The Journal of Nutrition 153 (2023) 2125–2132

American Society for Nutrition
Excellence in Nutrition Research and Practice

JN THE JOURNAL OF NUTRITION

journal homepage: https://jn.nutrition.org/

Nutritional Methodologies and Mathematical Modeling

Iron Bioavailability Should be Considered when Modeling Omnivorous, Vegetarian, and Vegan Diets

Dominique van Wonderen [1,*], Alida Melse-Boonstra [2], Johanna C Gerdessen [3]

[1] *Wageningen Economic Research, Wageningen University & Research, Wageningen, Netherlands;* [2] *Division of Human Nutrition, Wageningen University, Wageningen, Netherlands;* [3] *Group Operations Research and Logistics, Wageningen University, Wageningen, Netherlands*

A B S T R A C T

Background: To lower environmental impact of human food consumption, replacement of animal proteins with plant-based proteins is encouraged. However, the lower iron bioavailability of plant-based foods is rarely considered when designing healthy and sustainable diets by using diet modeling. The estimated absorbable iron content of vegetarian and vegan menu plans might therefore be too optimistic.
Objective: The main aim of this study was to investigate and compare the impact of various methods to estimate absorbable iron intake on the nutritional adequacy of omnivorous, vegetarian, and vegan menu plans designed for women of reproductive age.
Methods: A diet model was developed to design menu plans consisting of a selection of meals that best complied with nutritional requirements. Meals used for modeling were created based on food intake data from the National Health and Nutrition Examination Survey (NHANES). For each meal, absorbable iron concentrations were estimated by using 2 constant absorption factors (18% and 10%) and 2 diet-dependent absorption equations (Conway and Hallberg). For each absorption method and diet type, we used the diet model to design the optimal menu plan. Retrospectively, menu plans were evaluated by estimating the absorbable iron content by using the other absorption methods.
Results: Retrospective diet-dependent absorbable iron estimates were consistently lower than estimates based on constant absorption factors. Using diet-dependent estimates increased absorbable iron by optimizing enhancer and inhibitor concentrations.
Conclusion: Iron bioavailability should be considered when modeling diets.

Keywords: diet optimization, goal programming, iron bioavailability, menu planning, mixed-integer linear programming, protein transition

Background

To reduce the environmental impact of human food consumption, multiple stakeholders have advocated for transitioning from animal-based to plant-based diets [1–6]. However, it is still a subject of debate what trade-offs of partially or fully plant-based diets are to be expected with regard to human health. Some research showed that vegetarian diets do contribute to public health as such diets are associated with a lower risk of chronic diseases [2, 3, 5]. In contrast, other researchers expressed concern that vegetarian diets are more susceptible to nutritional inadequacies because of lower nutrient bioavailability [7–9].

Iron is one of the nutrients of greatest concern in vegetarian diets [10-12], especially for women of reproductive age [13]. Nonheme iron found in plant-based foods has a relatively low absorption (1%–15%) in humans compared with heme iron found in animal-sourced foods (15%–40%) [14]. This is because of the higher content of phytate and polyphenols in vegetarian diets, which inhibit the absorption of nonheme iron. Additionally, meat protein, which enhances the absorption of nonheme iron, is absent in vegetarian diets. To some extent, these effects are mitigated by the higher amounts of vitamin C in vegetarian diets, which enhances the absorption of nonheme iron. Nonetheless, the bioavailability of iron in vegetarian diets is substantially lower than in omnivorous diets [10, 15–21].

To optimize the nutritional adequacy and sustainability of diets, diet modeling is a quantitative technique that is commonly applied [22]. For the design of vegetarian and vegan diets, however, the lower bioavailability of iron is rarely taken into account as most diet models assume the same constant absorption factor as for

Abbreviations used: EAR, Estimated Average Requirement; FPED, Food Patterns Equivalents Database; IOM, Institute Of Medicine; LB, Lower Bound; MFP, Meat; Fish, and Poultry; UB, Upper Bound; UL, tolerable Upper Level; WWEIA, What we Eat In America.

* Corresponding author. *E-mail address:* dominique.vanwonderen@wur.nl (D. van Wonderen).

https://doi.org/10.1016/j.tjnut.2023.05.011
Received 30 January 2023; Received in revised form 3 May 2023; Accepted 10 May 2023; Available online 12 May 2023

omnivorous diets. Only few examples exist in literature where the applied iron absorption factor was adjusted based on the type of diet. For instance, Eustachio Colombo et al. [23] used a lower iron absorption factor for the design of vegetarian and vegan diets. Barre et al. [24, 25] developed a diet model to reduce meat consumption using diet-dependent absorption equations for iron, zinc, vitamin A, and protein quality.

In contrast to constant iron absorption factors, diet-dependent absorption equations estimate iron absorption based on enhancer and inhibitor concentrations within a specific diet. These equations are therefore considered to be more accurate. A question still left unanswered though, is to what extent menu plans based on either constant iron absorption factors or diet-dependent iron absorption equations differ from each other. Accordingly, the objective of the present study was to compare the estimated absorbable iron content of omnivorous, vegetarian, and vegan diets based on different methods to estimate absorbable iron intake for women of reproductive age.

Method

A diet model was developed to design various 2-wk menu plans: omnivorous, lacto-ovo-vegetarian (in this paper referred to as vegetarian), and vegan. Each menu plan consisted of a selection of meals that complied best with nutritional requirements. Meals were created based on dietary intake data of foods frequently consumed in the United States of America. For each meal, the bioavailability of iron was estimated by applying both constant absorption factors and diet-dependent absorption equations as explained below in more detail.

Meal data

Meals were created from dietary intake data provided by the NHANES 2017–2018 [26]. NHANES reports on demographics, food items and quantities consumed, meal type, and corresponding nutrient values that are based on the Food and Nutrient Database for Dietary Studies 2017–2018 [27]. To create a database of meals, we aggregated consumption data by respondent, interview day and time of eating occasion. An example of such a meal is given in Supplemental Table 1.

To obtain an example dataset of meals, the following filters were applied (Supplemental Figure 1): *1*) consumption for respondents below the age of 18 y was filtered out (5856 respondents remained); *2*) only breakfast, lunch, dinner, and snack meals were retained; *3*) meals that contained food items that were consumed by < 10 respondents were removed. Food items were counted by their first word before a comma or parenthesis of the USDA food name description. For example, "Rice, white, with corn, no added fat" and "Rice, white, with corn, fat added" were both counted as "Rice"; *4*) Meals that contained only drinks were excluded. In addition, meals that contained 400 g of drinks or more were filtered out; *5*) Breakfast and lunch meals were retained when they contained food items belonging to at least 2 of the following food groups: Fruit, Vegetables, Legumes, Grains, Dairy, Meat and seafood, Eggs, and Nuts; *6*) Dinner meals were kept either when they contained food items belonging to at least 2 of the aforementioned food groups and consisted of 4 food items or more, or when they contained food items belonging to at least 2 of the following food groups: Vegetables, Legumes, Grains, Meat, and seafood; *7*) Meals containing food items with artificially increased nutrient density (commercial breakfast cereals and oatmeal-based porridges, nutritional powder mix and drinks, nutrition bars, and energy drinks) were removed; *8*) Meals with very large portion sizes were removed. Portion sizes were regarded large when food group (Dairy, Fruits, Grains, Protein foods, Vegetables) amounts of 1 meal exceeded the daily recommended amount [28]; *9*) Meals were discarded when their caloric intake was lower than 400 kcal for lunch and dinner meals or larger than 1500 kcal; *10*) Duplicate meals were aggregated by taking the median value of food item quantities for meals that consisted of similar food items; *11*) Meals with nonheme iron absorption estimates above 50% (based on either of the 2 diet-dependent absorption equations, see next section) were excluded.

After the applied filtering steps, 8887 omnivorous meals remained of which 4850 meals were classified as vegetarian and 1541 meals as vegan (Supplemental Table 2). Meals were considered vegetarian when they did not contain meat, fish, or poultry. Meals that did not contain meat, fish, poultry, eggs, or dairy were labeled as vegan. This classification was established by using the food groups of the Food Patterns Equivalents Database (FPED) [29].

Iron absorption

Absorbable iron was estimated for each meal by applying different iron absorption estimation methods. Two constant absorption factors were utilized: 18% as used by the Institute of Medicine (IOM) [30] to set the nutritional requirement on iron intake for premenopausal women, and 10% as applied by Colombo et al. [23] to account for the lower bioavailability of vegetarian and vegan diets [31].

Furthermore, 2 diet-dependent absorption equations were deployed. The equation of Hallberg and Hulthén [18] (Hallberg) was selected as it was evaluated as one of the most accurate iron absorption models by multiple reviewing articles [16, 17, 32]. Secondly, **Conway** equation was selected because it has the advantage that it only requires information on food groups [16]. Estimation of nutrients that are not present in food composition databases can be avoided this way. The detailed formulation of both equations is presented in Supplemental Methods 1.

Hallberg's equation estimates the absorption of heme and nonheme iron for a meal based on the amount of phytate; vitamin C; meat, fish, and poultry (MFP); tannic acid, calcium, soy, eggs; and alcohol. For Conway's equation, the following food groups were used: high vitamin C fruit or fruit juice; MFP; soy; beans and lentils excluding soy; wholegrain cereal; black tea infusion; dairy excluding cream and cottage cheese; cheese; eggs; and nuts. Conway's equation only estimates nonheme iron absorption though. Therefore, heme iron absorption was assumed to be 25% [33]. In addition, iron absorption was adjusted for the serum ferritin concentration within an individual. In this study, serum ferritin was set at 15 μg/L, which is the cut-off value used by IOM [31] to calculate Dietary Reference Intakes for iron-deficient individuals.

After estimating heme and nonheme iron absorption, total absorbable iron (1) and total iron absorption (2) were calculated as follows:

$$\begin{aligned}&\text{Total absorbable iron (mg)} = \text{Nonheme iron absorption (\%)} \cdot \\ &\text{Nonheme iron content (mg)} + \text{Heme iron absorption (\%)} \cdot \\ &\text{Heme iron content (mg)}\end{aligned} \tag{1}$$

$$\text{Total iron absorption }(\%) = \frac{\text{Total absorbable iron (mg)}}{\text{Total iron (mg)}} \tag{2}$$

Food group and nutrient estimations

To estimate absorbable iron for all meals, we needed to estimate the food groups and nutrients used by the equations. The food groups used in Conway's equation were estimated based on the food categories available from the What we Eat In America (WWEIA) database [34] and FPED [29]. For example, MFP was calculated by taking the amount of WWEIA category "MFP." For WWEIA category "mixed dishes," MFP was estimated by multiplying FPED's equivalent "Total meat, poultry, seafood, organ meats, and cured meat" by a conversion factor 28.35 g/oz eq. [33].

For Hallberg's equation, nutrients that were not available in Food and Nutrient Database for Dietary Studies and therefore had to be estimated included (non)heme iron, tannic acid, and phytate. Heme iron was estimated to be half of the total iron content of MFP [35]. Tannic acid was assumed to be zero as no appropriate databases were available to make reliable estimations. Phytate was estimated by applying the method reported by Larvie and Armah [36]. The phytate content of a specific meal was estimated by multiplying the average phytate content of corresponding food groups by their FPED's unit equivalents. Subsequently, unit equivalents were converted to grams. For example, for a 155 g pizza that contains 2.91 oz eq. refined grains, the phytate content was estimated to be 2.91 oz eq. · 28.35 g/oz eq.[1] · 1.97 mg/g[2] = 162.5 mg.

Finally, added sugar was estimated as it is constrained in the diet model (Table 1) and is not included in Food and Nutrient Database for Dietary Studies. Added sugar was estimated by multiplying FPED equivalent "added sugar" by conversion factor 4.2 g/tsp. eq. [37].

Diet model

A mixed-integer linear goal programming model was developed to construct a 2-wk menu plan consisting of a selection of meals that best complied with nutritional requirements. For the selection of meals, a binary decision variable was defined that states whether or not a meal is used for a meal moment on a certain day of the 2-wk menu plan. One breakfast, lunch, and dinner meal and 2 snacks should be selected each day. To secure menu diversity, dinner and lunch meals could only be selected once every 2 wk. Breakfast meals and snacks could be selected twice every 2 wk. Furthermore, food item used for dinner and lunch meals was restricted. For example, each vegetable could only be selected twice per week.

To guarantee the nutritional adequacy of the menu plan, we placed lower and upper bounds on macronutrient intakes based on the DRI provided by IOM [30] (Table 1). The DRIs were adopted for women (19–50 y) as iron deficiency is most commonly observed in women of reproductive age, and dietary iron bioavailability is, therefore, most critical for this age group [13]. Micronutrient intakes were maximized for those nutrients for which RDA were available, with the exception of vitamin B12. Vitamin B12 is mainly derived from meat and fish [40], and

[1] Weight/unit equivalent refined grains [36].
[2] Phytate content refined grains[36].

TABLE 1
Dietary reference intakes (women 19–50 y) for nutrients considered by the diet model [30] [1]

Macronutrient	Unit	LB	UB
Energy[2]	kcal/d	2000	2400
Protein	E%	10	35
Total carbohydrates	E%	45	65
Dietary fiber	g	25	–
Added sugars	E%	–	10
Total fat	E%	20	35
Total saturated fatty acids	E%	–	10
Sodium	mg	–	2300

Micronutrient	Unit	EAR	RDA	UL
Calcium[3]	mg	800	1000	2500
Iron (Absorbable iron)[4]	mg	8.1 (1.5)	18 (3.2)	45 (8.1)
Zinc	mg	6.8	8	40
Vitamin A	µg	500	700	3000
Vitamin B1	mg	0.9	1.1	–
Vitamin B2	mg	0.9	1.1	–
Vitamin B3	mg	11	14	–
Vitamin B6	mg	1.1	1.3	100
Vitamin B9	µg	320	400	1000
Vitamin C	mg	60	75	2000

[1] LB, Lower Bound; UB, Upper Bound; EAR, Estimated Average Requirement; RDA, Recommended Daily Allowance; UL, tolerable Upper Level.
[2] [38].
[3] [39].
[4] Absorbable iron was calculated by multiplying the dietary reference intakes with IOM's (30) absorption factor of 18%.

would therefore constitute a bottleneck nutrient in the design of vegetarian and vegan diets. To allow the model to optimize absorbable iron (serum ferritin 15 µg/L), it was therefore decided to leave vitamin B12 out of the objective function. The objective function of the model was to minimize the largest deviation below the RDA. For a fair comparison between nutrients, deviations were normalized by scaling them between 0 and 1. Finally, tolerable upper intake levels were applied as upper bounds to prevent unhealthily high intake of micronutrients. Full model definitions are given in Supplemental Methods 2, Supplemental Table 3, and Supplemental Table 4.

The diet model was applied to create 3 types of 2-wk menu plans: omnivorous, vegetarian, and vegan. Additionally, 4 different methods to estimate iron absorption (IOM) were used by the diet model. This finally resulted in 3 * 4 = 12 menu plans in total.

Evaluation of results

The nutritional adequacy of the twelve menu plans was evaluated based on the EARs and RDAs for women (19–50 y) presented in Table 1. Furthermore, the absorbable iron content of the menu plans was compared with the content estimated by each of the other iron absorption methods. Thus for the omnivorous menu plan optimized based on IOM's estimate, referred to as IOM's omnivorous menu plan, the absorbable iron content was also calculated by applying Colombo's, Hallberg's, and Conway's absorption methods. These absorbable iron estimates that were calculated after the menu plans had been optimized will be referred to as retrospective estimates (e.g., Hallberg's retrospective estimate for IOM's menu plan). The statistical test used to compare the mean absorbable iron content of the meals selected for each menu plan is described in Supplemental Methods 3.

Additionally, the equation of Armah et al. [32] was selected for retrospective evaluation to be able to compare estimates based on single-meal equations and complete-diet equations. Single-meal equations (Conway and Hallberg) are based on consumption data of foods that are digested together during a single-meal moment. As such, the iron absorption factor of each meal can be calculated. In contrast, complete-diet equations (Armah) are fitted on the average daily dietary intake from 1 d or more and, therefore cannot be used to estimate the iron absorption of single-meals. The detailed formulation of Armah's equation is presented in Supplemental Methods 1.

Furthermore, it has been examined to which extent the optimized menu plans are unique (Supplemental Methods 4.1), and a sensitivity analysis was conducted to investigate the impact of a different serum ferritin concentration, and enhancer and inhibitor concentrations in the diet on the estimation of absorbable iron (Supplemental Methods 4.2). Lastly, we explored to what extent the meals used as data input for the diet model affect the nutritional adequacy of optimized menu plans (Supplemental Methods 4.3).

Results

To investigate the impact of the applied iron absorption method on the nutritional adequacy of menu plans, we used diet modeling to create menu plans based on 4 different absorption methods (IOM) for 3 types of diets (omnivorous, vegetarian, and vegan). The mean absorbable iron content of the meals used as input data for the diet model is displayed in Supplemental Table 5. An overview of the average nutrient content of these menu plans is given in Supplemental Figure 2. The menu plans complied with all RDAs except for the vegan menu plans of Colombo and Hallberg. Colombo's vegan menu plan could not satisfy the RDA for iron, calcium, and vitamin A. Hallberg's vegan menu plan did not satisfy the RDA for iron, calcium, and zinc. In the current section, only the absorbable iron content of the menu plans will be further analyzed.

When evaluating the menu plans based on IOM's constant absorption factor, the most notable observation is that IOM's absorbable iron estimates were significantly higher than the retrospective estimates based on the diet-dependent absorption equations (Conway, Hallberg, and Armah) (Figure 1A, Supplemental Table 6). All IOM's menu plans complied with the RDA for

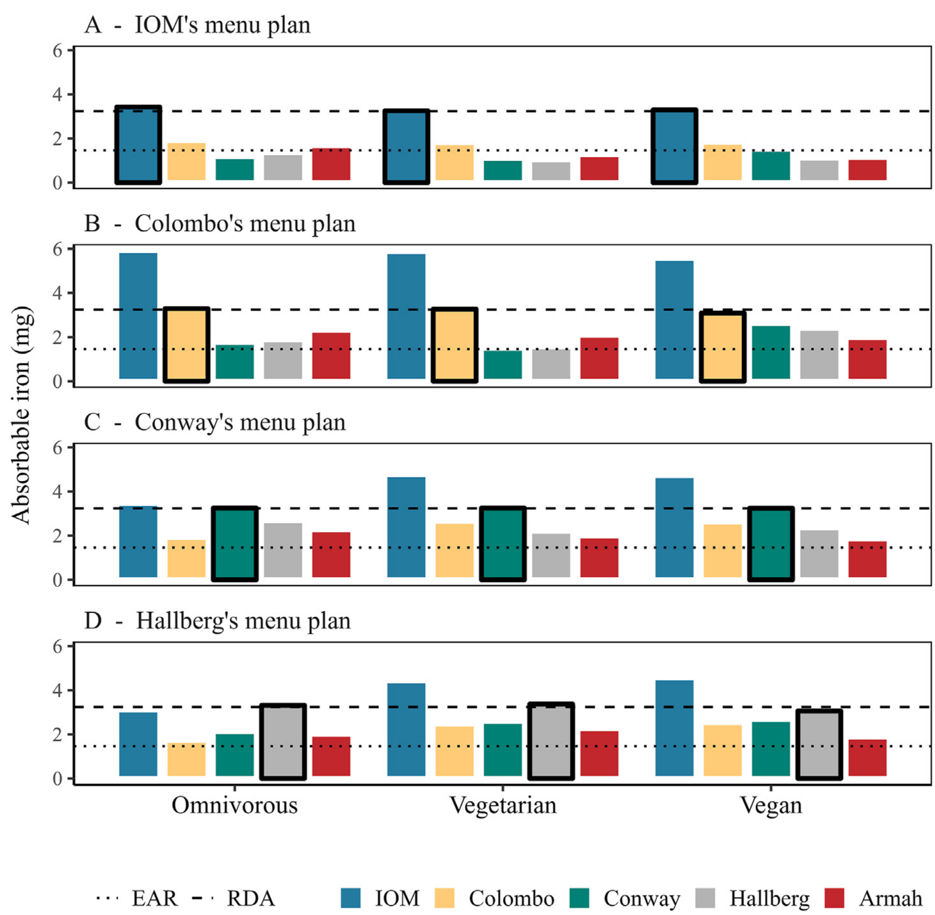

FIGURE 1. Average absorbable iron content (mg/d) compared with the EAR and RDA (women 19–50 y). The absorption of iron was estimated using a serum ferritin concentration of 15 μg/L. (A–D) The different absorption methods that have been applied by the diet model to optimize absorbable iron quantities (e.g., Figure 2A shows the menu plans that are based on IOM's absorption factor). The colored bars display which absorption method was used to estimate absorbable iron after the menu plans had been generated (e.g., Hallberg's retrospective estimate for IOM's menu plan). The outlined bars indicate the situation where the absorption method used by the diet model is the same as the method used to estimate absorbable iron retrospectively.

iron when the absorbable iron content was estimated by applying IOM's constant absorption factor. There were even 13 other omnivorous, 9 other vegetarian, and 1 other vegan menu plans that satisfied the RDA for iron (Supplemental Table 7, Supplemental Figure 3). However, when the absorbable iron content of IOM's menu plans was estimated retrospectively by applying the diet-dependent absorption equations, menu plans did not even satisfy the EAR except for Armah's retrospective estimate for IOM's omnivorous menu plan.

A similar pattern was observed for Colombo's menu plans (Figure 1B). Colombo's absorbable iron estimates were consistently higher than the retrospective estimates based on the diet-dependent absorption equations. All differences were statistically significant, except for Hallberg's and Armah's retrospective estimates for Colombo's omnivorous menu plan (Supplemental Table 6). Nonetheless, modeling with a lower constant absorption did increase the retrospective diet-dependent estimates with the result that the EAR could now be satisfied but not the RDA.

The absorbable iron estimates by diet-dependent equations were higher when Conway's and Hallberg's equations were used by the diet model. All menu plans complied with the RDA for iron except for Hallberg's vegan menu plan, which only satisfied the EAR (Figure 1C, D). The absorbable iron content of Conway's vegan menu plan was factor 1.2 higher than Conway's retrospective estimate for Colombo's vegan menu plan. Similarly, the absorbable iron content of Hallberg's vegan menu plan was a factor 1.3 higher than Hallberg's estimate for Colombo's vegan menu plan. When making the same comparison for IOM's vegan menu plan, Conway's and Hallberg's estimates were factor 2.2 and 2.8 higher, respectively. Higher diet-dependent absorption estimates were also observed for the omnivorous and vegetarian menu plans.

When comparing retrospective estimates based on Armah's complete-diet equation and Conway's and Hallberg's single-meal equations, it can be observed that Armah's estimates were slightly higher for IOM's and Colombo's omnivorous and vegetarian menu plans (Figure 1A, B). In contrast, Armah's estimates were slightly lower for the vegan menu plans. As regards the menu plans based on the diet-dependent equations (Figure 1C, D), Armah's estimates were also slightly lower than the other retrospective estimates (e.g., Armah's retrospective estimates for Conway's omnivorous menu plan is slightly lower than Hallberg's retrospective estimate). However, none of these differences were significant, except for Armah's and Conway's retrospective estimates for Hallberg's vegan menu plan (Supplemental Table 6).

Differences in absorbable iron estimates between the various menu plans become visible through differences in enhancer and

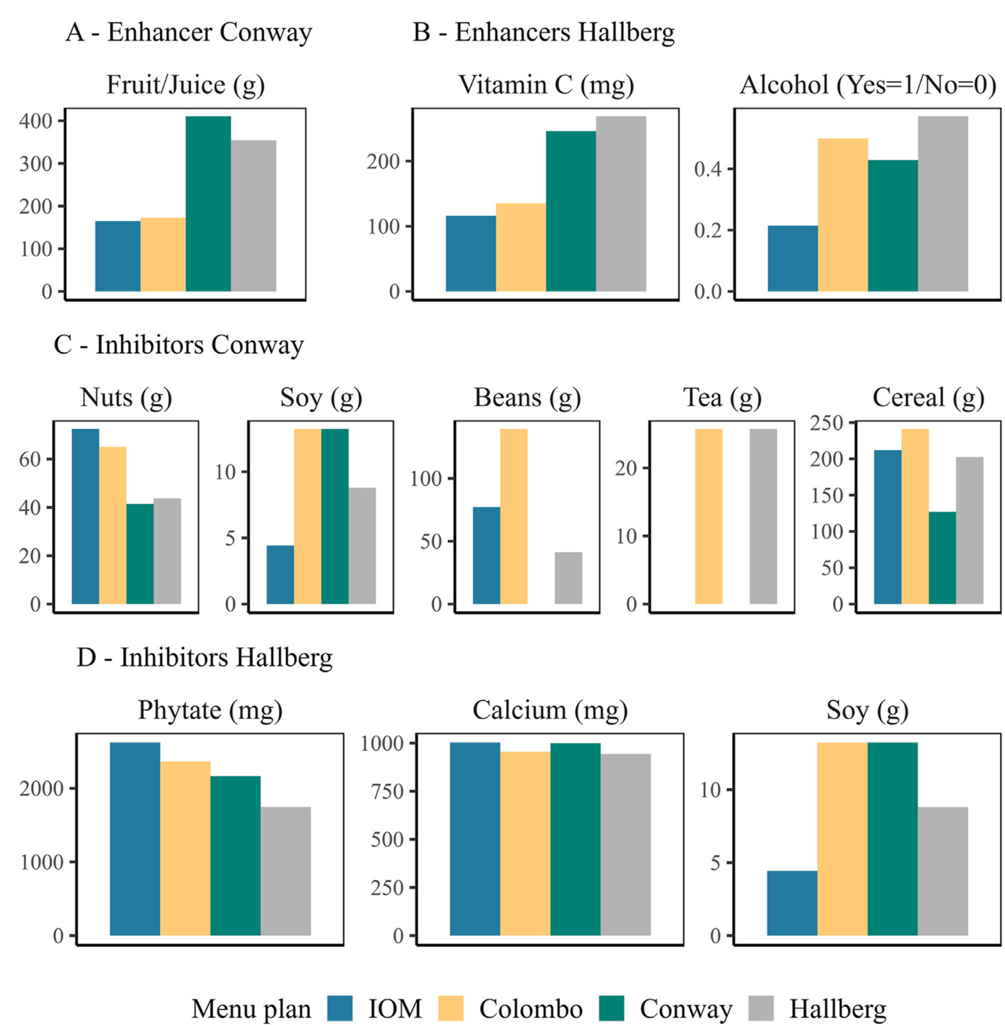

FIGURE 2. Average enhancer and inhibitor content (unit/d) of the vegan menu plans. Enhancers and inhibitors used by Conway's and Hallberg's equations are presented in (A–D), respectively.

inhibitor quantities (Figure 2). For example, Conway's absorbable iron estimate was higher for Conway's vegan menu plan (3.2 mg) than for IOM's vegan menu plan (1.5 mg) (Figure 1) because the enhancer concentration was higher (Figure 2A), and inhibitor concentrations were lower with the exception of soy (Figure 2C). Similarly, Hallberg's estimate for Hallberg's vegan menu plan (3.1 mg) was higher than for IOM's vegan menu plan (1.1 mg) (Figure 1) as the concentrations of Hallberg's enhancers were higher (Figure 2B) and the concentrations of inhibitors phytate and calcium were lower (Figure 2D).

The sensitivity analysis (where the content of enhancers and inhibitors in the meals were raised and lowered by 50%) showed that vitamin C and calcium had the largest impact on the estimation of iron absorption for Hallberg's equation (Supplemental Table 8). For Conway's equation, the most influential foods were high vitamin C fruit or juice, beans and lentils, wholegrain cereals and nuts.

Yet, the estimation of iron absorption was mostly affected by the applied serum ferritin concentration (Supplemental Table 8). Modeling with a serum ferritin level of 30 instead of 15 μg/L lowered absorbable iron estimates substantially (Supplemental Figure 4). Conway's and Hallberg's vegetarian and vegan menu plans complied no longer with the RDA. They only satisfied the EAR for iron. When the diet model was allowed to select meals containing food items with artificially increased nutrient density and meals with nonheme iron absorption estimates above 50% (Supplemental Figure 5), Conway's and Hallberg's vegetarian menu plans did satisfy the RDA (Supplemental Figure 6C, D). The vegan menu plans still only satisfied the EAR.

In summary, the absolute values of absorbable iron estimates based on diet-dependent equations greatly depended on the applied parameter input, but this was not the case for the relative outcomes. Regardless of the input data, retrospective diet-dependent absorbable iron estimates were consistently lower than the estimates based on the constant absorption factors.

Discussion

Our study demonstrated that the applied method to estimate iron absorption has a substantial impact on the estimated absorbable iron content of menu plans. All menu plans based on IOM's and Colombo's constant iron absorption factors failed to meet the RDA or even the EAR for iron when absorbable iron concentrations were evaluated retrospectively by the diet-dependent absorption equations of Conway, Hallberg, and Armah. This applied to all types of menu plans ranging from omnivorous to vegan diets. In contrast to the constant absorption factors, the diet-dependent absorption equations ensured the optimization of enhancer and inhibitor concentrations with the result that absorbable iron estimates were higher. As such, all menu plans based on the diet-dependent absorption equations complied with the RDA except for Hallberg's vegan plan, which only satisfied the EAR.

Nonetheless, our sensitivity analysis showed that these results can best be interpreted relatively. Although retrospective diet-dependent absorbable iron estimates were consistently lower than the estimates based on constant absorption factors, the absolute value of absorbable iron estimates heavily depended on the applied parameter input and the absorption equation used.

Of all parameter input, iron absorption estimates by diet-dependent equations are mostly affected by the serum ferritin concentration [32, 41]. Increasing the serum ferritin level from 15 to 30 μg/L lowered the estimation of absorbable iron with the result that the RDA for vegetarian and vegan diets could no longer be satisfied (Supplemental Figure 4). The requirement for absorbable iron is similar for those with low or high iron status, whereas absorptive capacity reduces at higher serum ferritin concentration [42], hence it becomes more difficult to satisfy the same requirement. This raises the question which serum ferritin concentration is most appropriate for diet modeling. IOM [31] applies a serum ferritin concentration of 15 μg/L to set their dietary reference intake for iron, while the European Food Safety Authority [41] uses a concentration of 30 μg/L. More recently, Galetti et al. [43] advised an even higher threshold value of 50 μg/L to define the onset of functional iron inadequacy, especially in young women. Although there are no universally adopted guidelines, which serum ferritin concentration to use for setting dietary requirements, it could be argued that the appropriate concentration for diet modeling depends on whether the goal is to establish functional adequacy (15 μg/L), maintain some iron reserves (30 μg/L), or build iron stores (50 μg/L). The latter 2 goals imply the use of lower estimates for iron bioavailability, and hence translate to higher dietary reference intake recommendations that are harder to achieve.

Furthermore, the level of iron absorption is affected by enhancer and inhibitor concentrations. For this study, several of these parameters had to be estimated. For example, Hallberg's equation required estimates of tannic acid. As regards tannic acid, there was no database available to make these estimations. Therefore tannic acid concentrations were assumed to be zero. However, the sensitivity analysis showed that raising the tannic acid content to 29 mg, which was the average content in meals of Hallberg and Hulthén's second study [18], lowered nonheme iron absorption by 31% (Supplemental Table 8). In that case, current absorption estimates would be too high with the result that it would have been more difficult to satisfy the RDA for iron.

Lastly, the outcome of iron absorption estimates depends on the applied absorption equation. For instance, the average nonheme iron absorption of the vegan meals was 29% higher for Hallberg's equation than for Conway's equation (Supplemental Table 5). A relevant question to answer is which absorption equation is most accurate. In literature, there has been an ongoing debate whether single-meal or complete-diet equations are more accurate. Multiple studies have reported that single-meal equations exaggerate the effect of enhancers and inhibitors on nutrient absorption compared with complete-diet equations [15, 21, 32, 33, 41, 42, 44]. On the other hand, De Carli et al. [17] reviewed multiple absorption equations and observed that some of the single-meal models outperformed the complete-diet equations that had claimed to be more precise. Our results, however, did only show minor differences between retrospective estimates based on Conway's and Hallberg's single-meal equations and Armah's complete-diet equation (Figure 1). All differences (except 1) were not statistically significant (Supplemental Table 6). In contrast, Conway's, Hallberg's and Armah's absorbable iron estimates were all (except 2) significantly lower than the estimates based on the constant absorption factors. We suggest further research is necessary to settle the debate about which equation is most appropriate for diet modeling.

Another reason why our results can best be interpreted relatively is because the nutrient content of the optimized menu plans heavily depends on the meals available to the diet model. In this study, we filtered consumption data to obtain the meals for diet modeling. However, these filtering steps can determine whether dietary guidelines can be satisfied or not. Our analysis showed that the RDA for all vegetarian menu plans could be satisfied when meals containing food items with artificially increased nutrient density and meals with nonheme iron absorption estimates above 50% were included, even when the modeled serum ferritin concentration amounted 30 μg/L (Supplemental Figure 6). Without these nutrient-dense meals, only the EAR could be satisfied (Supplemental Figure 4).

Apart from the fact that the meals used for diet modeling impact the nutritional adequacy of menu plans, these meals also affect the acceptability of designed menu plans. Many diet models design menu plans by adding food items to a so-called "food basket" [45]. However, the acceptability of the combination of these food items when preparing a meal is not considered this way. Yet, meal acceptability is key to encourage consumers to eat more healthily and sustainably [46]. We aimed to improve the acceptability of menu plans by modeling with consumer-reported meals instead of separate food items. Despite the applied filtering steps to obtain acceptable meals from consumption data, the designed menu plans still contained meals that may not be acceptable to all consumers. For example, 1 dinner meal in IOM's omnivorous menu plan consisted of raw avocado, tortilla chips and water. As such, the use of recipe data instead of consumption data could be investigated for designing menu plans, but even then menu plans may not be acceptable to all consumers. So far, no study has presented the ultimate solution to secure consumer acceptability [22].

In summary, we have investigated the impact of several common methods to estimate absorbable iron intake on the nutritional adequacy of omnivorous, vegetarian and vegan menu plans. Absorbable iron estimates based on constant absorption factors were consistently higher than the retrospective absorbable iron estimates based on diet-dependent equations. To reduce the risk of overestimating the absorbable iron content of menu plans, we advise applying diet-dependent absorption equations for the design of omnivorous, vegetarian, and vegan menu plans.

Acknowledgments

We thank Marleen C Onwezen (Wageningen Economic Research, Wageningen University & Research, Netherlands), Edith JM Feskens (Division of Human Nutrition, Wageningen University, Netherlands), Samantha N Heerschop (Division of Human Nutrition, Wageningen University, Netherlands), and Sander de Leeuw (Group Operations Research and Logistics, Wageningen University, Netherlands) for their helpful comments on the research design and manuscript. The authors' responsibilities were as follows — DW, AM-B, and JCG: designed research; DW: was primarily responsible for preprocessing of the data, conducting the diet modeling, and interpreting the results, with advisory inputs from AM-B and JCG; DW: drafted the manuscript; AM-B and JCG: provided critical comments on the manuscript. All authors were involved in critical revisions, had responsibility for the final content, and read and approved the final manuscript. The authors report no conflicts of interest.

Data availability

Data sharing: Data described in the manuscript, code book, and analytic code will be made available upon request.

Funding

Supported by Wageningen Economic Research, Wageningen University & Research; Division of Human Nutrition, Wageningen University; Group Operations Research and Logistics, Wageningen University.

Author disclosures

The authors report no conflicts of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tjnut.2023.05.011.

References

[1] H. Aiking, J. de Boer, The next protein transition, Trends Food Sci. Technol. 105 (2020) 515–522.
[2] J. Graça, C.A. Godinho, M. Truninger, Reducing meat consumption and following plant-based diets: current evidence and future directions to inform integrated transitions, Trends Food Sci. Technol. 91 (2019) 380–390.
[3] E.C. Hemler, F.B. Hu, Plant-based diets for personal, population, and planetary health, Adv. Nutr. 10 (Supplement 4) (2019) S275–S283.
[4] J. Sabaté, S. Soret, Sustainability of plant-based diets: back to the future, Am. J. Clin. Nutr. 100 (Suppl 1) (2014) 476S–482S.
[5] M. Vinnari, E. Vinnari, A framework for sustainability transition: the case of plant-based diets, J. Agric. Environ. Ethics 27 (3) (2014) 369–396.
[6] W. Willett, J. Rockström, B. Loken, M. Springmann, T. Lang, S. Vermeulen, et al., Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems, Lancet 393 (10170) (2019) 447–492.
[7] E. Andrewski, K. Cheng, C. Vanderpool, Nutritional deficiencies in vegetarian, gluten-free, and ketogenic diets, Pediatr. Rev. 43 (2) (2022) 61–70.
[8] R. Broekema, M. Tyszler, P. van't Veer, F.J. Kok, A. Martin, A. Lluch, H.T.J. Blonk, Future-proof and sustainable healthy diets based on current eating patterns in the Netherlands, Am. J. Clin. Nutr. 112 (5) (2020) 1338–1347.
[9] A.L. Elorinne, G. Alfthan, I. Erlund, H. Kivimäki, A. Paju, I. Salminen, et al., Food and nutrient intake and nutritional status of Finnish vegans and non-vegetarians, PLOS ONE 11 (2) (2016), e0148235.
[10] J.R. Hunt, Bioavailability of iron, zinc, and other trace minerals from vegetarian diets, Am. J. Clin. Nutr. 78 (3) (2003) 633S–639S.
[11] N. Martınez-Navarrete, M.M. Camacho, J. Martínez-Lahuerta, J. Martínez-Monzó, P. Fito, Iron deficiency and iron fortified foods—a review, Food Res. Int. 35 (2–3) (2002) 225–231.
[12] M.B. Zimmermann, R.F. Hurrell, Nutritional iron deficiency, Lancet 370 (9586) (2007) 511–520.
[13] A. Lopez, P. Cacoub, I.C. Macdougall, L. Peyrin-Biroulet, Iron deficiency anaemia, Lancet 387 (10021) (2016) 907–916.
[14] J.R. Hunt, Moving toward a plant-based diet: are iron and zinc at risk? Nutr. Rev. 60 (5 Pt 1) (2002) 127–134.
[15] R. Collings, L.J. Harvey, L. Hooper, R. Hurst, T.J. Brown, J. Ansett, et al., The absorption of iron from whole diets: a systematic review, Am. J. Clin. Nutr. 98 (1) (2013) 65–81.

[16] R.E. Conway, J.J. Powell, C.A. Geissler, A food-group based algorithm to predict non-heme iron absorption, Int. J. Food Sci. Nutr. 58 (1) (2007) 29–41.
[17] E. De Carli, G.C. Dias, J.M. Morimoto, D.M.L. Marchioni, C. Colli, Dietary iron bioavailability: agreement between estimation methods and association with serum ferritin concentrations in women of childbearing age, Nutrients 10 (5) (2018) 650.
[18] L. Hallberg, L. Hulthén, Prediction of dietary iron absorption: an algorithm for calculating absorption and bioavailability of dietary iron, Am. J. Clin. Nutr. 71 (5) (2000) 1147–1160.
[19] R.F. Hurrell, M.B. Reddy, M. Juillerat, J.D. Cook, Meat protein fractions enhance nonheme iron absorption in humans, J. Nutr. 136 (11) (2006) 2808–2812.
[20] R. Hurrell, I. Egli, Iron bioavailability and dietary reference values, Am. J. Clin. Nutr. 91 (5) (2010) 1461S–1467S.
[21] M.B. Reddy, R.F. Hurrell, J.D. Cook, Estimation of nonheme-iron bioavailability from meal composition, Am. J. Clin. Nutr. 71 (4) (2000) 937–943.
[22] C. van Dooren, A review of the use of linear programming to optimize diets, nutritiously, economically and environmentally, Front. Nutr. 5 (2018) 48.
[23] P. Eustachio Colombo, L.S. Elinder, A.K. Lindroos, A. Parlesak, Designing nutritionally adequate and climate-friendly diets for omnivorous, pescatarian, vegetarian and vegan adolescents in Sweden using linear optimization, Nutrients 13 (8) (2021) 2507.
[24] T. Barré, M. Perignon, R. Gazan, F. Vieux, V. Micard, M.J. Amiot, N. Darmon, Integrating nutrient bioavailability and co-production links when identifying sustainable diets: how low should we reduce meat consumption? PLOS ONE 13 (2) (2018), e0191767.
[25] A. Dussiot, H. Fouillet, J. Wang, M. Salomé, J.F. Huneau, E. Kesse-Guyot, F. Mariotti, Modeled healthy eating patterns are largely constrained by currently estimated requirements for bioavailable iron and zinc—a diet optimization study in French adults, Am. J. Clin. Nutr. 115 (3) (2022) 958–969.
[26] Centers for Disease Control and Prevention (CDC). National Center for Health Statistics (NCHS). National Health and Nutrition Examination Survey Questionnaire (or Examination Protocol, or Laboratory Protocol). Department of Health and Human Services, Centers for Disease Control and Prevention, Hyattsville, MD: USA, 2017–2018.
[27] U.S. Department of Agriculture, Agricultural Research Service, USDA Food and Nutrient Database for Dietary Studies 2013-2018, U.S. Department of Agriculture. Agricultural Research Service, 2020.
[28] U.S. Department of Health and Human Services & U.S. Department of Agriculture, Dietary guidelines for Americans, USDA and US DHHS, Washington (DC), 2020, 2020–2025.
[29] S.A. Bowman, J.C. Clemens, J.E. Friday, K.L. Lynch, A.J. Moshfegh. Food Patterns Equivalents Database 2017-2018: Methodology and User Guide, 2022.
[30] Institute of Medicine, Dietary Reference Intakes: The Essential Guide to Nutrient Requirements, National Academies Press, 2006.
[31] Institute of Medicine, Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc, National Academies Press, Washington (DC), 2001.
[32] S.M. Armah, A. Carriquiry, D. Sullivan, J.D. Cook, M.B. Reddy, A complete diet-based algorithm for predicting nonheme iron absorption in adults, J. Nutr. 143 (7) (2013) 1136–1140.
[33] S.M. Armah, E. Boy, D. Chen, P. Candal, M.B. Reddy, Regular consumption of a high-phytate diet reduces the inhibitory effect of phytate on nonheme-iron absorption in women with suboptimal iron stores, J. Nutr. 145 (8) (2015) 1735–1739.
[34] U.S. Department of Agriculture, U.S. Department of Health and Human Services. (2017–2018), What We Eat in America, *NHANES 2017–2018*.
[35] E.R. Monsen, Iron nutrition and absorption: dietary factors which impact iron bioavailability, J. Am. Dietc. Assoc. 88 (7) (1988) 786–790.
[36] D.Y. Larvie, S.M. Armah, S.M, Estimating phytate intake from the US diet using the NHANES data, J. Food Compos. Anal. 102 (2021), 104050.
[37] C.E. Cioffi, J. Figueroa, J.A. Welsh, Added sugar intake among pregnant women in the United States: National Health and nutrition examination survey 2003-2012, J. Acad. Nutr. Diet. 118 (5) (2018) 886–895.
[38] U.S. Department of Health and Human Services & U.S. Department of Agriculture. 2015–2020 Dietary Guidelines for Americans.
[39] Institute of Medicine, Dietary Reference Intakes for Calcium and Vitamin D, Institute of Medicine, 2011.
[40] T.A.B. Sanders, The nutritional adequacy of plant-based diets, Proc. Nutr. Soc. 58 (2) (1999) 265–269.
[41] N. EFSA Panel on Dietetic Products, Allergies, Scientific opinion on dietary reference values for iron, EFSA J. 13 (10) (2015) 4254.
[42] S.J. Fairweather-Tait, A. Jennings, L.J. Harvey, R. Berry, J. Walton, J.R. Dainty, Modeling tool for calculating dietary iron bioavailability in iron-sufficient adults, Am. J. Clin. Nutr. 105 (6) (2017) 1408–1414.
[43] V. Galetti, N.U. Stoffel, C. Sieber, C. Zeder, D. Moretti, M.B. Zimmermann, Threshold ferritin and hepcidin concentrations indicating early iron deficiency in young women based on upregulation of iron absorption, EClinMed 39 (2021) 101052.
[44] J.R. Dainty, R. Berry, S.R. Lynch, L.J. Harvey, S.J. Fairweather-Tait, Estimation of dietary iron bioavailability from food iron intake and iron status, PLoS One 9 (10) (2014), e111824.
[45] R. Gazan, C.M.C. Brouzes, F. Vieux, M. Maillot, A. Lluch, N. Darmon, Mathematical optimization to explore tomorrow's sustainable diets: a narrative review, Adv. Nutr. 9 (5) (2018) 602–616.
[46] C.G. Forde, E.A. Decker, The importance of food processing and eating behavior in promoting healthy and sustainable diets, Annu. Rev. Nutr. 42 (2022) 377–399.