposition model
378 of the effects. This dual choice seems a best option by resulting in a markedly reduced exposure to
379 pesticides from diet (56).

380 Interestingly, the protein budget coefficient of the meat-based cluster was higher than that of other
381 clusters, which could be explained by both the higher prices of protein foods characteristic of the diet
382 adopted by this cluster's participants (meat, poultry and processed meat) and their higher protein
383 intake (+6% compared to the whole sample). Inversely, both the lower protein intake of the healthy-
384 plant-based cluster eaters (-27% compared to the whole sample) and the lower prices of their diet's
385 proteins sources (soya-based foods, legumes and nuts), might explain the lower protein budget
386 coefficient. Indeed, it has been previously demonstrated in a meta-analysis assessing the nutritional
387 status of meat-based diets compared to plant-based diets, that the protein intake of meat eaters was
388 higher than that of people adopting a plant-based diet, although it was still within the recommended
389 levels (57).

390 **Multicriteria analysis of diets' sustainability according to protein intake**

391 The scarcity of studies on sustainability in its entirety is inherent to its multidimensionality, which
392 makes it complex to conduct research in this sense. Indeed, while a multi-criteria analysis of protein
393 profiles (22) close to our study only addressed 2 of the 4 dimensions of diets sustainability
394 (environment, nutrition and health) according to the FAO definition (21), we also focused on the
395 economic aspect since this dimension has rarely been accounted for in multi-criteria studies on
396 sustainability. The economic analysis we carried out aimed to provide an initial overview of the

397 aspect of economic affordability. However, cultural acceptability, which is a significant obstacle to
398 achieving changes in dietary behaviour, haven't been sufficiently addressed neither in our work nor
399 in that of Perraud et al. (22). On the other hand, the multiplicity of aspects making up these
400 dimensions prevent from covering them entirely. Indeed, although we assessed the environmental
401 pressures and impacts on 3 aspects, the above-mentioned study (22) evaluated other impacts by
402 mobilizing more indicators, but without distinguishing organic and conventional foods as we did. The
403 results of this study (22) remain consistent with ours, showing that protein profiles associated with
404 low meat consumption tend to be more sustainable on the two dimensions analysed, namely
405 environment, nutrition and health. Moreover, due to the difference in dietary behaviours of the
406 different populations considered in these two studies, discrepancies with our results are identified,
407 notably in the identification of clusters (distinction between ruminant and monogastric meat in the
408 protein profiles (22), identification of more plant-based protein profiles in our work).

409 **Action levers for greater sustainability**

410 Insofar as we concluded that the nature of protein intake is a discriminating factor in the
411 sustainability of diets, it is relevant to consider this factor for the development of action plans for
412 changing dietary patterns towards greater sustainability. As previously mentioned, meat
413 consumption is associated with socio-cultural values, making transitions to plant-based diets more
414 complex to manage in practice (58,59). To this end, some suggestions have been developed in the
415 literature. First, at the production stage, some environmental impacts could be reduced by
416 integrating crops and livestock (60) and promoting grazing systems. This could improve efficiency of
417 animal feeding and nutrient cycling, besides crop rotation through temporary grasslands. Also, non-
418 food biomass would serve as feed for animals, which provide organic fertilizer (60). Then, at the
419 consumption stage, an intrinsic change in diet at the food group level could be operated. As we
420 demonstrated that beef, pork and poultry consumption are correlated for the meat-based cluster,
421 replacing ruminant meat by poultry (13,61) could contribute to reduce some environmental
422 pressures, especially GHG emissions (13) and to lower the health risk compared to red meat (13).

423 However, this raises the question of the individualized nature of dietary pattern, which conditions
424 the feasibility of the effective transition from potential pathways to action plans for sustainable
425 dietary changes. Acceptability is thus enhanced by considering personalized and targeted
426 recommendations.

427 **Strengths and limitation**

428 First of all, it is important to note that the participants in the NutriNet-Santé cohort are volunteers,
429 who may have a greater interest in nutrition and health compared to the general population. As a
430 result, this sample exhibits certain characteristics such as a higher proportion of women, older
431 individuals, those with higher education and healthier dietary habits (62). However, the large sample
432 size allows access to a wide variety of dietary profiles and probably a higher representation of diets
433 rich in plant-based foods. However, our sample is not representative of the French population and
434 these results cannot be directly generalized. Secondly, the environmental data mobilized are limited
435 to the production stage. However, this stage represents the major part of the environmental impacts
436 of the food system. And, as mentioned above, the socio-cultural dimension associated with the
437 choice of protein sources in diets was not considered in this study. However, our study is the first to
438 provide a multi-criteria analysis of sustainability according to protein profiles, while including an
439 economic analysis. It covers a large French population, with various dietary patterns, including plant-
440 based diets. Moreover, our study considers production modes (organic, conventional), and the data
441 on food expenditures are quite accurate by considering consumers' places of purchase.

442 **Conclusion**

443 In conclusion, the nature of protein intake is a good discriminating factor of diets sustainability. The
444 healthy-plant-based and healthy-fish-based clusters were the most sustainable, allowing to conciliate
445 the trade-off between individual and environmental health. Conversely, the meat-based cluster
446 exhibited the highest environmental pressures, the lowest nutritional scores and a higher health risk
447 score. Additionally, although the healthy-plant-based cluster had the highest food budget coefficient,
448 their expenditure on protein intake was the lowest. However, this same expenditure was high for the

449 meat-based cluster, which is explained by both higher prices of the protein sources consumed and
450 their higher protein intake. These results could be useful for the development of food transition
451 strategies aimed at reducing animal protein consumption.

452

453 **Data Availability**

454 Analytic code will be made available upon request pending. Researchers from public institutions can
455 submit a collaboration request including information on the institution and a brief description of the
456 project to collaboration@etude-nutrinet-sante.fr. All requests will be reviewed by the steering
457 committee of the NutriNet-Santé study. If the collaboration is accepted, a data access agreement will
458 be necessary and appropriate authorizations from the competent administrative authorities may be
459 needed. In accordance with existing regulations, no personal data will be accessible

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644 **The authors' contributions are as follows:**

645 EKG, BA, DL, PP and JB, led the BioNutriNet project on which the data used.

646 HT conducted the analysis supervised by EKG.

647 HT wrote the statistical script, conducted analyses and drafted the manuscript.

648 All authors critically helped in the interpretation of results, revised the manuscript and provided
649 relevant intellectual input. They all read and approved the final manuscript.

650 EKG had primary responsibility for the final content, she is the guarantor.

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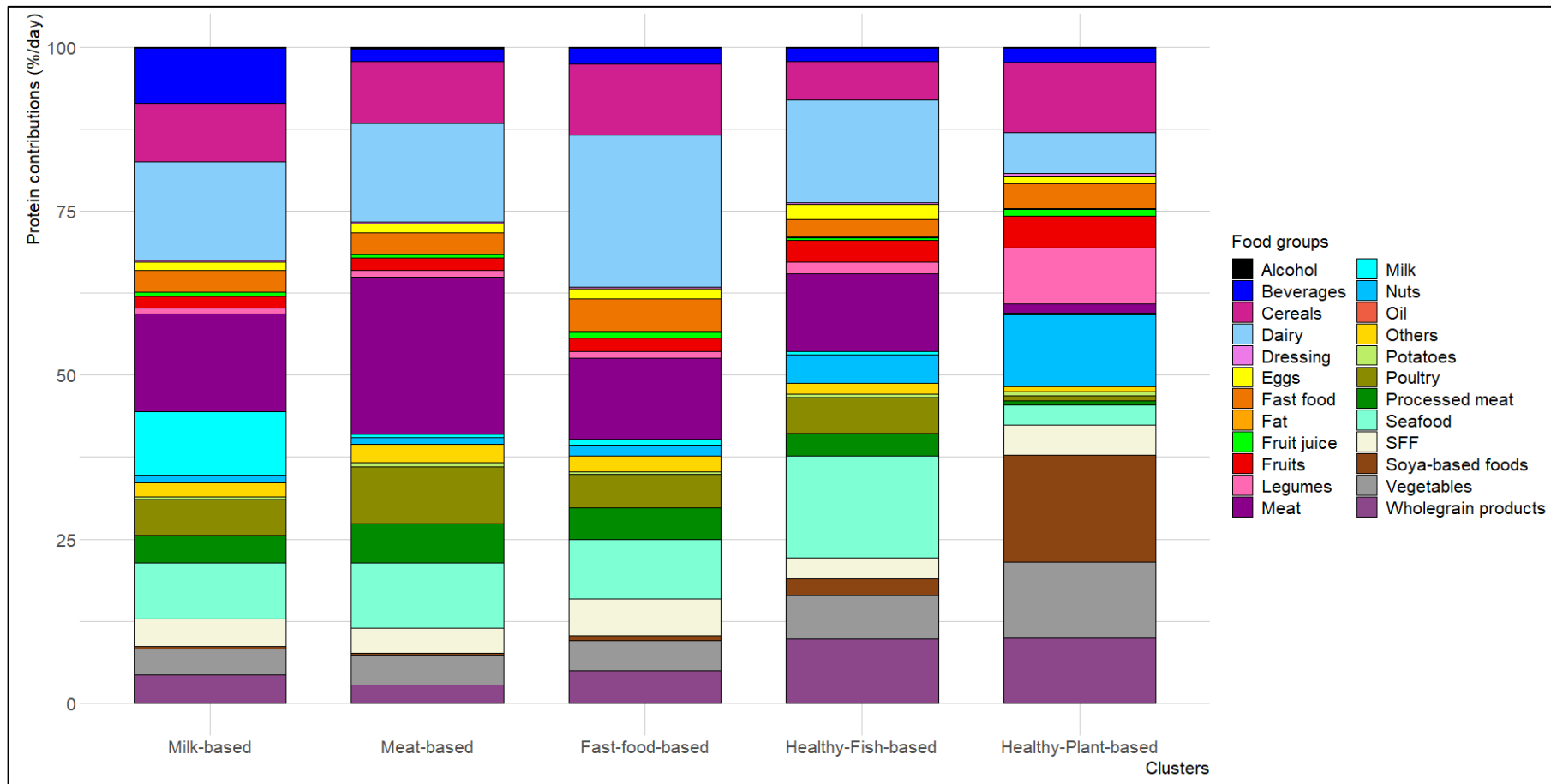
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661 **Additional Information**

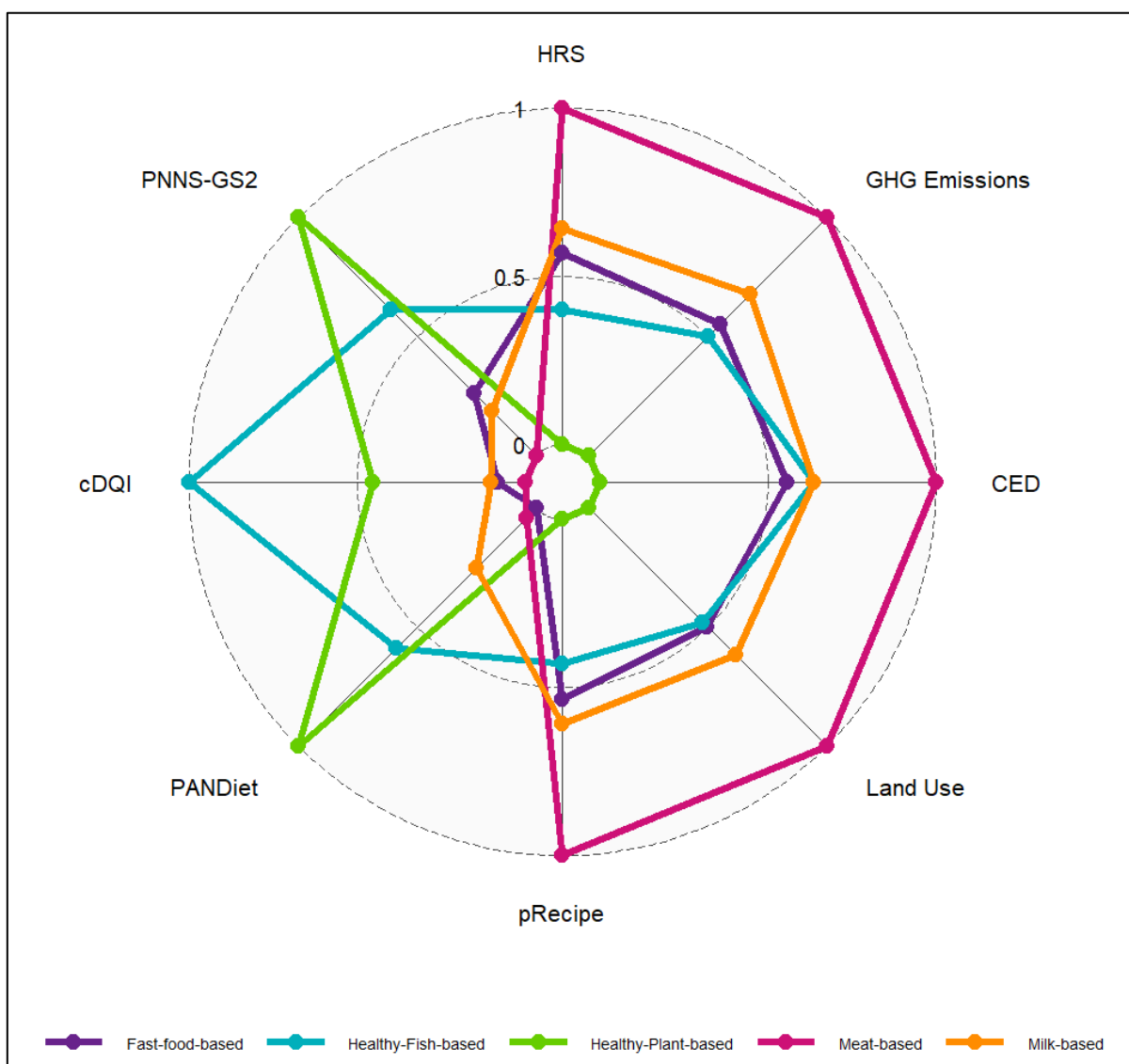
662 No author declared conflict of interest.

663 **Figure 1: Protein contributions per food group across clusters¹**



664 ¹ Values are energy-adjusted means of protein contributions of food groups (%/day) computed using ANCOVA model. Food groups are formed as follows: Vegetables include all vegetables and
 665 soups, fruit include fresh fruit, fruit in syrup and compote, dried fruit and seeds, beverages include fruit nectar, syrup, soda (with or without sugar), plant-based beverages (except soy-based),
 666 milk consumed with tea/coffee, Seafood, dairy products include yogurts, fresh cheese and cheese, potatoes include other tubers, cereals include breakfast cereal low in sugar, bread semolina,
 667 rice and pasta, SFF (sweet and fat foods) include croissants, pastries, chocolate, biscuits, milky dessert, ice cream, honey and marmalade, cakes, chips, salted oilseeds, salted biscuits, fast-food
 668 include sandwich, prepared foods such as pizza, hamburger, ravioli, panini, salted pancake, etc., soy includes soy-based food that are tofu, soy-based meat substitute and vegetable patties,
 669 soy-based yogurt, soy-based milk, animal fat (butter and lards) and dressing (ready-to-use salad dressing, mayonnaise or cream-based sauces) include sour cream and butter and all fat-based
 670 sauces, oil include plant-based oils, meat includes beef and pork.

672 **Figure 2: Sustainability indicators across clusters¹**

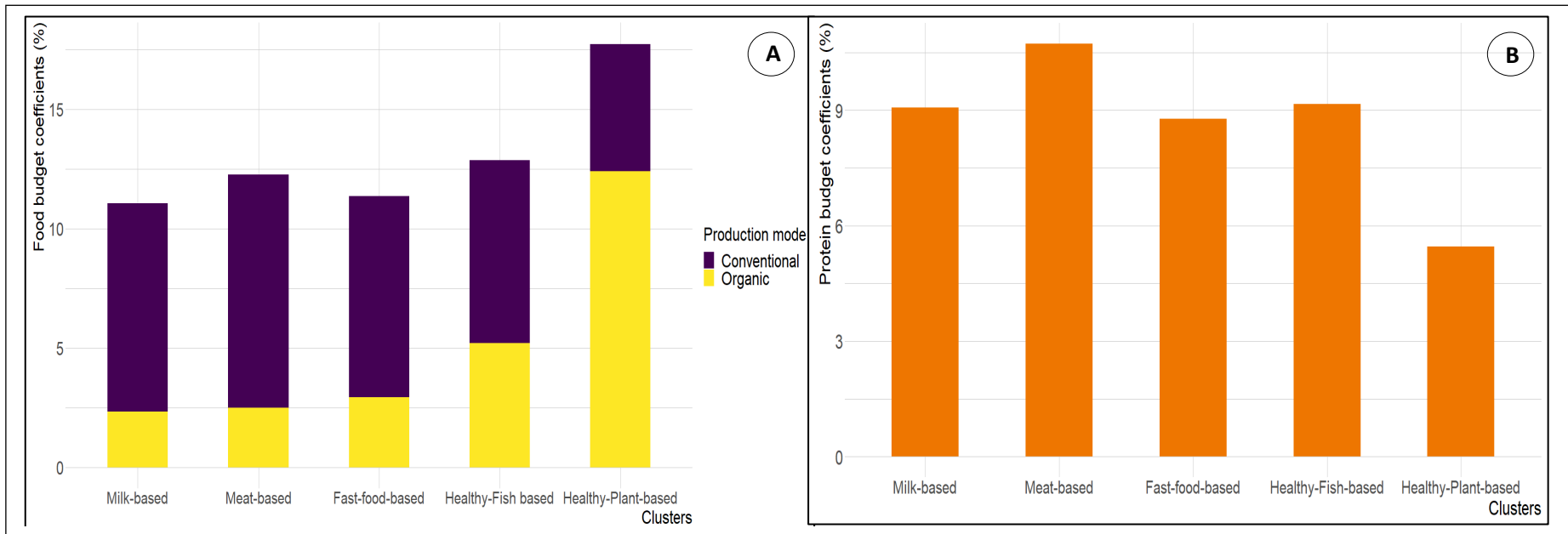


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 674 Abbreviations: HRS, Heath Risk Score; GHG, Greenhouse Gas (kg CO2 eq/d); CED, Cumulative Energy Demand (MJ/d); Land
 675 Use (m²/d); pRecipe, partial Recipe; PANDiet, Diet Quality Index based on the Probability of Adequate Nutrient Intake; cDQI,
 676 Comprehensive Diet Quality Index; PNNS-GS2, Program National Nutrition Health Guidelines Score.

677 ¹ The energy-adjusted means of indicators, computed using ANCOVA model, were rescaled to the same scale by equalizing
 678 the maximum value to 1 and the minimum value to 0 for each indicator. For the environmental indicators and the HRS,
 679 higher values denote higher impacts/risk. For nutritional quality indicators, higher values denote higher nutritional quality.
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681 **Figure 3 : Food budget coefficients across clusters according to production mode (A); Protein budget coefficients across clusters (B)¹.**

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¹ Values are energy-adjusted means of budget coefficients computed using ANCOVA model.
Panel A refers to food budget coefficients across clusters according to production mode (organic/conventional). Panel B refers to protein budget coefficients across clusters.

Table 1: Protein contributions of food groups across clusters^{1,2,3}

Food groups	Whole sample n = 29,210	Milk-based n = 4,966 (17%)	Meat-based n = 7,569 (26%)	Fast-food-based n = 8,469 (29%)	Healthy-fish-based n = 7,189 (25%)	Healthy-plant-based n = 1,017 (3%)	p
Legumes	1.41 (2.49)	0.86 (0.03)	0.95 (0.02)	1.06 (0.02)	1.71 (0.02)	8.49 (0.07)	< 0.0001
Soya-based foods	1.62 (4.72)	0.43 (0.05)	0.42 (0.04)	0.83 (0.04)	2.56 (0.04)	16.33 (0.12)	< 0.0001
Cereals	8.9 (6.38)	8.83 (0.09)	9.39 (0.07)	10.84 (0.07)	5.91 (0.07)	10.68 (0.19)	< 0.0001
Nuts	2.39 (4.37)	1.23 (0.05)	1.00 (0.04)	1.60 (0.04)	4.37 (0.04)	11.00 (0.12)	< 0.0001
Wholegrain products	5.59 (7.06)	4.26 (0.09)	2.74 (0.07)	4.91 (0.07)	9.73 (0.08)	9.93 (0.20)	< 0.0001
Fruits	2.41 (2.69)	1.83 (0.04)	1.98 (0.03)	2.07 (0.03)	3.35 (0.03)	4.81 (0.08)	< 0.0001
Fruit juice	0.61 (0.91)	0.59 (0.01)	0.44 (0.01)	0.89 (0.01)	0.42 (0.01)	1.07 (0.03)	< 0.0001
Vegetables	5.21 (3.63)	4.00 (0.05)	4.45 (0.04)	4.61 (0.04)	6.69 (0.04)	11.55 (0.10)	< 0.0001
Potatoes	0.46 (0.49)	0.39 (0.01)	0.59 (0.01)	0.42 (0.01)	0.41 (0.01)	0.60 (0.01)	< 0.0001
Alcohol	0.22 (0.53)	0.16 (0.01)	0.29 (0.01)	0.22 (0.01)	0.21 (0.01)	0.20 (0.01)	< 0.0001
Dressing	0.23 (0.28)	0.18 (0.00)	0.21 (0.00)	0.31 (0.00)	0.21 (0.00)	0.31 (0.01)	< 0.0001
Beverages	3.19 (4.24)	8.46 (0.05)	1.99 (0.04)	2.38 (0.04)	1.95 (0.04)	2.13 (0.11)	< 0.0001
Oil	0 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	< 0.0001
Meat	15.26 (10.16)	14.86 (0.12)	23.94 (0.10)	12.36 (0.10)	11.8 (0.10)	1.35 (0.26)	< 0.0001
Processed meat	4.55 (3.88)	4.22 (0.05)	5.99 (0.04)	4.84 (0.04)	3.50 (0.04)	0.55 (0.12)	< 0.0001
Eggs	1.6 (1.66)	1.34 (0.02)	1.36 (0.02)	1.47 (0.02)	2.25 (0.02)	1.23 (0.05)	< 0.0001
Fast food	3.64 (3.24)	3.22 (0.04)	3.31 (0.04)	4.94 (0.03)	2.73 (0.04)	3.81 (0.10)	< 0.0001
Fat	0.08 (0.13)	0.07 (0.00)	0.07 (0.00)	0.12 (0.00)	0.08 (0.00)	0.12 (0.00)	< 0.0001
Poultry	6.03 (5.14)	5.38 (0.07)	8.76 (0.05)	5.03 (0.05)	5.52 (0.06)	0.83 (0.15)	< 0.0001
Dairy	17.28 (10.06)	15.14 (0.13)	15.05 (0.11)	23.16 (0.10)	15.73 (0.11)	6.29 (0.29)	< 0.0001
Seafood	10.55 (7.84)	8.51 (0.10)	9.90 (0.08)	9.09 (0.08)	15.42 (0.08)	3.14 (0.23)	< 0.0001
Milk	2.19 (5.06)	9.68 (0.05)	0.57 (0.04)	0.87 (0.04)	0.57 (0.04)	0.31 (0.12)	< 0.0001
SFF	4.24 (3.42)	4.20 (0.05)	3.81 (0.04)	5.52 (0.04)	3.21 (0.04)	4.53 (0.10)	< 0.0001

Abbreviations: SFF, Sweetened and Fatty Foods.

¹ Values are mean (SD) contribution (%) for the whole sample, and energy-adjusted means of protein contributions (SEM) across clusters (ANCOVA model).

² P values were calculated using ANCOVA.

³ Other food groups with minor contribution to protein intake are not represented

Table 2: Sustainability indicators across clusters^{1,2}

Indicators	Whole sample	Milk-based	Meat-based	Fast-food-based	Healthy-fish-based	Healthy-plant-based	p
<i>Nutritional quality</i>							
PANDiet	64.97 (7.86)	65.17 (0.09)	63.01 (0.07)	62.65 (0.07)	68.53 (0.07)	72.68 (0.21)	< 0.0001
AS	78.86 (12.74)	78.43 (0.13)	78.11 (0.1)	75.73 (0.1)	83.79 (0.1)	77.64 (0.29)	< 0.0001
MS	51.08 (18.49)	51.9 (0.15)	47.9 (0.12)	49.57 (0.12)	53.27 (0.13)	67.72 (0.35)	< 0.0001
cDQI	51.48 (9.18)	49.57 (0.11)	48.56 (0.09)	49.33 (0.08)	58.21 (0.09)	52.97 (0.25)	< 0.0001
aDQI	15.86 (3.9)	16.84 (0.05)	14.59 (0.04)	15.73 (0.04)	17.05 (0.04)	13.16 (0.11)	< 0.0001
pDQI	35.62 (7.47)	32.72 (0.09)	33.96 (0.07)	33.6 (0.07)	41.16 (0.07)	39.81 (0.2)	< 0.0001
PNNS-GS2	2.51 (3.56)	1.96 (0.03)	1.01 (0.03)	2.34 (0.02)	4.15 (0.03)	6.13 (0.08)	< 0.0001
<i>Environmental impacts</i>							
GHG emissions (kg CO ₂ eq/d)	4.05 (2.48)	4.13 (0.02)	5.47 (0.02)	3.61 (0.01)	3.4 (0.02)	1.31 (0.05)	< 0.0001
Cumulative Energy Demand (MJ/d)	17.62 (7.56)	17.08 (0.06)	21.14 (0.05)	16.18 (0.04)	17.09 (0.05)	9.85 (0.14)	< 0.0001
Land Use (m ² /d)	10.6 (6.75)	10.57 (0.07)	14.24 (0.05)	9.33 (0.05)	9.15 (0.05)	4.52 (0.15)	< 0.0001
pRecipe	0.28 (0.16)	0.28 (0.00)	0.39 (0.00)	0.26 (0.00)	0.23 (0.00)	0.11 (0.00)	< 0.0001
Organic food share	0.29 (0.27)	0.21 (0.00)	0.21 (0.00)	0.26 (0.00)	0.41 (0.00)	0.67 (0.01)	< 0.0001
<i>Health risk</i>							
RR (%) Whole grain	19.51 (12.35)	20.59 (0.16)	17.45 (0.13)	21.17 (0.12)	17.1 (0.14)	32.9 (0.37)	< 0.0001
RR (%) Fruits	6.98 (7.59)	7.8 (0.10)	5.17 (0.08)	8.26 (0.08)	5.8 (0.08)	14.07 (0.23)	< 0.0001
RR (%) Vegetables	2.19 (2.58)	2.87 (0.03)	1.54 (0.02)	2.77 (0.02)	1.69 (0.02)	2.4 (0.07)	< 0.0001
RR (%) Nuts/Seeds	3.82 (3.17)	3.84 (0.04)	2.95 (0.03)	3.88 (0.03)	4.1 (0.03)	7.56 (0.09)	< 0.0001
RR (%) Legumes	10.24 (6.47)	10.29 (0.08)	7.63 (0.07)	10.63 (0.06)	12.21 (0.07)	12.14 (0.19)	< 0.0001
RR (%) Milk	6.65 (5.86)	3.03 (0.06)	4.41 (0.05)	6.95 (0.05)	9.15 (0.05)	20.65 (0.14)	< 0.0001
RR (%) Processed meat	16.87 (10.22)	16.58 (0.14)	18.26 (0.11)	17.73 (0.1)	16.47 (0.11)	3.75 (0.3)	< 0.0001
RR (%) Red meat	32.97 (16.75)	34.08 (0.21)	41.97 (0.17)	27.67 (0.16)	32.89 (0.17)	5.19 (0.46)	< 0.0001
RR (%) Sweetened beverages	0.73 (1.96)	0.86 (0.02)	0.58 (0.02)	0.88 (0.02)	0.53 (0.02)	1.29 (0.06)	< 0.0001
HRS	0.69 (0.29)	0.7 (0.00)	0.95 (0.00)	0.65 (0.00)	0.53 (0.00)	0.25 (0.00)	< 0.0001

Abbreviations: AS, Adequation sub-score of PANDiet; MS, Moderation sub-score of PANDiet; HRS: Health Risk Score; RR: relative risk

¹ Values are mean (SD) for the whole sample, and adjusted means of indicators on total energy intake (SEM) across clusters (ANCOVA model).

² P values were calculated using ANCOVA.