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Original Article

Iron and Zinc Bioavailability from Plant-Based Meat Alternatives: A Narrative Review on Nutritional Implications and Challenges

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ABSTRACT

The increasing popularity of plant-based meat alternatives (PBMAs) is driven by health, environmental, and sustainability concerns; however, the bioavailability of important micronutrients such as iron (Fe) and zinc (Zn) remains a major nutritional challenge. Unlike animal-based foods, PBMAs contain Fe and Zn only in non-heme forms, which are less efficiently absorbed and strongly affected by dietary inhibitors including phytate, polyphenols, and fiber, potentially increasing the risk of anemia, impaired immunity, and growth disturbances. This review aimed to evaluate scientific evidence regarding the content, bioavailability, and enhancement strategies of Fe and Zn in PBMAs. Literature searches were conducted in PubMed, Scopus, and Google Scholar using keywords related to iron bioavailability, zinc bioavailability, plant-based meat, absorption inhibitors, and enhancers. Articles were selected based on relevance, methodological quality, and significance of findings. Evidence shows that PBMAs derived from soy, pea, and wheat gluten provide meaningful amounts of Fe and Zn, although their bioavailability is generally lower than that of meat products. Several approaches, including fermentation, soaking, sprouting, mineral fortification, and co-consumption with vitamin C, have been shown to significantly improve mineral absorption. Although long-term physiological adaptation among vegetarians and vegans may partially compensate for reduced absorption, Fe and Zn status still tends to be lower than in omnivorous populations. Overall, PBMAs can support sustainable dietary patterns, but nutritional strategies and product innovations are essential to optimize Fe and Zn bioavailability and reduce the risk of micronutrient deficiencies.

Keywords: *bioavailability, iron, zinc, plant-based meat alternatives, fortification.*

ABSTRAK

Meningkatnya popularitas alternatif daging nabati (PBMA) didorong oleh kekhawatiran kesehatan, lingkungan, dan keberlanjutan; namun, ketersediaan hayati mikronutrien penting seperti zat besi (Fe) dan seng (Zn) tetap menjadi tantangan nutrisi utama. Tidak seperti makanan berbasis hewan, PBMA hanya mengandung Fe dan Zn dalam bentuk non- heme, yang kurang efisien diserap dan sangat dipengaruhi oleh penghambat makanan termasuk fitat, polifenol, dan serat, yang berpotensi meningkatkan risiko anemia, gangguan kekebalan tubuh, dan gangguan pertumbuhan. Tinjauan ini bertujuan untuk mengevaluasi bukti ilmiah mengenai kandungan, ketersediaan hayati, dan strategi peningkatan Fe dan Zn dalam PBMA. Pencarian literatur dilakukan di PubMed, Scopus, dan Google Scholar menggunakan kata kunci yang terkait dengan ketersediaan hayati zat besi, ketersediaan hayati seng, daging nabati, penghambat penyerapan, dan peningkat penyerapan. Artikel dipilih berdasarkan relevansi, kualitas metodologis, dan signifikansi temuan. Bukti menunjukkan bahwa PBMA yang berasal dari kedelai, kacang polong, dan gluten gandum menyediakan jumlah Fe dan Zn yang signifikan, meskipun bioavailabilitasnya umumnya lebih rendah daripada produk daging. Beberapa pendekatan, termasuk fermentasi, perendaman, perkecambahan, fortifikasi mineral, dan konsumsi bersama dengan vitamin C, telah terbukti secara signifikan meningkatkan penyerapan mineral. Meskipun adaptasi fisiologis jangka panjang di antara vegetarian dan vegan dapat sebagian mengimbangi penurunan penyerapan, status Fe dan Zn cenderung lebih rendah daripada pada populasi omnivora. Secara keseluruhan, PBMA dapat mendukung pola makan berkelanjutan, tetapi strategi nutrisi dan inovasi produk sangat penting untuk mengoptimalkan bioavaila.

Kata Kunci: *bioavailability, iron, zinc, plant-based meat alternatives, fortification.*

INTRODUCTION

The shift in dietary patterns toward processed plant-based products, known as plant-based meat alternatives (PBMAs), has increased rapidly over the past five years in line with growing concerns about sustainability and public health. These products are designed to mimic the texture, taste, and sensory characteristics of animal meat while offering a competitive nutritional profile [1]. However, although some PBMAs show iron (Fe) and zinc (Zn) contents that appear adequate, there are concerns regarding the bioavailability of these minerals compared to animal-based sources, which has implications for the nutritional status of populations consuming these products [2].

From an epidemiological perspective, iron and zinc deficiencies remain major public health problems. Data from the Global Burden of Disease (GBD) 2021 reported a global anemia prevalence of approximately 24.3% (~1.9 billion cases), with most cases worldwide caused by iron deficiency [3]. Additionally, national and regional estimates show substantial variation. The prevalence of zinc deficiency and the risk of hypozincemia are generally higher in Asia compared to Europe, with some studies reporting zinc deficiency rates in Asian populations far exceeding those in other regions [4]. In Indonesia, national surveys and studies indicate that anemia rates remain high, particularly among pregnant women, young children, and adolescents, along with evidence of deficiencies in other micronutrients, including zinc [5]. These findings highlight the importance of considering not only the total Fe and Zn content in food products (such as PBMAs) but also their bioavailability within the context of local epidemiology and at-risk groups. From a public health perspective, epidemiological evidence and nutritional status studies suggest that individuals following plant-based diets tend to have lower iron and zinc stores compared to meat consumers, particularly among vulnerable populations [6].

Biochemically, the main difference lies in the form of iron: animal-based foods provide heme iron, which is relatively easily absorbed, whereas PBMAs generally contain non-heme iron, whose clinical absorption is lower and influenced by other dietary components [2]. Furthermore, many plant-based raw materials contain antinutrients, particularly phytic acid (phytate), which can bind Fe and Zn and reduce their biological availability [7]. Comparative in vitro and ex vivo studies show substantial variation among PBMA products in the bioaccessible fraction of Fe/Zn; some products approach adequate levels when consumed as part of a diverse diet, but overall their bioavailability is lower than that of beef products [8].

The food industry and research sectors have responded to this issue through various formulation and processing strategies. Approaches such as fortification (adding bioavailable iron/zinc salts), the use of "heme-like" iron sources such as soy leghemoglobin, and fermentation techniques (e.g., tempeh from soybeans or fermentation with specific microorganisms) have been reported to increase the soluble and absorbable iron fraction in in vitro models and some human/microbiota models. However, the results vary depending on the product matrix, the form of minerals used, and the presence of absorption promoters or inhibitors [9][10]. Therefore, although PBMAs offer potential as a sustainable alternative protein source, a key challenge that must be addressed is the lower bioavailability of Fe and Zn compared to animal sources, necessitating formulation strategies and nutritional interventions to prevent deficiency risks in vulnerable populations.

METHODS

This study employed a narrative literature review approach to examine scientific evidence regarding the bioavailability of iron and zinc in plant-based meat alternatives (PBMAs) and their nutritional implications. Literature sources included original research articles, clinical studies, intervention studies, observational studies, systematic reviews, and scientific reports related to mineral bioavailability and PBMAs. The literature search was conducted using electronic databases including PubMed, Scopus, and Google Scholar using combinations of the following keywords: *iron bioavailability*, *zinc bioavailability*, *plant-based meat*, *plant-based meat alternatives*, *absorption inhibitors*, *phytate*, *fortification*, and *enhancers*. The search process was restricted to articles published between 2020 and 2025 to ensure the inclusion of recent evidence relevant to current PBMA formulations and nutritional research. Only articles published in English were included in this review.

Articles were selected based on predefined inclusion and exclusion criteria. The inclusion criteria consisted of studies discussing iron and/or zinc bioavailability in PBMAs or plant-based diets, studies evaluating factors affecting mineral absorption such as phytate, polyphenols, dietary fiber, fermentation, fortification, or vitamin C, as well as observational studies, intervention studies, in vitro studies, systematic reviews, and narrative reviews relevant to the topic. Meanwhile, exclusion criteria included articles unrelated to mineral bioavailability or PBMAs, opinion papers without empirical data, conference abstracts without accessible full texts, duplicate publications, and studies with unclear or weak methodologies. The selection process was based on relevance to the topic, methodological clarity, and significance of findings. After screening titles, abstracts, and full texts, a total of 59 articles were included in this review. The selected literature was synthesized narratively by comparing findings across different study designs, including in vitro studies, observational studies, intervention studies, and previous reviews. The analysis also considered methodological strengths and limitations, consistency of findings, conflicting evidence, and the biological plausibility of mechanisms influencing iron and zinc bioavailability in PBMAs.

RESULTS

The reviewed literature shows that plant-based meat alternatives (PBMAs) may contain meaningful amounts of iron (Fe) and zinc (Zn), but their nutritional contribution depends strongly on bioavailability rather than total mineral content alone. Across studies, a consistent pattern was observed: plant-based ingredients such as soy, peas, and wheat gluten provide Fe and Zn mainly in non-heme or plant-bound forms, whereas animal-based meat provides heme iron and a food matrix that supports higher mineral absorption [2,7,11,17]. While compositional analyses often report comparable mineral levels between PBMAs and meat, both in vitro and mechanistic studies consistently demonstrate lower bioaccessibility in PBMAs, highlighting a divergence between total content and physiological utility[17,39]. To strengthen the synthesis of evidence, the key studies included in this narrative review are summarized in Table 1. The table presents the study type, main findings, and relevance of each study to the issue of iron and zinc bioavailability in plant-based meat alternatives.

Table 1. *Synthesis of Selected Studies on Iron and Zinc Bioavailability in Plant-Based Meat Alternatives*

Author	Study Type	Main Findings	Relevance	Limitation
Harnack et al. (2021)	Nutrient composition analysis	Plant-based ground beef alternatives contained varying levels of iron and zinc, but nutrient content differed widely across products.	Shows that PBMAs may contain Fe and Zn, but mineral content depends on product formulation	Focused on nutrient composition only; no human absorption or bioavailability outcomes assessed.
Neufingerl & Eilander -2022	Systematic review	Adults consuming plant-based diets generally had lower iron and zinc status compared with meat- eaters.	Supports the public health concern that plant- based diets may increase risk of	Included heterogeneo us observationa l studies with potential confounding factors.

			lower Fe and Zn stores.	
Mayer Labba et al. (2022)	Nutritional composition and estimated bioavailability study	Meat substitutes available on the Swedish market had high phytate- to-mineral ratios, suggesting limited iron and zinc bioavailability.	Provides direct evidence that total mineral content in PBMAs may overestimate actual nutritional value.	Estimated bioavailability only; no direct human absorption measurements.
Latunde- Dada et al. -2023	In vitro mineral availability study	Plant-based burgers showed lower mineral availability than meat burgers, although some products had measurable Fe and Zn content.	Demonstra tes the bioavailabil ity gap between PBMAs and animal- based meat	In vitro study; findings may not fully reflect human digestion and absorption.
Andreani et al. (2023)	Narrative review	PBMAs offer environmental and market benefits but may have nutritional limitations, including micronutrient bioavailability issues.	Provides broader context on nutritional challenges and formulation opportuniti es in PBMAs.	Narrative review design may be subject to selection bias and lacks quantitative synthesis.
Craig et al. -2021	Guideline/ review article	Well-planned plant-based diets can be nutritionally adequate, but attention is needed for nutrients such as iron and zinc.	Highlights the need for dietary planning when PBMAs are used as meat substitutes.	Broad dietary guideline; not specific to PBMAs or clinical mineral outcomes.
Faizal et al. (2023)	Review on food processing	Processing methods such as soaking, germination, and fermentation can reduce antinutrients in plant-based foods.	Supports processing strategies to improve Fe and Zn bioavailabil ity in PBMAs.	Mostly based on experimental and food-processing studies rather than clinical outcomes.
Wilson et al. (2024)	In vitro bioavailability comparison	Fermented tempeh-based products showed improved iron bioavailability compared with several PBMAs, likely due to reduced phytate.	Shows that fermentatio n can improve mineral bioavailabil ty and narrow the gap with meat.	In vitro comparison only; limited applicability to long-term human nutritional status.
Nsabimana et al. -2024	Experimental fermentation study	Fermentation, especially when combined with soaking or germination, reduced phytate and improved iron and	Supports the use of fermentation and phytate reduction as product- level strategies.	Conducted on maize model systems rather than commercial PBMAs.

		zinc bioavailability in maize.		
Klein et al. - 2023	Cross- sectional nutritional status study	Vegetarians and vegans showed differences in zinc and trace element status compared with omnivores.	Provides population-level evidence linking plant-based dietary patterns with lower zinc status.	Cross- sectional design cannot establish causality; possible dietary and lifestyle confounding.
Dawczynski et al. (2022)	Cross- sectional study	Vegetarian and vegan participants had different nutrient intake and status profiles compared with omnivores.	Supports the discussion that dietary pattern affects mineral intake and status.	Observation al design with possible confounding from supplement use and dietary variation.
Alexy et al. - 2021	Cross- sectional study in children/ adolescents	Vegetarian and vegan children and adolescents showed differences in nutrient intake and iron status compared with omnivores.	Relevant for identifying vulnerable groups such as children and adolescents.	Limited by observational design and potential growth- related confounders.
Perera et al. (2023)	Review on iron absorption and fortification	Iron absorption is affected by inhibitors and enhancers; fortification may help improve iron intake and status.	Supports fortification as a strategy to improve Fe bioavailability in PBMAs.	Review article; limited direct evidence from PBMA- specific intervention studies.
Boukid et al. - 2023	Review on fermentation in plant-based alternatives	Fermentation can improve nutritional, technological, and sensory characteristics of plant-based meat and dairy alternatives.	Supports fermentatio n as a practical strategy in PBMA formulation	Mainly focused on technological applications; limited human clinical evidence.
Piskin et al. - 2022	Review on iron absorption	Non-heme iron absorption is strongly affected by dietary inhibitors and enhancers, while heme iron is more efficiently absorbed.	Explains the biological mechanism behind lower iron bioavailabil ity in PBMAs.	General review on iron absorption; not specifically focused on PBMAs.

Iron and Zinc in Plant-Based Meat Alternatives

PBMAs formulated from soy, peas, and wheat gluten generally provide measurable amounts of Fe and Zn. Soy and pea ingredients may contain substantial mineral concentrations, while wheat-based ingredients also contribute Fe and Zn, although levels may decrease during protein isolation or refinement [12–15]. However, these findings should not be interpreted as evidence of equivalent nutritional value to animal meat, because total mineral content does not necessarily reflect the fraction that can be absorbed by the human body [17].

The available evidence indicates that minerals in PBMAs are largely present in non-heme or plant-bound forms. This makes their absorption more dependent on meal composition and more vulnerable to inhibitors such as phytate, polyphenols, and dietary fiber [16,17,23–27]. In contrast, animal-based meat contains heme iron, which is absorbed more efficiently and is less affected by dietary inhibitors [19,22,38]. This mechanistic difference explains why PBMAs may show comparable Fe or Zn content on paper but still provide lower mineral bioavailability in practice [17,39].

Nevertheless, the bioavailability gap is not identical across all PBMA products. Some products with fermentation, fortification, or mycoprotein-based formulations show improved mineral bioaccessibility compared with conventional legume- or cereal-based PBMAs [10,49,41,46]. This suggests that PBMAs should not be treated as a single homogeneous category. Their mineral quality depends on ingredient type, phytate content, processing method, fortification strategy, and the presence of absorption enhancers [23,24,35,36].

Factors Affecting Iron and Zinc Bioavailability

Current literature identifies phytate as the main inhibitor of Fe and Zn bioavailability in PBMAs. Phytate forms insoluble complexes with mineral ions, thereby reducing their solubility and limiting intestinal absorption [7,17,25]. This effect is particularly important in legume- and cereal-based PBMAs, which naturally contain high levels of phytate [23–25].

However, phytate does not act alone. Polyphenols and tannins can bind non-heme iron and reduce absorption, while dietary fiber may decrease mineral availability by binding minerals or accelerating intestinal transit [26,27,30]. Calcium may also interfere with iron absorption when consumed in large amounts together with iron-containing foods [28]. These findings suggest that reduced mineral bioavailability in PBMAs is caused by cumulative interactions within the plant-based food matrix rather than by a single inhibitory factor.

In contrast, vitamin C and organic acids are repeatedly identified as enhancers of non-heme iron absorption. Vitamin C can reduce ferric iron into the more soluble ferrous form and prevent iron from forming insoluble complexes with phytate or polyphenols [29–31]. Organic acids such as citrate and malate may also support mineral solubility by forming soluble complexes and lowering intestinal pH [31]. For zinc, certain proteins and peptides produced during processing or fermentation may improve absorption by forming more soluble mineral complexes [32].

Processing technologies also influence mineral bioavailability. Extrusion and heating may reduce some antinutritional factors, but their effects on Fe and Zn are inconsistent and depend on raw materials, temperature, moisture, and processing intensity [33,34]. Fermentation and enzymatic phytase treatment appear more consistent because they directly reduce phytate and improve mineral bioaccessibility in cereal and legume matrices [35,36]. However, excessive processing, overheating, or the addition of binding components may reduce these benefits, indicating that formulation and processing conditions must be carefully optimized [37].

Comparison with Animal-Based Meat

Animal-based meat remains superior to most PBMAs in terms of iron bioavailability because it provides heme iron, which is absorbed through a more efficient pathway and is less affected by dietary inhibitors [19,22,38]. In contrast, PBMAs contain non-heme iron, whose absorption depends heavily on solubility, intestinal transport, and the presence of enhancers such as vitamin C [29,31,38]. This explains why PBMAs may contain meaningful amounts of Fe but still contribute less effectively to iron status than animal meat [17,39].

Comparative studies support this biological explanation. Analyses of PBMAs available on the Swedish market found high phytate-to-mineral ratios, suggesting that their actual contribution to Fe and Zn intake may be lower than indicated by total mineral content [17]. Similarly, in vitro comparisons reported that beef released more bioavailable Fe and Zn than several plant-based burgers, although some mycoprotein-based products showed values closer to beef [39]. Wilson et al. also reported lower Fe bioavailability in Beyond Burger and Impossible Burger compared with beef, while fermented tempeh mealworm showed improved Fe bioavailability, likely due to reduced phytate levels [10,41].

Evidence from population studies generally supports the concern that plant-based diets may be associated with lower mineral status. The NuEva study reported lower zinc intake and lower serum zinc concentrations among vegetarian and vegan participants, especially women, compared with omnivores and flexitarians [42,45]. The VeChi Youth Study also found lower serum zinc concentrations among vegan and vegetarian children and adolescents compared with omnivores [43]. For iron status, the same study reported higher serum ferritin concentrations in omnivores than in vegetarian and vegan participants, indicating lower iron stores among plant-based diet groups [44].

However, these findings should be interpreted cautiously. Many nutritional status studies are observational or cross-sectional, making them vulnerable to confounding factors such as supplement use, menstrual status, inflammation, total diet quality, socioeconomic background, and long-term dietary patterns [42–45]. In addition, some evidence suggests that long-term adherence to plant-based diets may induce physiological adaptation that improves non-heme iron absorption [21]. Therefore, lower ferritin or serum zinc status among vegetarians and vegans should not be attributed solely to PBMAs, although PBMAs may contribute to the problem if they are poorly formulated or consumed without appropriate dietary planning.

Strategies to Improve Bioavailability

The reviewed evidence suggests that improving Fe and Zn bioavailability in PBMAs requires both product-level and diet-level strategies. At the product level, fortification is one of the most widely discussed approaches. NaFeEDTA appears promising for iron fortification because it is less affected by phytate and polyphenols than some conventional iron salts, making it suitable for high-phytate food matrices [46,47]. For zinc, zinc sulfate and zinc oxide are commonly used because they are relatively effective and economical [46]. However, fortification alone may not be sufficient if the food matrix still contains high levels of inhibitors.

Processing strategies such as soaking, germination, fermentation, and phytase treatment directly target phytate reduction. Soaking may reduce soluble phytate and other antinutrients, while germination activates endogenous phytase enzymes that break down phytate [48,49]. Fermentation appears particularly useful because microbial activity can reduce phytate, improve protein quality, and enhance sensory properties [35,36,50]. However, the effectiveness of fermentation depends on microbial strain, fermentation time, pH, temperature, and substrate composition [35,50]. Therefore, processing methods should be optimized for each PBMA formulation rather than applied generically.

At the dietary level, pairing PBMAs with vitamin C-rich foods may improve non-heme iron absorption by increasing iron solubility and preventing its binding with phytate or polyphenols [29,31,51]. This strategy is practical and low-cost, but it depends on consumer behavior and may not be sufficient for vulnerable groups with high mineral requirements, such as children, adolescents, pregnant women, and women of reproductive age [3,5,18]. Therefore, the most effective approach is likely a combined strategy involving phytate reduction, mineral fortification, food-pairing education, and monitoring of mineral status in at-risk groups.

Emerging technologies such as nanoencapsulation and hybrid fortification may offer additional opportunities to improve mineral delivery in PBMAs [53,54]. Nanoencapsulation may protect minerals from interactions with inhibitors and allow controlled release in the gastrointestinal tract [53]. Hybrid fortification strategies, such as combining fermentation with iron-rich ingredients, may also improve iron solubility and bioavailability [41,54]. Nevertheless, evidence for these newer technologies remains more limited than evidence for phytate reduction, vitamin C enhancement, and conventional fortification. More human intervention studies are needed before strong clinical claims can be made.

DISCUSSION

The findings indicate that the main nutritional limitation of PBMAs is not necessarily low total Fe or Zn content, but reduced bioavailability. This distinction is important because total mineral content may appear adequate, while the absorbable fraction remains limited by antinutrients and plant-based food matrices [17,25]. Across the reviewed studies, this pattern was consistent: PBMAs based on soy, peas, and wheat gluten may provide meaningful amounts of Fe and Zn, but these minerals are mainly present in non-heme or plant-bound forms that are less efficiently absorbed than minerals from animal-based meat [11–17,38,39].

The mechanistic differences between heme and non-heme iron provide a strong biological explanation for the lower iron bioavailability of PBMAs. Heme iron from animal-based foods is absorbed through a more efficient pathway and is less affected by dietary inhibitors, whereas non-heme iron from PBMAs is strongly influenced by phytate, polyphenols, calcium, fiber, and meal composition [19,22,28,38]. This mechanism is supported by comparative studies showing lower estimated Fe and Zn bioavailability in several PBMA products than in beef [17,39]. However, the evidence is not entirely uniform, because fermented products, mycoprotein-based products, and fortified formulations may partly narrow this gap [10,39,41,46]. Thus, the nutritional quality of PBMAs should be evaluated by formulation and processing method, not merely by product category.

Although phytate is consistently reported as a major inhibitor of mineral absorption, the magnitude of its effect varies substantially depending on food matrix, processing methods, and co-consumed nutrients. This indicates that the nutritional impact of phytate cannot be generalized across all PBMA products. Some fermented or fortified PBMAs may achieve substantially improved mineral bioavailability, whereas minimally processed high-phytate products may still pose a higher risk of inadequate Fe and Zn absorption. Therefore, evaluating PBMAs solely based on total mineral content may lead to an overestimation of their nutritional adequacy.. In contrast, evidence for newer technologies such as nanoencapsulation, hybrid fortification, and heme-like plant ingredients remains more limited and often depends on experimental or in vitro models rather than long-term human outcomes [9,41,53,54]. Therefore, these strategies are promising, but further controlled human studies are required before firm conclusions can be drawn regarding their clinical effectiveness.

The molecular mechanisms described in the literature support the observed differences in mineral bioavailability. Phytate forms insoluble complexes with Fe and Zn ions, reducing their solubility in the intestinal lumen [17,25]. Polyphenols and tannins can bind non-heme iron, while fiber and calcium may reduce mineral availability through binding, altered intestinal transit, or competitive effects during absorption [26–28,30]. Conversely, vitamin C, organic acids, and peptides generated during processing or fermentation may improve mineral solubility and bioaccessibility [29,31,32,35,36]. These findings indicate that mineral absorption from PBMAs is determined by the balance between inhibitors and enhancers within the whole meal, rather than by mineral content alone.

Effective mitigation strategies emerge at both product and dietary levels. At the product level, fortification with mineral forms that are less affected by inhibitors, such as NaFeEDTA for iron and zinc sulfate or zinc oxide for zinc, may improve mineral availability in high-phytate matrices [46,49]. Processing methods such as fermentation, germination, soaking, and phytase treatment can also reduce phytate and improve mineral bioaccessibility, although their effectiveness depends on processing parameters and ingredient composition [35,36,48–50]. Among these methods, fermentation and phytase treatment appear to have more consistent effects because they directly degrade phytate, whereas soaking alone may produce more variable results [35,36,48].

At the consumption level, pairing PBMAs with vitamin C-rich foods or organic acids can enhance non-heme iron absorption by increasing iron solubility and reducing its interaction with phytate and polyphenols [29,31,51]. However, this strategy depends on dietary behavior and may not be sufficient for vulnerable populations with higher Fe and Zn requirements [3,5,18]. In addition, complete removal of phytate may not always be desirable because phytate may also have functional health benefits, including antioxidant-related properties [52]. Taken together, the current evidence suggests that concerns regarding mineral bioavailability in PBMAs are justified, particularly for products with high phytate content and limited fortification. However, these concerns may be reduced when PBMAs are properly formulated, processed, fortified, and consumed as part of a diverse diet containing absorption enhancers. The literature also presents a nuanced and partly conflicting picture regarding plant-based diets. On one hand, observational studies often report lower ferritin or serum zinc concentrations among vegetarians and vegans compared with omnivores [42–45]. On the other hand, some evidence suggests that long-term plant-based consumers may adapt by increasing non-heme iron absorption [21]. These findings are not necessarily contradictory. Physiological adaptation may improve fractional absorption, but it may not fully overcome the combined effects of lower mineral bioavailability, higher phytate intake, and increased requirements in certain groups. This suggests that the nutritional success of PBMAs depends less on the plant-based concept itself and more on formulation quality, processing strategy, and overall dietary context. [3,5,18,21].

Several important limitations should be considered when interpreting these findings. First, PBMAs vary widely in ingredients, fortification, processing methods, and phytate content, which limits the generalizability of findings across all products [23,24,33]. Second, many studies rely on in vitro digestion models or bioaccessibility estimates, which are useful for product comparison but do not fully reflect actual human absorption, microbiota interactions, or long-term nutritional status [17,35,36,39–41]. Third, many studies assessing mineral status in vegetarian or vegan populations are cross-sectional, making them susceptible to confounding from supplement use, menstrual status, inflammation, total diet quality, and lifestyle factors [42–45]. Therefore, more controlled clinical trials are needed to determine whether improved PBMA formulations can meaningfully improve Fe and Zn status in humans.

A critical gap in the current literature is the limited availability of long-term controlled human studies assessing mineral status in PBMA consumers across different product formulations and dietary patterns. Most available evidence is derived from in vitro experiments, short-term interventions, or observational studies, which may not fully capture long-term physiological adaptation, habitual dietary interactions, and real-world consumption patterns. Future studies should therefore prioritize well-controlled longitudinal human trials to determine whether improvements in PBMA formulation can translate into clinically meaningful improvements in Fe and Zn status.

However, the evidence is not entirely consistent across study types. In vitro studies uniformly report reduced mineral bioaccessibility in PBMAs, whereas human studies show more variable findings. Some observational studies report lower ferritin and zinc levels among plant-based populations, while others suggest adaptive increases in non-heme iron absorption. These discrepancies highlight the gap between controlled experimental models and real-world dietary conditions. Despite these limitations, a consistent mechanistic framework supports the observed trends. Phytate remains the dominant inhibitor, while vitamin C and fermentation-based processing act as key enhancers. The balance between these factors determines mineral bioavailability more than absolute mineral content alone.

CONCLUSION

PBMAs contain significant amounts of iron and zinc; however, limitations in bioavailability due to antinutrients and the plant-based matrix make it challenging to meet mineral requirements, particularly in vulnerable populations. Therefore, attention to dietary patterns and product formulation should be part of a multidisciplinary approach to ensure nutritional adequacy. Technical strategies and simple dietary interventions need to be individualized and integrated into care plans or nutrition education. Monitoring iron and zinc status in at-risk groups, along with further research on the effectiveness of PBMA formulations, will help reduce the risk of deficiencies and ensure that PBMAs can serve as nutritionally safe substitutes for meat.

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