

Nutritional Analysis of Plant-Based Meat: Current Advances and Future Potential

Padma Ishwarya Shankaran ¹ and Priyanka Kumari ^{2,*} ¹ The Good Food Institute (GFI) India, Mumbai 400076, Maharashtra, India; padmai@gfi.org² Sight and Life, P.O. Box 2116, 4002 Basel, Switzerland

* Correspondence: priyanka.kumari@sightandlife.org

Abstract: This perspective article delves into the current state of the art pertaining to the nutritional aspects of plant-based meat and identifies future opportunities for improvement in this line of research. A comparative overview of the macro- and micronutrients of plant-based meat products vis-à-vis conventional animal meat is presented in the initial section. This article explains the differences in their nutritional profiles, highlighting the advantages (equivalent protein content, low saturated fat, source of dietary fiber) and challenges (incomplete amino acid profile, anti-nutrients, and low bioavailability of nutrients) of plant-based alternatives. Emphasis has been placed on the health challenges posed by anti-nutrients in plant-based meat and the role of phytase as a promising solution for mitigating these concerns. The latter sections of this article highlight the ability of phytase enzymes to cause a substantial reduction in phytic acid content and improve the absorption of iron and zinc from the food matrix while not affecting the textural attributes of end products. By deliberating on these critical factors, the article aims to contribute to the ongoing dialogue on the nutritional aspects of plant-based meat and the scientific strategies to mitigate the nutritional challenges currently associated with this category of alternative protein products.

Keywords: plant-based meat; protein; saturated fat; dietary fiber; anti-nutrients; phytase



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1. Introduction

According to the Food and Agriculture Organization (FAO), food production needs to increase by 60% to feed a projected global population of nearly 10 billion by 2050 [1]. However, increased production does not guarantee food security. Current volumes are enough to feed everyone, but one third of the food gets wasted or lost, and the remaining is not nutritious or accessible. Approximately 735 million people suffered from chronic hunger and 2 billion did not have access to nutritious food in 2022 [2]. Minimizing waste and transitioning to a healthier diet is a way forward. A healthy diet has a balanced composition of macro- and micronutrients. Plant-based alternative proteins have emerged as a potential choice in recent years. The term “plant-based foods” refers to products made from ingredients solely derived from plants, which are alternatives to animal-based products. This includes plant-based meat, eggs, dairy and seafood. Plant-based food products, like animal-derived ones, contain essential nutrients, such as protein, fat, vitamins, and minerals, while also providing complex carbohydrates and fiber, replicating the appearance, taste, and cooking properties of traditional animal-based products.

Several studies have documented the health benefits of plant-based whole foods such as legumes, whole grains, and vegetables and their role in alleviating the risk of diet-related illness and mortality [3–5]. Most studies have concluded that a diet rich in plant-based foods offers a dual advantage in terms of health and environmental benefits. Moreover, such diets benefit both people and the planet [6]. These findings and consumer trends are projected to increase the Indian plant-based meat market from 12.6 USD million in 2022 to 228 million by 2030 at a 44% year-on-year growth rate [7]. A recent study found that

72% of customers who bought plant-based meat intend to buy again, citing protein content, health, and nutrition as key reasons, highlighting the importance of understanding the nutritional aspects of plant-based meat due to its increasing popularity [8]. Evidence-based claims must be established on the linkage between plant-based meat, nutrition, and health. Preliminary studies have shown that replacing conventional meat with plant-based options could reduce the risk of heart disease [9,10], improve gut health [11,12], and help maintain a healthy weight [13]. Nevertheless, the nutritional challenge associated with protein quality and the presence of anti-nutritional factors associated with ingredients in plant-based meat should be addressed. Mitigation of anti-nutritional factors and enhancing the digestibility and bioavailability of nutrients in plant-based meat are highly relevant.

Owing to the breadth and depth of the subject, this perspective article focuses on the nutritional aspects of plant-based meat products. Their nutritional quality and composition of macro- and micronutrients vis-à-vis their animal-derived counterparts will be reviewed in the initial sections of this article. The latter sections focus on the challenges of plant-based meat from a nutritional standpoint, emphasizing the anti-nutritional factors and the scientific means of alleviating the same. In this context, the application of “phytase”, a type of phosphatase enzyme, will be discussed as a solution to address the challenges associated with anti-nutrients in plant-based meat products.

2. Plant-Based Meat versus Conventional Meat: A Nutritional Stance

Nutrition is not just limited to calories. The amount of macronutrients and micronutrients and their ability to cater to the dietary requirements of consumers govern the nutritional quality of any food product. Plant-based meat is no exception to this! Indeed, this product category has emerged due to the increasing demand for protein and the consequent innovations led by the food industry [14]. Generally, under-consumption of plant-based foods and over-consumption of red and processed meat and foods high in salt, sugar, and saturated fat have been associated with diet-related illness and death. On the other hand, plant-based meat can satisfy many of the nutritional requirements met by conventional meat and often has less saturated fat and more fiber. The optimal choice of processing methods can aid in enhancing the nutrient content and digestibility of plant-based meat products [15]. The following subsections present a comparative overview of the different macro- and micronutrients and energy provided by plant-based meat and conventional meat.

Protein content (as a percentage) is prioritized among the macronutrients in plant-based meat products. This is relevant, as scientists working in alternative proteins and amino acids are investigating strategies to comply with the FAO's requirements for meat [16]. A recent report by the Good Food Institute (GFI) Europe [17] showed that the protein content per 100 g of most plant-based meat products in the European market (comprising the UK, Sweden, Germany, and The Netherlands) was slightly lower than conventional meat. However, nutritious protein sources are not just determined by the protein content by weight but also in terms of the percentage of calories provided by protein content (at least 20% of the calories), rather than carbohydrates or fat in a food product. Hence, the report concluded that plant-based foods are more similar to conventional meat based on the energy provided by their protein content.

Differences are observed in the proportion of essential amino acids between different plant-based meat products as a function of their protein source and product format [18]. For instance, a nutritional label analysis study conducted on 269 plant-based meat products across different formats (steaks, patties, meatballs, cutlets, and cured meats) sold on the Italian market showed that only plant-based patties and meatballs had a lower protein content than their conventional meat counterparts [19]. The other plant-based meat products that had more protein than their animal-derived equivalents contained cereals and legumes and a combination of plant protein sources, which could have contributed to their enhanced protein content. Legumes (15.0 g/100 g) offer significantly higher protein content than a combination of legumes and vegetables (10.1 g/100 g) or cereals and vegetables

(5.4 g/100 g) [20]. The dietary fat content and source of fat are also crucial in assessing nutrition, and plant-based products are often associated with foods with a lower fat content. A recent study found lower saturated fat levels and total fat content (on average 30%) in plant-based patties relative to patties of animal origin (40%) [21]. Generally, the carbohydrate content of plant-based meat products is comparable to that of conventional meat. However, it varies with the product type, depending on its ingredients. Some plant-based meat products may also contain added carbohydrates in the form of fillers, binders, or flavorings.

Reducing the risk of cardiovascular disease and death by high-fiber intake is well supported by the literature [22]. The development of a healthy gut and microbiota and a decrease in inflammation are associated with high fiber consumption [23]. Contrary to conventional meat, plant-based meat is regarded as a source of fiber. Added plant-based components provide the small amount of fiber in animal-derived meat products. Fiber is an essential component of a balanced diet. High fiber intake has been associated with a lower risk of major diseases like pancreatic cancer, coronary artery disease, cardiovascular disease, and all-cause mortality [22]. With respect to energy, plant-based meat products generally provide fewer calories per serving compared to traditional animal meat counterparts that have higher fat content, especially saturated fat. This is particularly true if the plant-based meat is made with leaner ingredients and lower fat content. Plant-based meat may contain fiber from plant sources, contributing to a feeling of fullness and satiety without adding many calories. Table 1 shows comparative data on the nutritional composition of plant-based meat and conventional meat.

Table 1. Median values for nutrients per 100 g of plant-based meat versus conventional meat (adapted and reproduced with permission from [24]).

Product (per 100 g)	Product	Calories (kcal)	Saturated Fat (g)	Protein (g)	Fiber (g)
Sausages	Conventional meat	277 (17)	6.8 (1.4)	15 (1.3)	1.0 (0.8)
		279 (42.5)	7.5 (1.3)	20 (3.3)	0.9 (0.85)
	Plant-based	149 (15.5)	2.5 (2.23)	8.6 (6.55)	6.4 (2.25)
Beef patties	Conventional meat	247.5 (35.25)	7.6 (0.68)	20 (1.48)	0.5 (0.28)
		255.5 (57.75)	7.5 (3.78)	21 (3.9)	0.5 (0.23)
	Plant-based	212.5 (48.5)	1.6 (0.8)	16.6 (1.38)	6.1 (1.5)
Chicken nuggets	Conventional meat	262.5 (17)	2.1 (0.88)	14.0 (1.15)	1.6 (0.48)
	Plant-based	253 (23.25)	0.9 (0.13)	12.4 (0.85)	4.9 (1.78)
Mince	Conventional meat	195.5 (33.75)	4.5 (1.83)	20.8 (3.88)	0.0 (0.2)
	Plant-based	141 (30.25)	0.9 (2.48)	17.4 (3.48)	5.3 (1.05)
Meatballs	Conventional meat	216.5 (47)	5.4 (2.45)	20.5 (3.38)	0.5 (0.60)
	Plant-based	177 (31.75)	1.3 (0.55)	15.6 (2.38)	5.1 (1.53)

Values within the parentheses indicate the interquartile range.

The micronutrient content of plant-based meat products compared to conventional animal meat can vary significantly based on their ingredients and fortification. Legumes, grains, vegetables, and seeds used in plant-based meats can contribute to vitamin C, vitamin A, folate, and minerals like magnesium and potassium. Animal meats, especially red meats like beef, are high in heme iron, which is more readily absorbed by the body than non-heme iron found in plant-based sources. However, some plant-based meat products are fortified with iron to enhance their nutritional value. Vitamin B₁₂ is primarily found in animal products, including meat, fish, eggs, and dairy. Plant-based meat substitutes typically do not naturally contain vitamin B₁₂ unless fortified with this nutrient. Both plant-based and animal-based sources can provide zinc, but the bioavailability of zinc from plant sources may be lower due to anti-nutritional factors like phytates that can inhibit its absorption.

3. Nutritional Challenges in Plant-Based Meat Products

Compared to conventional meat, the nutritional quality of plant-based meat is mainly limited by its lower protein quality due to the incomplete amino acid profile caused by the lack of one or more essential amino acids that the human body cannot synthesize on its own. Animal proteins derived from meat, dairy, and eggs generally contain all essential amino acids in sufficient amounts, making them complete proteins. The incomplete amino acid profile and presence of anti-nutritional factors can reduce the digestibility and bioavailability of amino acids available in plant-based meat. Anti-nutritional factors hinder the absorption of minerals and other nutrients. The subsequent sections elaborate on these challenges and the associated consequences.

3.1. Protein Quality

The nutritional adequacy of any food product is governed by its protein quality. Protein quality can be defined as the minimum intake of high-quality protein containing all the essential amino acids that supports the maintenance of an appropriate body composition and promotes growth at a normal rate for age, assuming normal physical activity [25]. According to the Food and Drug Administration (FDA), adults must consume 50 g of protein per day as part of a 2000-calorie diet. Nevertheless, an individual's specific requirements for protein will depend on their age, sex, activity levels, and other factors. The recommended dietary allowance to prevent protein deficiency in an average sedentary adult is 0.8 g/kg of body weight [26,27]. Generally, protein quality is ascertained by measuring its digestibility and quantity of essential amino acids. FAO has recommended the DIAAS (digestible indispensable amino acid score) as a metric to measure protein quality, which is determined using the following equation [28]:

$$\text{DIAAS}(\%) = 100 \times \frac{\text{mg of digestible dietary indispensable amino acid in 1 g of the dietary protein}}{\text{mg of the same dietary indispensable amino acid in 1 g of the reference protein}} \quad (1)$$

Though plant-based meat products are made from protein-rich sources such as soy, wheat gluten, and pea, they often lack a balanced composition of essential amino acids. Factually, plant-based meat products have a higher content of glutamic acid and cysteine and a lower amount of alanine, glycine, and methionine [29]. This could be because of the deficiency of these amino acids in their respective sources of plant protein. Cereals lack lysine, and legumes are lacking in sulfur-containing essential amino acids such as methionine and cysteine. Hence, plant proteins are nutritionally incomplete due to their deficiency in one or more essential amino acids. Table 2 compares the essential amino acid content between proteins derived from different plant and animal sources. The deficiency of plant proteins in essential amino acids can lead to lower muscle protein synthesis associated with the consumption of plant-based foods [30]. This is a major concern with respect to the elderly population, who are vulnerable to muscle depletion [31]. The recommendation is to consume a broad variety of plant proteins to warrant the intake of an adequate amount of all the amino acids [32].

Table 2. Comparison of the essential amino acid content between selected sources of plant proteins and animal proteins (values expressed in g/100 g of protein).

Essential Amino Acid/Protein Source	Histidine	Lysine	Isoleucine	Leucine	Methionine	Phenylalanine	Threonine	Tryptophan	Valine	Reference
Finger millet	2.37 ± 0.46	2.83 ± 0.34	3.70 ± 0.44	8.86 ± 0.54	2.74 ± 0.27	5.70 ± 1.27	3.8 ± 0.45	0.91 ± 0.30	5.65 ± 0.44	[33]
Pearl millet	2.15 ± 0.37	3.19 ± 0.49	3.45 ± 0.74	8.52 ± 0.86	2.11 ± 0.50	4.82 ± 1.18	3.55 ± 0.40	1.33 ± 0.30	4.79 ± 1.04	
Sorghum	2.07 ± 0.20	2.31 ± 0.40	3.45 ± 0.63	12.03 ± 1.51	1.52 ± 0.50	5.10 ± 0.50	2.96 ± 0.17	1.03 ± 0.21	4.51 ± 0.71	
Little millet	2.35 ± 0.18	2.42 ± 0.10	4.14 ± 0.08	8.08 ± 0.06	2.21 ± 0.10	6.14 ± 0.10	4.24 ± 0.12	1.35 ± 0.10	5.31 ± 0.16	
Kodo millet	2.14 ± 0.07	1.42 ± 0.17	4.55 ± 0.22	11.96 ± 1.65	2.69 ± 0.16	6.27 ± 0.34	3.89 ± 0.16	1.32 ± 0.19	5.49 ± 0.23	
Amaranth seed (pale brown)	1.98 ± 0.50	5.50 ± 0.35	2.85 ± 0.04	4.94 ± 0.17	1.95 ± 0.12	4.75 ± 0.41	2.99 ± 0.21	1.69 ± 0.10	4.30 ± 0.27	
Quinoa	2.98	5.55	3.75	6.08	2.24	4.35	3.01	1.25	4.55	
Bengal gram	2.39 ± 0.34	6.06 ± 0.52	4.25 ± 0.26	6.91 ± 0.65	1.12 ± 0.31	5.97 ± 1.06	3.24 ± 0.34	1.09 ± 0.25	4.09 ± 0.41	
Black gram	2.64 ± 0.11	6.22 ± 0.21	3.75 ± 0.92	7.93 ± 0.45	1.31 ± 0.35	5.68 ± 0.91	2.99 ± 0.19	1.07 ± 0.12	4.61 ± 1.06	
Field bean, black	3.21	6.79	4.57	8.91	1.36	5.88	4.12	0.73	5.24	
Field bean, brown	3.23	6.75	4.59	8.88	1.38	5.72	3.97	0.78	5.16	
Field bean, white	2.82 ± 0.76	6.13 ± 0.68	4.41 ± 0.36	8.48 ± 0.66	1.40 ± 0.18	5.76 ± 0.32	3.97 ± 0.31	0.89 ± 0.07	4.96 ± 0.36	
Green gram	2.55 ± 0.26	6.09 ± 1.06	4.07 ± 1.11	7.90 ± 0.99	1.05 ± 0.23	6.20 ± 0.61	3.36 ± 0.60	1.24 ± 0.42	5.21 ± 1.28	
Lentil	1.93 ± 0.32	6.12 ± 0.71	3.74 ± 0.91	7.10 ± 0.86	0.54 ± 0.19	5.10 ± 0.73	3.31 ± 0.24	0.81 ± 0.07	5.02 ± 0.39	
Cowpea, brown	2.93 ± 0.42	6.67 ± 1.26	4.10 ± 0.58	7.49 ± 1.23	1.38 ± 0.16	5.47 ± 0.49	3.80 ± 0.61	1.05 ± 0.03	4.87 ± 0.59	
Cowpea, white	3.25	7.14	4.40	7.96	1.53	5.63	4.10	0.92	5.31	
Black gram	2.64 ± 0.11	6.22 ± 0.21	4.34 ± 0.23	7.40 ± 0.31	1.16 ± 0.16	6.26 ± 0.70	3.55 ± 0.31	0.95 ± 0.07	4.58 ± 0.51	
Animal-derived proteins										
Chicken (poultry, leg, skinless)	4.47 ± 0.17	7.26 ± 0.28	2.76 ± 0.18	7.84 ± 0.17	6.04 ± 0.32	7.07 ± 0.21	5.66 ± 0.29	1.16 ± 0.22	4.92 ± 0.22	[33]
Goat, liver	4.23 ± 0.47	8.39 ± 0.98	3.04 ± 0.42	6.02 ± 0.25	6.27 ± 0.18	5.64 ± 1.19	6.58 ± 0.68	1.22 ± 0.11	4.53 ± 0.99	
Beef, round (leg)	5.07 ± 0.36	8.09 ± 0.22	3.67 ± 0.50	6.43 ± 0.16	5.41 ± 0.17	7.00 ± 0.85	5.10 ± 0.13	1.42 ± 0.16	4.67 ± 0.18	
Pork, shoulder	4.83 ± 0.29	8.39 ± 0.12	3.86 ± 0.46	5.50 ± 0.13	5.32 ± 0.44	6.51 ± 0.58	4.39 ± 0.43	1.32 ± 0.11	4.41 ± 0.29	
Whole egg	4.65 ± 0.07	8.37 ± 0.19	2.15 ± 0.07	7.95 ± 0.18	6.72 ± 0.27	6.29 ± 0.32	6.34 ± 0.23	1.59 ± 0.15	5.82 ± 0.20	
Egg white	4.54 ± 0.17	8.35 ± 0.20	2.25 ± 0.14	7.94 ± 0.25	6.24 ± 0.33	5.28 ± 0.56	6.90 ± 0.21	1.50 ± 0.11	6.89 ± 0.19	[34]
Egg yolk	5.69 ± 0.09	8.58 ± 0.29	2.19 ± 0.08	7.24 ± 0.23	6.17 ± 0.22	7.08 ± 0.38	6.14 ± 0.10	1.47 ± 0.12	5.66 ± 0.33	
Cow milk	2.14 ± 0.13	8.59 ± 0.20	6.20 ± 0.55	10.66 ± 0.41	2.51 ± 0.12	5.09 ± 0.42	4.81 ± 0.07	1.46 ± 0.11	6.40 ± 0.24	[33]
Whey	1.53 ± 0.03	7.37 ± 0.18	5.30 ± 0.04	8.52 ± 0.15	1.69 ± 0.03	2.59 ± 0.02	5.47 ± 0.11	1.63 ± 0.02	4.97 ± 0.05	[35]

3.2. Anti-Nutritional Factors

The presence of a high amount of anti-nutritional factors, including phytic acid, lectins, oxalates, tannins, saponins, and enzyme inhibitors (Table 3), in plant-based meat is another major nutritional challenge [36]. “Anti-nutrients” are chemicals naturally produced by plants as a defense mechanism or synthetic compounds that interfere with nutrient absorption and reduce nutrient intake, digestion, and utilization in the human body [37]. The primary health consequence of anti-nutritional factors associated with plant-based meat is reduced nutrient bioavailability [38]. In addition, anti-nutrients can also impart an unpleasant flavor, such as bitterness, when used in plant-based meat product analogues [16]. Apart from anti-nutritional factors, plant sources may also contain indigestible constituents such as non-starch polysaccharides or fibers that limit enzyme access to proteins and reduce protein digestibility [39].

Table 3. Plant-based sources and effects of anti-nutritional factors.

Anti-Nutrients	Source	Interaction with Nutrients
Phytic acid	Cereals, legumes, nuts, and seeds that are used to produce extruded plant-based meat products	It can bind to amino acids and minerals such as iron, zinc, and calcium, making them less bioavailable for absorption by the body.
Lectins	Legumes, grains, and vegetables belonging to the group of plants in the Solanaceae family (ex. tomatoes, eggplant)	Some lectins may interfere with nutrient absorption and cause digestive issues.
Oxalates	Spinach, beet greens, and nuts	Oxalates can bind to calcium and other minerals, potentially reducing their absorption.
Tannins	Tea, coffee, and certain plant foods like legumes, nuts, and some fruits.	Tannins can interfere with iron absorption and may cause digestive discomfort.
Protease inhibitors	Legumes and grains	Protease inhibitors can interfere with protein digestion.
Saponins	Legumes, whole grains, and some vegetables	Saponins may interfere with nutrient absorption and cause digestive issues.

Among all anti-nutritional factors, phytic acid is of prime concern for human nutrition. It is a compound present in plants, soils, legumes, cereals, seeds, and nuts (Table 4) [40]. It can be chemically described as the hexaphosphoric ester of the hexahydric cyclic alcohol meso-inositol and is the principal storage form of phosphorus in plant tissues. Its unique structure, with 12 replaceable hydrogen ions and a highly negative charge [41], helps it to strongly bind to minerals (iron, zinc, magnesium, and calcium) and amino acids [42–44], forming an insoluble complex called phytate, which inhibits protein and micronutrient absorption by the body [40,45,46]. Several single-meal isotope studies have shown phytate influencing absorption and bioavailability from added and inherent iron [47,48]. Phytate works in a broad pH region and has low solubility even at very low intestinal pH.

Moreover, phytate can impact carbohydrate and lipid absorption as well. Phytate–carbohydrate complexes inhibit amylase activity and decrease carbohydrate degradation, hence reducing glucose’s solubility, digestibility, and absorption. The formation of lipid–phytate complexes leads to metallic soaps in the gut lumen, resulting in lower lipid availability and metabolism. Hence, phytates must be eliminated to improve the nutritional value of plant-based meat. There are various preparation and processing techniques to reduce phytates in food [45,46,49]. In the last decade, research and development (Table 5) have focused on developing methods and solutions such as extrusion, soaking, germination, malting, cooking, fermentation, and adding isolated phytase [43,45]. All methods help to degrade phytates in food at some level. However, enzymatic methods, such as phytase addition and fermentation, have demonstrated superior benefits over physical extraction methods [50,51]. The use of added or native phytase during food processing or food consumption can result in complete dephytinization and increase the bioavailability

of added and native minerals [48,52,53]. Hence, phytase can potentially enhance the effects of fortification and absorption of inherent amino acids and minerals in plant-based meat.

Table 4. Examples of high-phytate plant materials, as a percentage of dry weight.

Food	Phytic Acid
Almonds	0.4–9.4%
Beans	0.6–2.4%
Brazil nuts	0.3–6.3%
Hazelnuts	0.2–0.9%
Lentils	0.3–1.5%
Maize, corn	0.7–2.2%
Peanuts	0.2–4.5%
Peas	0.2–1.2%
Rice	0.1–1.1%
Rice bran	2.6–8.7%
Sesame seeds	1.4–5.4%
Soybeans	1.0–2.2%
Tofu	0.1–2.9%
Walnuts	0.2–6.7%
Wheat	0.4–1.4%
Wheat bran	2.1–7.3%
Wheat germ	1.1–3.9%

Table 5. Methods used to reduce phytic acid in food material.

Method	Variables Analyzed	Food Source	Phytic Acid Reduction (%)	Conditions	Study
Phytase addition	Phytase activity	Dark rye bread	99% IP6 degraded	Sourdough fermented 10–12 h	Engelsen et al., 2007 [54]
Phytase addition	Phytic acid content	Whole wheat flour	35.3–69.2	N/D	Akhter et al., 2012 [55]
Phytase addition	Phytic acid reduction	Infant cereals	68.6–93.4	Cereal mix roasted in oven at 120 °C for 30 min. 60 g roasted flour suspended in 124 mL deionized water. Phytase added to the suspension 20 min incubation at 55 °C and pH 5.5 under gentle agitation.	Sanz-Penella et al., 2012 [56]
Phytase addition	Phytase activity	Bread with bran	90%	N/D	Watson W et al., 2014 [57]
Phytase addition	Phytic acid content	70:30 blend of pea and oat protein	32%	15% dry matter; pH = 6.7. The suspension was heated to 40 °C. 1.5% of phytase (Phyzyme® XP) added to the suspension 4-h incubation at 40 °C under minimum agitator speed.	Kaleda et al., 2020 [58]

Table 5. Cont.

Method	Variables Analyzed	Food Source	Phytic Acid Reduction (%)	Conditions	Study
Phytase addition	Phytase activity	Sorghum flour	65% IP6 degraded	Grains (four varieties) washed and dried in an oven at 50 °C for 4 h. Grains milled in a knife mill and sieved in a 20-mesh sieve. Flour stored at −18 °C	Rebellato et al., 2020 [59]
Soaking	Phytase activity	Grains and seeds	10–60	100 g whole grains or seeds soaked in 500 mL water in a covered beaker for 16 h in the dark at 25 °C	Egli et al., 2002 [60]
Soaking	Heat pretreatment	Brown rice	14–28	Soaking in demineralized water for 24 h at 25 °C	Liang, Han, Nout, and Hamer, 2008 [61]
Autoclave	Autoclaving time, pH	Wheat and rice bran	Wheat: max 95 Rice: max 95.6	Autoclave at 121 °C for 0.5, 1.0, or 1.5 h, pH levels of 3.5–6.5	Özkaya, Turksoy, Özkaya, and Duman, 2017 [62]
Germination	Time of malting	Millet	72 h: 23.9 96 h: 45.3	Germination for 72 or 96 h	Coulibaly et al., 2011, Makokha et al., 2002 [63,64]
Germination	Time (steeping and sprouting)	Brown rice	Steeping: <20 Sprouting: 60 Red kidney beans: 35.90	Steeping: 24 h Sprouting: 72 h	Liang et al., 2008 [61]
Extrusion	Type of beans	Fava and red kidney beans	Fava beans: 26.7 Red kidney beans: 21.4	156 °C, 100 rpm, 385 g/min	Alonso et al., 2000 [65]
Extrusion	Moisture-Temperature	Bran of wheat, rice, barley, oat	Wheat: 64.4 Barley: 63.5 Oat: 26.4	115 °C and moisture content of 20%	Kaur et al., 2015 [66]
Extrusion	Moisture-Temperature	Whole rice grain	25	160 °C and moisture content of 16.5%	Albarracín et al., 2015 [67]
Fermentation	Type of fermented microorganism	Whole wheat dough	70	Sourdough fermentation or lactic acid (pH 5.5)	Leenhardt, Levrat-Verny, Chanliaud, and Rémésy, 2005 [68]
Fermentation	Use starter enrichment (0/1/2/3 cycles)	Brown rice	56–96	Brown rice and demineralized water were fermented naturally (24 h at 30 °C)	Liang et al., 2008 [61]
Fermentation	Type of flour	Bran-enriched bread Whole-wheat flour	Whole-wheat bread: 44 Bran-enriched bread: 67	<i>Bifidobacterium</i> strains	Sanz-Penella, Tamayo-Ramos, Sanz, and Haros, 2009 [69]

This next section will highlight the potential solutions and their effects on nutrition of plant-based meat.

4. Current and Potential Solutions to Improve Plant-Based Meat Nutrition

According to our analyses, the most efficient solution should address improving the protein quality and reducing phytate content in plant-based meat sustainably.

4.1. Balanced Amino Acid Composition for Better Meat Protein Quality

With respect to addressing the deficiency of one or more essential amino acids in plant proteins, arriving at a strategic combination of two or more protein sources has often been the approach to achieve a balanced amino acid composition in plant-based meat. For instance, combining protein derived from chickpea (a legume deficient in cysteine, methionine, and tyrosine) and rice (a cereal deficient in lysine) can aid in increasing the PDCAAS (protein digestibility corrected amino acid score) of the resultant protein blend. Alternatively, plant-based meat manufacturers may supplement their products with the missing essential amino acids [38].

According to the FAO/WHO, the protein digestibility–corrected amino acid score (PDCAAS) is the preferred method to measure the protein value in human nutrition. The method is based on comparing the concentration of the first limiting essential amino acid in the test protein with that of the amino acid in a reference (scoring) pattern. This scoring pattern is obtained from the essential amino acid requirements of the preschool-age child. The resultant chemical score is corrected for true fecal digestibility of the test protein (Schaafsma, 2000).

4.2. Phytase Treatment to Reduce Phytate Content in Plant-Based Meat

Phytase is the phytate-degrading enzyme found naturally in plants, animals, and microorganisms [50]. It is chemically described as myoinositol(1,2,3,4,5,6)-hexakisphosphate phosphohydrolase. Phytase sequesters orthophosphate groups from the inositol ring of phytic acid to produce free inorganic P and break the phytate complex, thereby freeing minerals and amino acids (Figure 1) [45,46]. In food processing, phytase of microbial origin is the most stable in wide-ranging pH and thermal conditions, and much work has been done with microbial-derived phytase on an industrial scale [70]. In cereal- and legume-based foods, phytase has been used to increase the bioavailability of iron, zinc, and calcium and the quality and digestibility of amino acids [45,46,71–73].

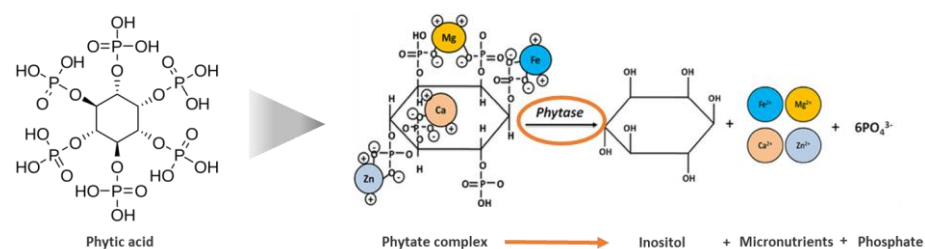


Figure 1. Phytic acid, phytate complex, and phytase enzymatic reaction representation (adapted from [46]).

The effect of phytase on micronutrient absorption has been assessed in various studies. Table 6 summarizes eight studies that showed statistically significant improvements in iron absorption, ranging from 1.0- to 11.6-fold more absorption [74–81]. Across the iron absorption studies included in the review, three studies specifically examined the effect of phytase on iron bioavailability in humans using phytase to degrade phytate during food processing [75–77]. Five studies used phytase as an active enzyme ingredient [74,78–81]. Regarding the type of microorganism used, one processing study used *Aspergillus niger*. In four of the studies that added the active enzyme to meals, a phytase from *Aspergillus niger* was used, while the last used endogenous phytase. Concerning zinc absorption, six studies were analyzed, all of them showing statistically significant improvements in zinc absorption (1.4- to 2.0-fold greater absorption) [82–87]. Four used phytase derived from

Aspergillus niger or cereals to support food processing, and two used phytase derived from *Aspergillus niger* as a food ingredient in fortified porridges.

Table 6. Summary of clinical trials on phytase effects with statistically significant improvements in iron and zinc absorption.

Study	Study Subjects		Sample Size	Test Meal	Phytase	Outcome
	Adults/Women/ Children/Infants	Details				
Iron absorption studies						
Layrisse et al., 2000 [74]	Adults	15 to 50 years	14	Bread with white wheat flour	<i>A. niger</i> ; ~300 FTU/100 g flour	$p < 0.05$; Fe absorption increased 1.7- to 2-fold
Davidsson et al., 2001 [75]	Women	20 to 28 years	10	Pea formula	Not disclosed	$p < 0.0001$; Fe absorption increased 1.6-fold
Hurrell et al., 2003 [76]	Adults	21 to 38 years	6 to 11 per study	Cereal porridges (wheat, rice, oat, maize, sorghum)	<i>Aspergillus niger</i>	$p < 0.0001$ to <0.05 ; Fe absorption increased 1.3- to 11.6-fold
Zhang et al., 2007 [77]	Adults	19 to 35 years	20	Oat drink	Exogenous phytase	$p = 0.003$; Fe absorption increased 1.8-fold
Troesch et al., 2009 [78]	Women	NA	16 to 18	Maize porridge	Genetically modified culture of <i>Aspergillus niger</i> ; ~190 FTU/serving	$p < 0.05$; Fe absorption increased 1.2- to 1.8-fold
Cercamondi et al., 2013 [79]	Children	19 to 36 months	16 to 18	Millet porridge	<i>Aspergillus niger</i> ; 400 FTU/serving	$p < 0.001$ to <0.05 ; Fe absorption increased 1.6- to 2.8-fold
Koréissi- Dembélé et al., 2013 [80]	Women	18 to 30 years	16	Fonio wheat flour porridge	Endogenous wheat phytase; dose not disclosed	$p < 0.0001$; Fe absorption increased 3.2-fold
Monnard et al., 2017 [81]	Women	18 to 45 years	14	Whole-grain maize flour-based meal	<i>A. niger</i> ; 190 FTU/portion	$p < 0.001$; Fe absorption increased 1.9-fold
Zinc absorption						
Davidsson et al., 2004 [82]	Infants	61 to 191 days	9	Soy formula	<i>Aspergillus niger</i>	$p = 0.03$; Zn absorption increased 1.4-fold
Egli et al., 2004 [83]	Adults	Not disclosed	9	Wheat and soy porridge enriched with	Endogenous wheat phytase	$p = 0.005$; Zn absorption increased 1.5 fold
Kim et al., 2007 [84]	Women	22 to 75 years	7 to 10	High- vs. low-phytate diet of common Korean food	<i>Aspergillus niger</i> ; 10 FTU/100 g brown rice; 20 FTU/100 g soybean curd residue; 3 months	$p < 0.001$; Zn absorption increased 1.7 to 1.9-fold
Brnic et al., 2010 [85]	Adults	18 to 45 years	9	Maize porridge	Genetically modified culture of <i>Aspergillus niger</i> ; 190 FTU/portion	$p < 0.001$; Zn absorption increased 1.9-fold

Table 6. Cont.

Study	Study Subjects		Sample Size	Test Meal	Phytase	Outcome
	Adults/Women/ Children/Infants	Details				
Brnic et al., 2017 [86]	Children	12 to 24 months	35	Millet-based porridge	Genetically modified culture of <i>Aspergillus niger</i> ; 20.5 FTU/portion	$p < 0.0001$; Fe absorption increased 1.7-fold
Zyba et al., 2019 [87]	Children	18 to 23 months	26	Millet-based porridge	<i>A. niger</i> —exogenous phytase; 588 FTUs/portion	$p < 0.001$; Zn absorption increased 1.9-fold

Note: The activity of the phytase is measured as the amount of enzyme that liberates 1 mmol of inorganic phosphorous per minute and is expressed in phytase units (FTUs).

Phytase may enhance the digestibility and bioavailability of a denatured protein [88]. Studies have demonstrated that adding phytase to food products such as bread and de-fatted soymilk can increase soluble protein by 41% and 28%, respectively [89,90]. Protein digestibility of a food product increases with rising protein solubility/soluble protein. A study using simulated in vitro digestion explored how enzymatic phytase treatment and lactic acid bacteria fermentation impacted phytic acid reduction, protein quality, and digestibility of fava bean flour. Phytase treatment significantly decreased phytic acid levels by up to 89%, leading to improved protein solubility at lower pH levels. This enhancement in solubility boosted the digestibility of fava bean proteins and the release of free amino nitrogen during the initial digestion phase [91].

When used in plant-derived protein products such as soy-protein isolate, soy formula, pea formula, and oat drink, phytase increased iron absorption by one- to [75,77,82]. A recent study [58] showing application of phytase to a pea-protein blend resulted in phytate reduction by 32% improving nutritional properties of the blend. Phytase addition had statistically insignificant impacts on extrusion process and physiochemical, textural, and sensorial properties of extrudates because it did not add to the release of volatile compounds or their precursors [58,92,93]. Hence, phytase addition enhances nutritional properties of plant protein while maintaining the intended taste.

5. Conclusions and Future Directions

The information presented in this perspective article provided an overview of the nutritional advantages and current challenges associated with plant-based meat products. Analysis of published literature in this context shows that researchers have been focusing on preemptive rather than reactive approaches to mitigating these challenges. The achievements of strategic combinations of plant proteins and using phytase as a solution to alleviate the concerns associated with incomplete amino acid profile and anti-nutrients, respectively, endorse the upstream approaches followed by researchers and manufacturers. A recommendation from the present work would be to assess the techno-economic potential and study the cost-effectiveness of these approaches to transform them into commercially viable options to address the nutritional challenges of plant-based proteins and plant-based meat products. The present article encourages the study of phytase-enriched plant-based meat products to understand phytase impact on phytic acid degradation, mineral absorption, amino acid digestibility and overall human health. This could be established through in vitro digestive system trials, stable isotope studies, and human intervention trials. As plant-based meat products are gaining prominence in the global market, it is imperative to demonstrate the effectiveness of formulations and processing-based interventions in enhancing their nutritional and health benefits using scientific evidence. With increasing consumer awareness, these technical validations can aid in resolving the ambiguities within this product category and increase repeat purchases.

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