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Plant-based meat substitutes are useful for healthier dietary patterns when adequately formulated – an optimization study in French adults (INCA3).

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3 Figures, 2 Tables

1 Supplementary Data (1 Supplemental Method, 9 Supplemental Tables, 1 Supplemental Figure)

Running title: Plant-based meat substitutes and diet optimization

Abbreviations used: ALA, α -linolenic acid; ANSES, French Agency for Food, Environmental and Occupational Health and Safety; CIQUAL, French Information Centre on Food Quality; DD, Diet departure; HDP, Healthy Dietary Pattern; INCA3, Third Individual and National Study on Food Consumption Survey; LA, linoleic acid; NRV, Nutrient Reference Value.

Abstract

Purpose: We studied to what extent plant-based meat substitutes could improve the nutritional adequacy and healthiness of dietary patterns, depending on their nutrient composition.

Methods: From diets observed in French adults (INCA3, n=1125), modeled diets were identified by allowing various dietary changes, between and within food categories, when two plant-based meat substitutes were made available: an average substitute (from 43 market substitutes) and a theoretical nutritionally-designed substitute, fortified or not with zinc and iron at 30% or 50% of Nutrient Reference Values. Under each scenario, healthier but acceptable modeled diets were identified using multi-criteria optimization, by maximizing a health criteria related to Dietary Guidelines while minimizing deviation from the observed diets, under constraints for nutrient adequacy.

Results: Without fortification, the average substitute was hardly introduced into modeled diets, whereas the optimized substitute was preferentially introduced, in large amounts, yet together with a moderate reduction of red meat (-20%). The comparative advantages of the optimized substitute were its higher contribution to vitamins B6 and C, fiber and α -linolenic acid (ALA) intakes and its lower contribution to sodium intake. When fortified with iron and zinc, substitutes were introduced in larger amounts into modeled diets, with much higher red meat reductions (down to -90%). The optimized substitute continued to be preferred, leading to healthier modeled diets that deviated less from the observed.

Conclusion: Plant-based meat substitutes can be levers for healthy diets only when well nutritionally designed with enough zinc and iron for a substantial red meat reduction.

Keywords: Plant-based meat substitutes; Diet optimization; Healthy dietary patterns;
Nutrient fortification

Introduction

Plant-based meat substitutes are products that aim to mimic the appearance and use of meat products and are seeing strong commercial development [1,2]. These products are considered as a good way to replace meat in a dish without disrupting the meal pattern [3] so they could assist in the transition towards more plant-based diets that are being advocated for health and environmental reasons [4,5].

Indeed, as well as their considerable environmental impacts [6-8], current dietary patterns in western countries are not healthy, favoring the development of non-communicable diseases [9]. In this context, modeling studies have been used to identify healthier dietary patterns that could assist in defining food-based dietary guidelines [10,11]. For instance, the most recent French dietary guidelines are based on an optimization method for modeling dietary patterns that could favor long-term health, based on epidemiological relationships between the consumption of different food groups and the risk of non-communicable diseases [12-14]. As with many dietary guidelines, consuming plant-based foods (vegetables, fruits, whole-grain products, legumes) is to be encouraged while consuming sweet and salty foods, red meat and processed meat should be reduced [12,15,16].

However, the potential role for plant-based meat substitutes in modeling healthy diets has rarely been considered [17]. Indeed, there are concerns whether plant-based substitutes could be part of a healthy diet, as their impacts on health have been little studied and many appear to be ultra-processed [18,19]. Furthermore, their nutritional composition and impacts on diet may vary depending on the type of meat substituted (red meat and/or poultry) and of the type of substitute and ingredients used [20,21]. Plant-based meat

substitutes generally contain low amounts of total and saturated fats and high amounts of fiber when compared to meat, but they may also contain high amounts of sodium [20,22], while the meat products they are intended to replace are important contributors of indispensable nutrients such as iron and zinc [16,23].

The objective of this study was therefore to investigate whether plant-based meat substitutes could be a potential nutritional lever to support healthier dietary patterns, by effectively replacing meat while maintaining a diet close to the observed one regarding other food groups. We explored the degree to which the availability of plant-based meat substitutes in the food repertoire could be useful when modeling healthy eating patterns, and whether this would depend on the nutrient composition of the meat substitute.

To achieve this, we used multi-criteria optimization to identify modeled diets that would be nutritionally adequate and healthier while remaining close to observed diets, according to a series of scenarios where two distinct meat substitutes with or without theoretical fortification in iron and zinc, were made available into the food repertoire to potentially replace meat and also possibly other food groups. The first meat substitute corresponded to an average substitute having the average nutrient composition of meat substitutes available on the market, while the second meat substitute was a substitute for which the recipe has been previously optimized in terms of its nutrient content [24]. This mainly pulse-based substitute was made from minimally processed ingredients and designed to maximize the diet quality (as assessed using the PANDiet score) when replacing meat, under technological and nutritional constraints to ensure formulation feasibility and nutrient security, respectively [24].

Methods

Input of dietary data

The data used for this study were extracted from the French Individual and National Study on Food Consumption Survey 3 (INCA3) conducted in 2014-2015. The INCA3 survey is the most recent representative cross-sectional survey of the French population and its method and design have been fully described elsewhere [25]. Men aged 18-64y (n=564) and women aged 18-54y (n=561), not identified as under-reporters as previously described [26,27], were included in the present study; the final sample contained 1125 adults.

Dietary data were collected by professional interviewers assisted by a dietary software from three (two weekdays and one weekend day) unplanned, non-consecutive, 24h dietary recalls spread over a 3-week period. Portion sizes were estimated using validated photographs [25] and the nutrient contents of different food items came from the 2016 food composition database operated by the French Information Centre on Food Quality (CIQUAL) [28]. Mixed foods were broken down into ingredients and then gathered into 45 food groups (Supplemental Table 1), by using a food grouping with an appropriately high level of detail for modeling healthier, more plant-based diets as in a previous study by our group [29]. For each sex, the nutrient content of each food group was calculated as the mean nutrient content of food items constituting the food group weighted by their mean intake by the sex considered, as previously described [29].

Multi-criteria optimization of the diet under constraints

We used a multi-objective, non-linear mathematical optimization program to identify the modeled diet (i.e., the modeled consumptions of the 45 food groups) with a maximal health profile and minimal deviation from the observed diet (taking account of cultural acceptability and inertia), under constraints that would ensure adequate nutrient intakes and remain within current consumption limits. In this context, we investigated the relative value of introducing different plant-based meat substitutes into the food repertoire. Each modeled diet was characterized by the optimized consumptions of the 45 food groups plus that of the meat substitute(s) added to the food repertoire.

Optimization was performed using the OPTMODEL procedure of SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA.). Optimization was implemented at the population level but in men and women separately, because of their differences in nutritional requirements and observed consumptions. The optimized diets of men and women were then gathered to derive optimized diets for the overall population by weighting each population by its relative distribution in the study population.

Objective function

The optimization procedure consisted in maximizing the health profile of the modeled diet (*Healthy Dietary Pattern* criterion, *HDP*) while minimizing its deviation from the current diet (*Diet Departure* criterion, *DD*), as previously described [13,29].

The *HDP* criterion set as its objective dietary recommendations based on epidemiological studies that had assessed associations between the consumption of different food groups and the risk of chronic diseases [14,29]. Its aim was thus to limit the consumption of red meat, processed meat and sweetened beverages while promoting the consumption of

whole cereal products, vegetables and fruits, in accordance with current French recommendations [12]. *HDP* was thus expressed and maximized as:

$$\text{Max } HDP = \sum_{i=1}^3 \left[\frac{\text{Opt}(i)}{\text{P95}(i)} \right] - \sum_{j=1}^3 \left[\frac{\text{Opt}(j)}{\text{Max}(j)} \right]$$

Where *i* denotes the food groups to be increased (vegetables, fruits and whole cereal products), *j* denotes the food groups to be decreased (red meat, processed meat and sweetened beverages), *Opt*(*i*) and *Opt*(*j*) are the optimized consumptions of food groups *i* and *j*, respectively (in g/d), *P95*(*i*) is the current 95th percentile of consumption of food group *i* (in g/d) and *Max*(*j*) is the upper limit of consumption of food group *j* (in g/d). This latter value was of 71, 25 and 263 g/d respectively for red meat, processed meat and sweetened beverages, as defined by the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) [13].

The *DD* criterion was designed to minimize deviation from the observed diet in order to account for dietary cultural acceptability and inertia. It was defined as the sum of the squares of the differences between observed and optimized food group consumptions standardized by their observed standard deviations [29]. *DD* was thus expressed and minimized as:

$$\text{Min } DD = \sum_{k=1}^n \left[\frac{\text{Obs}(k) - \text{Opt}(k)}{\text{SD}(k)} \right]^2$$

Where *k* is the number of food groups, *Obs*(*k*) and *Opt*(*k*) are respectively the observed and optimized consumptions of food group *k* (in g/d) and *SD*(*k*) is the current standard deviation of the consumption of food group *k*.

Some food groups were however considered to be easily interchangeable because they are usually consumed in the same way: this concerned the intra-category substitutions within fruits groups (fresh/dry/processed fruits), bread groups (refined/whole grains), other starches groups (refined/whole grains), vegetable fats groups (low/high in alpha-linolenic acid), sweetened beverages groups (sodas/fruits juices), fish groups (fat/lean fishes), fresh dairy products groups (natural/sweetened) and soups/bouillon groups. Most meat groups (beef and veal/pork and other meats/poultry) were also considered to be substitutable between each other and with plant-based meat substitutes, based on the rationale that these products are designed to replace meat in a meal [3]. In the *DD* criterion, the food groups within each easily substitutable category were grouped together so that only variations in their sums (and not their individual variations) would be considered, and that such intra-category substitutions were allowed without cost.

Finally, the optimization procedure consisted in minimizing a whole objective function combining the two objective criteria: $\min Obj = \min (DD - HDP)$ in order to both minimize *DD* and maximize *HDP*.

Constraints

Nutritional constraints were applied during optimization to ensure adequate nutrient intakes in the men and women populations (Supplemental Table 2). These constraints were based on the most recent reference values from ANSES [30]. Because the absorption of iron and zinc is dependent on dietary factors, the requirements were based on bioavailable iron and zinc calculated from the dietary intake using equations that predict their absorption (notably taking into account the limiting effect of phytate) [31-34], as detailed in a previous study by our group [29]. Previous work had demonstrated that

current recommendations regarding bioavailable iron and zinc are very constraining when trying to model healthier diet, but that allowing more flexibility would increase the prevalence of iron deficiency [29]. Therefore, in this work, nutritional constraints for bioavailable iron and zinc were based on current intakes so as to avoid any increase in the prevalence of iron and zinc deficiency in the modeled diets. A sensitivity analysis was nevertheless conducted, by comparing the results obtained when using the current recommendations versus the current intakes as lower bounds for bioavailable iron and zinc (Supplemental Method 1).

Dietary constraints were applied to the food groups included in the *HDP* criterion for which the consumption needed to be limited: red meat intake (beef and veal/pork and other meats/offal) was limited at 71g/d, processed meat intake at 25g/d and sweetened beverages intake (sodas/fruits juices) at 263 mg/d (corresponding to the average portion size) [13]. Acceptability constraints were also applied to keep the food group intakes within the range of observed intakes, by bounding each food group intake between its 5th and 95th percentile of observed consumption in men and women separately (Supplemental Table 3), with the exception of food groups for which a dietary constraint with an upper limit was already defined (red meat, processed meat and sweetened beverages). In addition, most food groups that were considered to be easily substitutable in the *DD* criterion were grouped together for the acceptability constraints. Additional constraints were also applied to restrict the introduction of meat substitutes so that the total intake of meat and meat substitutes would not exceed the 99th percentile of the initial meat consumption (Supplemental Table 3).

Plant-based meat substitutes in modeling scenarios

In order to study the potential of plant-based meat substitutes to model healthier diets, two types of plant-based meat substitute, which were not initially consumed in the observed diets, were made available for addition to the food repertoire of men and women during the diet optimization procedure. In the observed diets, the “Substitutes of animal products” food group denoted both the meat and dairy substitutes initially consumed. In the modeled diets, the intake of this group was kept constant and equal to its low observed value (<5g/d), in order not to interfere with the newly made available substitutes being tested. As explained above, beef and veal, pork and other meat and poultry groups could be replaced with meat substitutes without cost in the *DD* criterion.

The first substitute was an average meat substitute that corresponded to the mean nutrient composition of 43 plant-based meat substitutes (Supplemental Table 4), the detailed nutrient compositions of which were extracted from French databases [28,35,36]. The second substitute was an optimized meat substitute whose ingredients had previously been optimized to improve the diet quality of French adults when replacing meat products with this substitute [24]. Its ingredient composition is shown in **Table 1**. The nutrient compositions of the average and optimized meat substitutes are shown in **Table 2**.

We also tested the same meat substitutes after their theoretical fortification in zinc and iron to reach 30% or 50% of the Nutrient Reference Values (NRVs) [37]. The value of 30% was chosen because it is the minimum value required for the nutrition claim ‘High in’ and ‘increased in’. The value of 50% was selected as a significantly higher value than 30% that would yet not exceed commonly used levels in the field of fortification. Without fortification, the average and optimized substitutes initially contained 2.4 and 4.4 mg/100g of iron and 1.4 and 2.4 mg/100g of zinc, respectively (total content and not bioavailable

content). With fortification at 30% of the NRVs, the average and optimized substitutes contained 4.2 and 4.4mg/100g of iron, respectively (because the optimized substitute already contained more than 30% of the iron NRV) and both contained 3 mg/100g of zinc. With fortification at 50% of the NRVs, both substitutes contained 7 mg/100g of iron and 5 mg/100g of zinc.

Two different options regarding the introduction of meat substitutes were investigated: the average substitute only could be introduced into the food repertoire (AS scenarios) or both the average and optimized substitutes could be introduced, at different proportions (OS scenarios). These two options were implemented with or without the two levels of substitute fortification, thus producing a total of six modeling scenarios. We therefore identified modeled diets involving possible introduction of the average substitute that was non-fortified (AS) and fortified with zinc and iron at 30% (AS-30%) and 50% (AS-50%) of the NRVs, and modeled diets involving the possible introduction of both substitutes, either non-fortified (OS) and fortified for zinc and iron at 30% (OS-30%) and 50% (OS-50%) of the NRVs.

Analysis of the relative influence of nutritional constraints and food group contributions to limiting nutrients

The dual values associated with each constraint during optimization represent what would be the potential gain in objective function in case of a one-unit relaxation in the limiting bound (lower or upper) of the considered constraint. In order to compare the relative influence of the nutritional constraints on modeled diets, all constraints were standardized by the value of their limiting bound. This resulted in standardized dual values reflecting the potential gain in objective function if the limiting bound was relaxed by 100%, and

enabled classification of the nutritional constraints from the most limiting (highest absolute standardized dual value) to the least limiting (lowest value, close or equal to zero), as previously explained [29].

For the most limiting nutrients in the different modeled diets (i.e. nutrients with the most limiting constraints) we studied the contributions of different food groups to that nutrient intake in each modeled diet of all scenarios.

Results

Modeled diets including non-fortified plant-based meat substitutes

By construction, compared to the observed diets, all the modeled diets were both nutrient-adequate (because the nutritional constraints ensured adequate intakes for all nutrients, except for bioavailable iron and zinc for which levels were only constrained to be greater or equal to current intakes) and healthier (because of the optimization of the *HDP* criterion based on food group consumptions). Without iron and zinc fortification, when only the average meat substitute was made available into the repertoire (scenario AS), it was virtually not introduced into the diet (1g/d); when both substitutes could be introduced into the repertoire (scenario OS), only the optimized meat substitute was introduced into the diet, in substantial quantities (90g/d) (**Figure 1**). Compared to the observed diet, both scenarios led to healthier dietary patterns with more vegetables, fruits and whole grain products and less refined grain products, processed meats and sweetened beverages. There was also a higher intake of seafood, dairy products, eggs, potatoes and vegetable fat and a lower intake of animal fat (Supplemental Table 5). The *HDP* gain (defined as the difference in *HDP* values between the modeled and observed diets) was similar under both scenarios (2.6 with AS and 2.4 with OS) but the *DD* was lower under the OS scenario (2.3) than the AS scenario (3.9), meaning a higher similarity with the observed diet for the OS scenario (**Figure 2**).

In terms of meat consumption (**Figure 3**), under the AS scenario that hardly introduced the average meat substitute, the consumption of poultry doubled (+97%) and that of red meat remained unchanged compared to the observed diet. In contrast, under the OS scenario that significantly integrated the optimized substitute, poultry was entirely

removed and red meat was moderately reduced (-20%). Furthermore, under both scenarios, there were considerable disparities regarding the different types of red meat: offal systematically increased markedly (respectively +180% and +160% under the AS and OS scenarios) and beef and veal consumption increased moderately (respectively +39% and +11%) while that of pork and other meats were entirely removed (Supplemental Table 6).

There were also some differences in meat pattern consumptions between sexes (Supplemental Table 6). In men, red meat decreased similarly under both scenarios (-10%) to reach its upper limit (71g/d) without going below, processed meat was removed and poultry increased under the AS scenario (+203%) but was removed in the OS scenario. In women, red meat increased under the AS scenario (+17%) but decreased under the OS scenario (-38%); poultry remained stable under the AS scenario but was removed in the OS scenario, and processed meat decreased under both scenarios (-73% under AS and -53% under OS). Both the *HDP* gain and *DD* values were higher in men than in women (Supplemental Table 7).

Influence of iron and zinc fortification on modeled diet composition and *HDP* and *DD* values

Iron and zinc fortification (at 30 or 50% of the NRV) led to a higher introduction of meat substitutes in dietary patterns (Figure 1). While the average meat substitute was hardly introduced into the AS scenario, it reached 62g/d under the AS-30% scenario and 69g/d under the AS-50% scenario. However, it was never introduced into diets when both substitutes were available in the repertoire because the optimized meat substitute was

always preferred and introduced in quantities that increased in line with its fortification level (106g/d under the OS-30% scenario and 115g/d under the OS-50% scenario).

Introducing fortified meat substitutes led to greater reductions in meat intake, especially with the optimized meat substitute (Figure 3). Reductions in red meat consumption ranged from -19% and -56% under AS-30% and AS-50%, respectively, to -43% and -91% under OS-30% and OS-50%, respectively. While pork and other meats were always removed and offal increased, a reduction in beef and veal was only seen under the AS-50%, OS-30% and OS-50% scenarios. Processed meat was reduced but not entirely removed (-83% to -91%) and the reduction in poultry ranged from -72% to -100% (Supplemental Table 6). Red meat reductions were generally higher in women than in men but offal increased more in women, while processed meat persisted in women but not in men. Changes to other food groups in the modeled diets were similar to scenarios with non-fortified substitutes.

Introducing fortified meat substitutes increased the *HDP* gain while slightly decreasing the *DD* (Figure 2). The *HDP* gain was however slightly more important and the *DD* always largely lower with the optimized meat substitute than with the average meat substitute (Supplemental Table 7).

For sensitivity analysis, we tested an alternative optimization procedure where the nutritional constraints on bioavailable iron and zinc were based on recommended intakes rather than observed intakes (Supplemental Tables 8 and 9). In this case, the reduction in red meat was much lower and only effective under the AS-50% and OS-50% scenarios. This was especially marked in women with “high” iron requirements (20% of women, see Supplemental Method 1) where red meat intake systematically increased to reach its

upper limit (71g/d). For other women with “low-to-medium” iron requirements, red meat intake also increased, except under the OS-50% scenario. For men, modeled changes to meat intake were quite similar but less marked when using recommended intakes rather than observed levels of bioavailable iron and zinc as nutritional constraints.

Identification of limiting nutritional constraints in the different optimization scenarios

The nutritional constraints identified as limiting were those that prevented the identification of healthier but acceptable dietary solutions. The limiting nutrients thus identified were sources of conflicts between nutrient adequacy and the health value of the dietary pattern. Whatever the scenario, the most limiting nutritional constraints in both men and women were for bioavailable zinc, sodium, saturated fatty acids and vitamin A (Supplemental Table 7). Some nutritional constraints were more limiting in women than in men (iodine and sugars excluding lactose). The constraint on bioavailable iron was not limiting, but its influence could be revealed by relaxing the zinc constraint (Supplemental Table 7). Indeed, the constraints on bioavailable zinc and iron worked together by involving similar dietary changes, and the constraint on bioavailable zinc was so predominant that it masked the influence of the bioavailable iron constraint. The constraint on bioavailable zinc was more limiting in men than in women and the constraint was less limiting when meat substitutes were fortified at 50% of the NRV in iron and zinc. The constraint on sodium was more limiting in scenarios involving the average meat substitute, and constraints on fiber, ALA and vitamin B6 were only limiting under these scenarios.

Contributions of food groups to nutrient intakes under different optimization scenarios

We investigated the contribution of each food group to the intake of the most limiting nutrients (i.e. nutrients with the most limiting constraints) and of the nutrients where meat (red meat, poultry and processed meat) and/or meat substitute contributed significantly (>10% of nutrient intake in the observed diet or a modeled diet) (Supplemental Figure 1).

In the observed diets, meat was an important contributor to bioavailable iron (43%), bioavailable zinc (39%), vitamin B6 (27%) and vitamin A (23%) intakes. Meat substitutes gradually replaced the contribution of meat to bioavailable iron and zinc intakes according to the degree of their fortification. The optimized meat substitute was also effective in compensating for the contribution of meat to vitamin B6 intake. However, meat substitutes were not able to compensate for the important contribution of processed meat to vitamin A intake, and this compensation tended to be achieved by an increase in offal under all scenarios. The contribution of meat to linoleic acid (LA) intakes in observed diets (15%) was completely compensated for in modeled diets by meat substitutes (which became important contributors, at between 17% and 25%). For sodium and saturated fatty acids, where the observed intakes were above upper levels and needed to be lowered in the modeled diets, meat substitutes contributed little to intakes, except for the average meat substitute which made a substantial contribution to sodium intake (~13-14%).

Finally, meat did not contribute to intakes of ALA, vitamin C and fiber in observed diets, but meat substitutes became important contributors of these nutrients as they were introduced into the diet. In particular, the optimized meat substitute added substantial quantities of ALA, fiber and vitamin C to the modeled diets (with contributions of 43%, 36% and 20%, respectively, under the OS-50% scenario).

Discussion

In this diet optimization study, we have shown that plant-based meat substitutes could offer good nutritional levers for the design of nutrient-adequate and healthier dietary patterns if they have been formulated to convey the relevant nutrients and are fortified with iron and zinc. We have indeed shown that the average meat substitute currently available is ineffective in rearranging the diet in order to improve its quality, whereas a nutritionally-designed meat substitute [24] could largely be used as a lever for healthier patterns. Fortifying any substitute with iron and zinc increased its usefulness as a nutritional lever.

As we aimed to explore the nutritional usefulness of plant-based substitutes in a general way covering distinct alternative uses, various dietary changes were allowed, within a food category (such as partial to total replacement of any type of meat with plant-based meat substitutes) and also between food categories, even though the latter were hindered by the search for a healthier dietary pattern that would remain close to current eating habits. Without fortification, the average meat substitute was not introduced to a significant degree in the modeled diet, showing that it had a nutrient composition insufficient to act as a nutritional lever. Fortification with iron and zinc enabled its introduction, along with important reductions in red meat, processed meat and poultry intakes. Overall, our findings are in line with those of Mertens *et al.* who reported that theoretical fortifications in iron and certain vitamins (B1, B2, B3 and B12) led to larger quantities of meat substitutes and smaller quantities of meat in modeled diets compared to those involving non-fortified meat substitutes [17]. In contrast however, in our different scenarios, group B vitamins were generally not identified as nutrients of concern (except for vitamin B6 and

B12, to a lower extent, in some scenarios in women), because sufficient intakes were provided by higher than observed consumptions of fish and dairy products. In addition to the low iron and zinc content of the average meat substitute, introduction of the average substitute may have been limited by its relatively high sodium content, because sodium intake was initially excessive in the observed diets. High amounts of sodium in plant-based meat substitutes have been highlighted [22], and in view of the detrimental effects of excessive sodium intake [9], a reduction in the sodium content of plant-based meat substitutes is critical to their nutritional value.

Under scenarios where both substitutes were added to the repertoire, the optimized meat substitute was always more useful to build healthier diets, even when fortifications led to the same amounts of iron and zinc in the average and optimized substitutes. Indeed, when compared to the average meat substitute, the optimized meat substitute was introduced in higher quantities, along with a much higher reduction in red meat intake. This meat substitute had previously been optimized to improve global nutrient adequacy, containing ingredients rich in nutrients that are currently insufficiently consumed [24]. In this regard, it is not surprising that it proved to be useful when modeling healthier diets, but it ultimately contrasted dramatically with the average available market substitute.

Like its low sodium content, the high contents in iron and zinc (before fortification) of the optimized meat substitute were of considerable value. The nutritional requirements for bioavailable zinc and the sodium intake limit were indeed the most limiting constraints which had the greatest impact on the composition of the modeled diets, whatever the scenario. Another advantage of the optimized substitute was its higher content in fiber and

ALA, the intake of which was also identified as limiting when using the average meat substitute.

Interestingly, with both the optimized meat substitute and the average meat substitute, iron and zinc fortifications were necessary to elicit a substantial reduction in or near elimination of red meat. Iron and zinc absorptions are generally lower with plant-based than animal-based foods, particularly because the amount of phytate is a very limiting factor regarding their absorption. This hampers the use of plant-based products to compensate for these nutrients that are largely provided by animal products [38,39]. Fortification in iron and zinc does indeed appear necessary to level the nutritional composition of beef, but not poultry, when modeling meat substitutes [40].

In addition, we found that introducing the consumption of meat substitutes did not result in consistent changes to meat consumption across meat types. While pork, poultry and processed meat were readily reduced, or even removed, a reduction in beef required the fortification of meat substitutes. By contrast, the consumption of offal increased under all scenarios (up to ~7 g/d in general), starting from a very low observed intake (3 g/d) while remaining at a level considered acceptable at the population level (far below 25 g/d, the 95th percentile of observed consumption). Offal is very rich in nutrients [41] and we can assume that while the optimization procedure drives towards a reduction in total red meat, some preference is given to the most nutrient-dense subcategory within red meat.

One important finding of this study was that although contents in zinc and iron were critical characteristics of a meat substitute to favor meat reduction, the composition in other nutrients was also important when modeling healthy dietary patterns. Indeed, one advantage of plant-based meat substitutes is that they can contribute to an intake of

nutrients other than those provided by meat, although the nutritional composition of plant-based meat substitutes varies markedly depending on their ingredients [20,42]. When formulating meat substitutes, the choice of ingredients may tend to be driven more by a willingness to reproduce the appearance and taste of meat [1,43], as this is an important element in consumer acceptance [44], rather than nutritional quality, consideration of which appears to be limited to mainly the macronutrient and particularly protein content [42,43]. Conversely, a nutritionally-optimized meat substitute as the one used in this study, although the prototype had acceptable orosensory characteristics (24), should rather be emphasized on the basis of its nutritional value.

Therefore, if plant-based meat substitutes are appropriately designed from a nutritional point of view (especially in terms of zinc and iron) they could be useful to favor healthier dietary patterns, by supplying the nutrients that come from both meat and plant ingredients while limiting deviation from observed diets, that is, limiting the extent of other dietary changes. During this study, we considered that replacing meat with a meat substitute would not count as a deviation from the structure of observed diets (as was done for wholegrain products replacing refined grains), because meat substitutes are designed to be consumed in the same way as meat [3,45]. However, replacing meat with meat substitutes was not the only change to the modeled diets, and this substitution will not be sufficient to achieve healthy and sustainable diets [17]. Indeed, if the initial dietary pattern is unhealthy, using a meat substitute will not be sufficient to reach an healthier diet [18], which actually requires major direct (intra-category changes between easily substitutable foods) and indirect (inter-category changes consisting a remodeling of the overall dietary pattern) changes. Here, we found that the utility of appropriate and nutritionally-designed

meat substitutes stemmed from their dual effects on enhancing the health value of the diet and reducing the need for other indirect dietary changes deemed less culturally acceptable. This was because the better intrinsic nutritional quality of such optimized meat substitutes induces less need for changes to the consumption of other food groups in order to meet nutritional requirements.

Meat substitutes with a good nutrient package can be integrated in large quantities and widely replace meat, but this may raise other questions regarding potential adverse effects. Many plant-based meat substitutes are ultra-processed [1,19,42] and they would replace foods that are generally minimally processed (except processed meat). An excessive intake of ultra-processed foods can be expected to have adverse effects on health [46-48]. Meat substitutes may therefore appear to be effective for the design of healthier dietary patterns if the aim is to stay close to observed diets, but may be ineffective if the goal is to promote the consumption of minimally processed foods that are currently little consumed (such as legumes and nuts). In the latter case, it would certainly be necessary to deviate to a greater extent from the observed diets. Of note, since the optimized meat substitute is made of simple unprocessed or minimally-processed ingredients (coco bean, yellow sweet pepper, flaxseed, etc.), it can be prepared at home as a plant-based patty to replace meat, but, alternatively, its ingredients can be included separately as foods in an overall diet with less meat [24]. The advantage of its formulation as a meat substitute is to offer an easy replacement for meat.

This study has some limitations. First, as the average meat substitute we took the mean of 43 meat substitutes that have very diverse nutritional compositions (some of them containing egg or cheese), but using an average substitute was a robust scenario taking

into account overall the diversity of the food offers while avoiding using a large number of scenarios which are more difficult to interpret together. Second, the optimization procedure at the population level did not take account of the diversity of diets, which may be important when modeling healthier diets [49]. Third, in the absence of adequate specific data, the cultural acceptability of dietary changes was only theoretically and imperfectly considered, by searching for the smallest combined deviations in food group consumptions while bounding them between their observed 5th and 95th percentiles. Finally, most of the results presented in this study were obtained by considering observed levels of bioavailable zinc and iron rather than the recommended levels of intake as a nutritional constraint. Zinc and iron references are very constraining and limit the modeling of healthy diets [29] but removal of these constraints might have led to much lower intakes of iron and zinc. As a compromise we therefore chose not to degrade the current situation and to model diets that supplied at least the same levels of absorbed iron and zinc as the observed diets. Using recommendations rather than observed intakes led to the same conclusions, except that fortifications with iron and zinc appeared to be much more necessary.

To conclude, the standard meat substitutes that are currently available are of little use when modeling healthy dietary patterns unless they are fortified with iron and zinc, and they constitute a potential vector for sodium. By contrast, a meat substitute that had been nutritionally designed proved to act as an efficient lever to improve observed diets, but iron and zinc fortifications were required in order to drastically reduce the consumption of red meat. Finally, plant-based meat substitutes may be useful to implement healthier dietary patterns involving less red meat consumption, provided that they contain enough

iron and zinc. Formulation of meat substitutes should consider their nutritional quality and choose ingredients that are both low-sodium, nutrient-dense and especially rich in iron and zinc. Fortification must also be considered when seeking to design products which aim to fully replace red meat. We have thoroughly and rigorously evaluated how the composition of meat substitutes affects the nutritional adequacy of the modeled diets in which they are incorporated, while designing these diets to find the best trade-off between their long-term health value and their proximity to current diets. However, their cultural acceptability was only theoretically and imperfectly assessed. Further studies are also needed to jointly assess impacts on other dimensions of sustainability, such as diet cost and environmental footprints.

Acknowledgments and statement of authors' contributions to the manuscript

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MS, HF and FM: designed the research; HF: conducted the research; HF, MS and FM analyzed the data; AD, J-FH and EK-G provided methodological support; MS wrote the first draft of the manuscript and all authors provided critical comments on the manuscript. MS, HF and FM had primary responsibility for the final content and all authors have read and approved the final manuscript.

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Table 1. Ingredient content of the optimized meat substitute [6].

Ingredient	Content (g/100g)
Coco bean, boiled/cooked in water	41.6
Pepper, sweet, yellow, sautéed/pan-fried, without fat	15.0
Chick pea, boiled/cooked in water	5.8
Wheat bran	5.6
Flaxseed	5.0
Couscous (precooked durum wheat semolina), cooked, unsalted	5.0
Shiitake mushroom, dried	5.0
Wheat germ	4.4
Potato starch	3.9
Rapeseed oil	3.6
Sweet potato, cooked	2.7
Sunflower oil	1.4
Thyme, dried	1.0

Table 2. Nutrient composition (per 100g of product) of the average meat substitute and the optimized meat substitute made available into the repertoire for diet modeling.

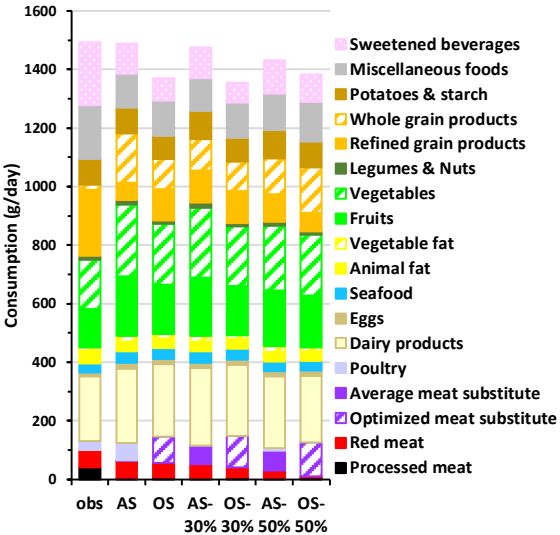
	Average meat substitute /100g	Optimized meat substitute
Energy (kcal)	187.22	211.42
Protein (g)	14.30	8.83
Fiber (g)	4.46	12.98
Sugar excluding lactose (g)	1.79	2.21
Lipids (g)	8.44	8.15
Saturated fatty acids (g)	1.19	0.86
Linoleic acid (g)	3.06	2.26
Alpha-linolenic acid (g)	0.23	1.24
Vitamin A (µg)	13.64	37.11
Vitamin B1 (µg)	105.55	263.12
Vitamin B2 (mg)	0.06	0.13
Vitamin B3 (mg)	0.68	2.70
Vitamin B5 (mg)	0.35	1.50
Vitamin B6 (mg)	0.09	0.29
Vitamin B9 (µg)	43.08	75.13
Vitamin B12 (µg)	0.04	0.00
Vitamin C (mg)	1.70	20.76
Vitamin D (µg)	0.07	0.26
Vitamin E (mg)	2.46	2.88
Vitamin K1 (µg)	11.72	24.27
Calcium (mg)	78.19	75.33
Copper (mg)	0.27	0.57
Iron (mg)	2.42	4.37
Iodine (µg)	8.92	7.72
Magnesium (mg)	88.24	97.10
Manganese (mg)	1.03	2.09
Phosphorus (mg)	183.44	240.76
Potassium (mg)	313.90	489.83
Selenium (µg)	9.36	9.75
Sodium (mg)	483.78	9.33
Zinc (mg)	1.39	2.41
Phytate (g)	80.00	176.71

Figure legends

Figure 1. Consumptions of different food groups in observed and modeled diets according to different optimization scenarios in the whole population. Obs, observed diet. AS, AS-30%, AS-50%, modeled diets with the possible introduction of the average meat substitute: not fortified, fortified with iron and zinc at 30% and 50% of the NRVs, respectively. OS, OS-30%, OS-50%, modeled diets with the possible introduction of average and optimized meat substitutes: not fortified, fortified with iron and zinc at 30% and 50% of the NRVs, respectively. RG, refined grains; WG, wholegrains. Water and hot beverage consumptions are not shown, for clarity. Miscellaneous foods include Soups, Bouillons, Sweet products or sweet and fatty products, Substitutes of animal products, Salt, Condiments and Aromatic herbs, spices except salt groups. Details about food grouping are given in Supplemental Table 1 and consumptions of food groups or categories not shown here are given in Supplemental Tables 5, 6, 8 and 9.

Figure 2. *Healthy dietary pattern (HDP) gain* (difference in *HDP* values between modeled and observed diets) vs *Diet Departure (DD)* for the different modeled diets. AS, AS-30%, AS-50%, modeled diets with the possible introduction of the average meat substitute: not fortified, fortified with iron and zinc at 30% and 50% of the NRVs, respectively. OS, OS-30%, OS-50%, modeled diets with the possible introduction of average and optimized meat substitutes: not fortified, fortified with iron and zinc at 30% and 50% of the NRVs, respectively.

Figure 3. Consumption of red meat (beef & veal, pork & other meats, offal), processed meat, poultry and meat substitutes in the observed and modeled diets. Obs, observed diet. AS, AS-30%, AS-50%, modeled diets with the possible introduction into the repertoire of the average meat substitute: not fortified, or fortified with iron and zinc at 30% or 50% of the NRVs, respectively. OS, OS-30%, OS-50%, modeled diets with the possible introduction of average and optimized meat substitutes: not fortified, or fortified with iron and zinc at 30% or 50% of the NRVs, respectively.



Gain in Healthy Dietary Pattern (HDP)

3.3
3.2
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3

1.0

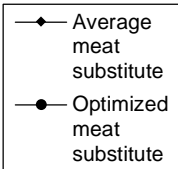
2.0

3.0

4.0

5.0

Diet Departure (DD)



OS-50%

AS-50%

OS-30%

AS-30%

OS

AS

