Annals of Animal Science
Volume 27 · pp. 228–260 · DOI: 10.2478/aoas-2027-0019

Annals of Animal Science

Phytate-bound phosphorus in horse nutrition: Digestive utilization, phytase supplementation, and environmental implications

Review Article

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Received 24 April 2026; Accepted 13 August 2026

Abstract: In equine nutrition, phosphorus (P) is a critical nutrient essential for bone development, energy metabolism, and various physiological functions. However, the bioavailability of phosphorus in common feedstuffs, particularly in the phytate form found in cereals, poses a challenge for efficient nutrient utilization by horses. This review delves into the distinctive digestive physiology of horses as monogastric herbivores, focusing on the utilization and digestibility of dietary phosphorus. It explores the mechanisms of phosphorus absorption in horses, the role of microbial phytase in the hindgut, and the influence of various factors, including feed composition, processing methods, and calcium-to-phosphorus ratios on phosphorus digestibility. Additionally, the review addresses the environmental implications of phosphorus excretion, particularly its potential to contribute to eutrophication and water contamination if not properly managed. This article also discusses strategies to enhance phosphorus utilization in horses, including the use of low phytic acid crops, precise ration formulation, and supplementation with exogenous phytase. These strategies have the potential to improve nutrient efficacy and reduce phosphorus excretion despite the limited research on phytate metabolism in mature horses. The review underscores the need for further research on phosphorus requirements across different life stages of horses and the implication of sustainable measures to regulate phosphorus emissions from equine farms. In conclusion, optimizing phosphorus utilization will not only enhance equine health and performance but also contribute to environmental sustainability by mitigating the ecological impact and pollution associated with phosphorus use.

Keywords: *Dietary fibre • Digestibility • Equine gastrointestinal health • Horse nutrition • Metabolism • Phosphorus absorption*

1. Introduction

Ensuring that horses receive adequate minerals is crucial for their skeletal health, metabolic balance, neuromuscular function, and athletic performance. Phosphorus (P), a macro-mineral, plays a critical role in hydroxyapatite synthesis, energy metabolism (ATP), cellular signalling, and the maintenance of acid–base equilibrium (National Research Council NRC, 2007; Toribio, 2011; Peacock, 2021). The skeleton stores a substantial proportion of phosphorus (80–85%) alongside calcium (Ca), underscoring the importance of maintaining an optimal Ca:P balance for proper growth, skeletal maturity, and long-term health (Burns et al., 2021; Maier & Kienzle, 2024; Rogers et al., 2021).

Horses are classified as non-ruminant herbivores and hindgut fermenters (Cichorska et al., 2014). Their nutrient digestion involves enzymatic hydrolysis in the stomach and small intestine, followed by extensive microbial fermentation in the cecum and colon (Frape, 2010; Geor et al., 2013). Most minerals, such as calcium and phosphorus, are primarily absorbed in the small intestine via regulated active and passive transport mechanisms. Phosphorus homeostasis in horses is affected by dietary phosphorus intake, the calcium-to-phosphorus ratio, renal regulation, and endocrine factors, including parathyroid hormone (PTH), fibroblast growth factor-23 (FGF23), and vitamin D. However, the regulation of intestinal phosphorus absorption by vitamin D is less pronounced in horses

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compared to many other monogastric species (Toribio, 2011; Coenen, 2013; Harris & Shepherd, 2021; Wagner, 2024). Structural carbohydrates that are not digested before reaching the cecum undergo fermentation in the hindgut, producing volatile fatty acids, which serve as a significant energy source (Julliand et al., 2008; Muhonen et al., 2021). The bioavailability of minerals is notably influenced by the anatomical separation between the sites of microbial fermentation and enzymatic digestion (Saha & Pathak, 2021; Singh & Kim, 2021).

Phytic acid, or myo-inositol hexakisphosphate, constitutes the primary phosphorus storage form in seeds and cereal grains and is prevalent in plant-based diets (Asghar et al., 2024; Kumar et al., 2023). Phytate can reduce mineral solubility and pre-cecal absorption by forming complexes with divalent cations, such as calcium, magnesium, zinc, and iron, due to its strong chelating properties (Julliand, 2005; Rueda-Carrillo et al., 2022). The use of exogenous microbial phytase has been explored as a potential nutritional strategy to enhance phytate hydrolysis, improve phosphorus utilization, and decrease phosphorus excretion in horses. Nevertheless, unlike its application in poultry and swine nutrition, phytase supplementation has not been extensively adopted in equine feeding, with its effectiveness remaining inconsistent under current experimental conditions (Fowler et al., 2015; Patterson et al., 2002; Salem et al., 2015). Direct extrapolation of these findings to equine nutrition is inappropriate due to fundamental physiological differences, notably that horses depend on extensive hindgut fermentation rather than foregut microbial digestion (Geor, 2010; Philippi et al., 2023; Rodehutscord et al., 2022).

Research specific to equines indicates that the breakdown of total tract phytate can surpass 90% under optimal feeding conditions (Van Doorn et al., 2004; Lavin et al., 2013; Fowler et al., 2015). The apparent phosphorus digestibility in horses is significantly influenced by factors such as nutritional phosphorus content, calcium-to-phosphorus (Ca:P) ratio, physiological stage, and endogenous secretion, although it remains highly variable (Schryver et al., 1971; Saastamoinen et al., 2020; Maier & Kienzle, 2024). Notably, while microbial degradation of phytate predominantly occurs in the hindgut, phosphorus absorption in horses primarily takes place in the small intestine. Consequently, phosphorus released during post-ileal microbial fermentation is unlikely to be absorbed as efficiently as phosphorus released prior to the main absorptive sites. Thus, extensive phytate degradation does not necessarily lead to proportional improvements in systemic phosphorus retention or apparent phosphorus digestibility (Coenen, 2013; Harris & Shepherd, 2021; Fowler et al., 2015). During growth, the demand for phosphorus is markedly increased due to rapid accretion associated with skeletal development (Donabédian et al., 2006; Rogers et al., 2021). Therefore, maintaining a balanced mineral diet is crucial. Mineral imbalances, particularly improper Ca:P ratios, have been associated with developmental orthopaedic problems and altered bone metabolism (Toribio, 2011). In mature horses, the apparent digestibility of phosphorus may be low in forage-based diets, potentially contributing to faecal phosphorus excretion and environmental loading (Saastamoinen et al., 2020; Aronsson et al., 2022). However, phosphorus often meets or exceeds recommended levels (National Research Council NRC, 2007). Consequently, phosphorus nutrition in horses holds both physiological and environmental significance. Despite numerous controlled studies examining phytate decomposition and phytase supplementation in equines (Morris-Stoker et al., 2001; Patterson et al., 2002; Hainze et al., 2004; Van Doorn et al., 2004; Lavin et al., 2013; Fowler et al., 2015), the findings remain inconsistent. In horses, phytase supplementation has not consistently enhanced phosphorus digestibility or retention, unlike in other monogastric species, suggesting that responses may be highly context dependent.

A comprehensive evaluation of phytate phosphorus utilization in horses is warranted due to the increasing focus on environmental sustainability, skeletal health, and precision nutrition within equine production systems. This review seeks to integrate existing equine-specific research on phosphorus digestibility, phytate degradation, mineral homeostasis, and phytase supplementation. It also aims to identify physiological processes and experimental variables that may clarify the variability in reported outcomes. Particular attention is given to differentiating between biologically significant phosphorus absorption, retention, and total tract phytate disappearance within the framework of equine digestive physiology.

2. Material and methods

A structured literature review was undertaken to synthesize existing knowledge on the use of phytate-bound phosphorus, mineral digestibility, phytase supplementation, mineral deficiencies, and environmental phosphorus excretion in equines. Peer-reviewed articles were identified through systematic searches of PubMed, Web of Science, ScienceDirect, Scopus, and Google Scholar. The final search was completed in December 2025. The following search terms employed included: “horse” OR “equine” AND “phosphorus digestibility,” “phytate,” “phytase,” “mineral metabolism,” “calcium-to-phosphorus

ratio," "endogenous phosphorus losses," "phosphorus excretion," and "equine manure." Additionally, reference lists of relevant articles were screened to locate primary studies not captured in the database searches.

Emphasis was placed on peer-reviewed research specifically examining equine phosphorus metabolism, phytate degradation, phytase supplementation, mineral homeostasis, and associated nutritional or environmental outcomes. In instances where equine-specific evidence was scarce, studies from other monogastric species were judiciously selected to offer mechanistic insights and were explicitly identified in the article as supportive rather than directly applicable to equines. The inclusion criteria encompassed: (1) controlled experimental studies in horses or ponies evaluating phosphorus digestibility, mineral balance, or phytase supplementation; (2) research addressing mineral metabolism and endocrine regulation within equine physiology; (3) studies investigating mineral deficiencies and their clinical implications in horses; and (4) environmental studies assessing phosphorus excretion or soil phosphorus accumulation in equine-managed systems. To elucidate the biochemical pathways of phytate hydrolysis and mineral transport in contexts with limited equine-specific data, mechanistic literature from other monogastric species was meticulously incorporated.

Studies focusing solely on non-equine species without direct mechanistic relevance were excluded. To encompass both historical context and current scientific insights, both classical and contemporary literature was considered. Approximately 70% of the 142 references included were published within the past 15 years. Consequently, a structured qualitative comparative synthesis was utilized, as a formal statistical meta-analysis was not impractical due to significant heterogeneity in experimental design, horse age and physiological status, dietary formulation, phytate quantification, phytase supplementation protocols, calcium-to-phosphorus ratios, and phosphorus digestibility assessment methodologies. This methodological variability precluded meaningful quantitative comparison and aggregation of results across studies.

3. Digestive physiology and determinants of mineral absorption in horses

The digestibility of nutrients in horses is influenced by the anatomical and physiological characteristics of the equine gastrointestinal system (Leishman et al., 2024). As non-ruminant herbivores and hindgut fermenters, horses possess a digestive system that combines extensive microbial fermentation in the hindgut with enzymatic digestion in the foregut (Moore & Dehority, 1993; Santos et al., 2011). Enzymatic hydrolysis initiates nutrient digestion in the stomach and small intestine, while structural carbohydrates are fermented in the cecum and colon by a diverse microbial community (Frape, 2010; Geor et al., 2013; Huang et al., 2025). This dual digestive strategy enables horses to efficiently use fibrous diets, yet it imposes physiological constraints on the absorption of certain nutrients, especially minerals associated with anti-nutritional substances (Miyaji et al., 2008; Schryver et al., 1972; Gordon et al., 2013; O'Connor et al., 2008).

The small intestine serves as the primary site for the absorption of the most nutrients, including proteins, fatty acids, basic carbohydrates, and the majority of dietary minerals (Julliand et al., 2008; Jing et al., 2025; Krägeloh et al., 2018; Bertone et al., 1989). Phosphorus absorption mainly occurs in the jejunum and ileum through passive diffusion and active transport mechanisms. In equines, phosphorus homeostasis is influenced by dietary phosphorus intake, the calcium-to-phosphorus ratio, renal excretion, and endocrine factors including PTH, FGF23, and vitamin D. However the regulation of intestinal phosphorus absorption by vitamin D is less significant in horses compared to other monogastric species (Toribio, 2011; Coenen, 2013; Muscher-Banse et al., 2017; Harris & Shepherd, 2021; Peacock, 2021; Wagner, 2024). The rapid transit of digesta through the small intestine in horses may impact the efficiency of mineral absorption, which is further influenced by feed composition, mineral solubility, and dietary chelators such as phytic acid (Fielding et al., 2023; Lavin et al., 2013; Hainze et al., 2004; Rosenfeld & Austbø, 2009; Westendorf et al., 2020).

Following the ingestion of undigested dietary components, the hindgut serves as the primary site of extensive microbial fermentation within the cecum and large colon (Jouany et al., 2009; Julliand et al., 2018). During this process, microorganisms break down structural carbohydrates, resulting in the production of volatile fatty acids, which constitute a crucial energy source for the horses (Muhonen et al., 2021). Nevertheless, as the majority of mineral transport occurs earlier in the digestive tract, minerals generated through microbial activity in the hindgut may not be efficiently absorbed (Hintz & Schryver, 1972; Wilkens & Muscher-Banse, 2020).

3.1 Phosphorus digestibility in horses

The apparent total tract phosphorus digestibility in horses varies widely, ranging from low values in forage-based diets to higher values in growing animals under balanced

Ca:P conditions (Fowler et al., 2015; Saastamoinen et al., 2020). Apparent digestibility reflects net retention following endogenous secretion, which may lead to an underestimation of actual absorption (Fowler et al., 2020; Fowler & Lawrence, 2019; Velásquez et al., 2021; Oliveira et al., 2008). The concentration of dietary phosphorus significantly influences measured digestibility (Bhardwaj et al., 2021; Metwally et al., 2022; Nielsen, 2023). Absorption efficacy can decline due to homeostatic regulation and increased renal excretion when intake surpasses requirement thresholds (National Research Council NRC, 2007). Furthermore, the formation of insoluble complexes at elevated Ca:P ratios can decrease phosphorus solubility, thereby limiting its availability in the intestinal tract (Van Doorn et al., 2004; Makowiecki et al., 2022; Ögren et al., 2013; Pozza et al., 2014; Zewdie, 2019; Zhang & Adeola, 2017). A significant portion of phosphorus in plant-derived feeds is present as phytate-bound phosphorus, which is inadequately hydrolysed before reaching the small intestine. Although phosphorus released during post-ileal fermentation may be inefficiently assimilated, leading to faecal excretion rather than systemic utilization, microbial populations in the hindgut can significantly degrade phytate. The anatomical separation between phytate breakdown and mineral absorption is a primary constraint on phosphorus bioavailability in horses.

Mineral utilization is influenced by both age and physiological stage. Growing horses exhibit greater phosphorus retention and apparent digestibility compared to mature horses, attributed to increased skeletal mineral accretion and heightened physiological demand (Fowler et al., 2015; Oliveira et al., 2008). Pregnant and lactating mares similarly require elevated levels of calcium and phosphorus to support foetal skeletal development and milk production. Exercising horses experience altered mineral turnover and homeostatic regulation due to increased metabolic demand (Toribio, 2011; Jarrett et al., 2014; Pomar et al., 2014; Raspa et al., 2022). The prediction of phosphorus digestibility based solely on feed is complicated by factors such as dietary phytate, calcium concentrations, vitamin D supplementation, environmental conditions, animal age, and research methodologies (Bohn et al., 2018; Esen, 2023; She et al., 2017; Zewdie, 2019). Developing horses demonstrate higher phosphorus retention efficiency than mature animals, likely due to enhanced skeletal growth and hormonal adaptation (Saastamoinen & Särkijärvi, 2018). Exercise has also been shown to influence mineral homeostasis and regulatory mechanisms (Vervuert et al., 2006). Understanding these digestive limitations is crucial for evaluating phytate–phosphorus interactions and the potential impact of phytase supplementation on enhancing mineral absorption in equine diets.

3.2 Phosphorus metabolism and homeostatic regulation in horses

Phosphorus is an essential macro-mineral integral to several physiological processes, such as skeletal mineralization, cellular energy metabolism, and acid–base homeostasis (Li et al., 2016; Wilkens & Muscher-Banse, 2020; Zhai et al., 2022). Approximately 80–85% of the body's phosphorus is stored in bones and teeth as hydroxyapatite crystals alongside calcium, while the remainder participates in metabolic activities, including ATP synthesis, phospholipid formation, and intracellular signalling pathways (Peacock, 2021; Wagner, 2024). The absorption efficiency of phosphorus in horses is affected by various dietary and physiological factors, including the chemical form of phosphorus, the dietary calcium-to-phosphorus ratio, intestinal pH, and the concentrations of calcium, vitamin D, iron, aluminium, manganese, and dietary fat (Ndiaye et al., 2020; Vorland et al., 2017).

In equines, the absorption of dietary phosphorus primarily occurs in the small intestine via both passive diffusion and active sodium-dependent transport pathways (Prasad et al., 2015; Perumal & Padidela, 2024). The process of intestinal phosphorus absorption is regulated by vitamin D-dependent transport systems and is influenced by dietary factors, including phosphorus concentration, the calcium-to-phosphorus ratio, and the presence of anti-nutritional components such as phytic acid (Toribio, 2011; Wilkens & Muscher-Banse, 2020; Kiela & Ghishan, 2016).

Systemic phosphorus homeostasis is governed by integrated processes of intestinal absorption, skeletal storage, and renal excretion. Key endocrine regulators, including PTH, calcitriol (1,25-dihydroxyvitamin D), and FGF23, play a crucial role in maintaining circulating phosphorus levels within a narrow physiological range (Peacock, 2021; Perumal & Padidela, 2024; Wagner, 2024). An excess intake of dietary phosphorus results in enhanced renal excretion to preserve mineral balance, whereas insufficient phosphorus intake triggers endocrine mechanisms that increase intestinal absorption and release phosphorus from skeletal reserves.

Physiological demand exerts a significant influence on phosphorus metabolism in equines (Hainze et al., 2004). Growing animals, lactating mares, and racing horses exhibit elevated phosphorus requirements due to skeletal development, milk production, and metabolic activity (National Research Council (NRC) 2007; Rogers et al., 2021). Conversely, older horses engaged in moderate workloads generally experience reduced phosphorus turnover.

The regulation of phosphorus homeostasis is closely associated with dietary mineral composition (Ciosek et al., 2021; Mishchenko et al., 2023). Variations in the calcium-to-phosphorus ratio can impact mineral absorption efficacy and hormonal responses, while phytate-bound phosphorus in plant-based feeds may limit the bioavailability of dietary phosphorus for absorption (Fowler et al., 2020; Villa-Etchegoyen et al., 2019; Welcome, 2018). Therefore, both dietary content and physiological regulation must be considered when evaluating phosphorus utilization in equine nutrition. Although mechanistic studies in other monogastric species have significantly enhanced the understanding of phosphorus transport, phytate hydrolysis, and mineral metabolism, caution is warranted when extrapolating these findings to horses. Horses possess a distinctive hindgut-fermenting digestive system, where extensive microbial fermentation occurs primarily in the cecum and colon, subsequent to the primary sites of mineral absorption. As a result, the digestive fate of phytate-bound phosphorus, the efficacy of exogenous phytase, and the effectiveness of exogenous phytase and the regulation of phosphorus utilization differ from those observed in pigs and poultry (Frape, 2010; Geor et al., 2013; Coenen, 2013; Wilkens & Muscher-Banse, 2020). Consequently, conclusions regarding phytate degradation, phosphorus bioavailability, and phytase supplementation should be derived primarily from equine-specific evidence, with findings from other monogastric species serving as supportive mechanistic background rather than direct evidence for horses (Toribio, 2011; Harris & Shepherd, 2021; Maier & Kienzle, 2024). This physiological distinction forms the basis for understanding why phytate-bound phosphorus behaves differently in horses compared to other monogastric species and highlights the necessity of evaluating phytate utilization within the context of equine-specific digestive physiology.

3.3 Phytic acid: sources, structure, and anti-nutritional effects

Phytic acid (myo-inositol hexakisphosphate; IP6) serves as the primary storage form of phosphorus in plant seeds, cereals, and legumes, constituting a significant portion of the total phosphorus content in various equine feed components (Bloot et al., 2023). Cereals and cereal by-products commonly incorporated into equine diets, such as maize, oats, wheat bran, and rice bran, may contain 60–80% of their phosphorus in the form of phytate (Raboy, 2009; Rousseau et al., 2020). These compounds provide an energy source and act as antioxidants for germinating seeds, rendering phytate a prevalent element in plant-derived feeds (Kumar et al., 2022; Schlemmer et al., 2009; Afinah et al., 2010). From a nutritional standpoint, this form of phosphorus presents inherent challenges due to its strong chelating properties and limited enzymatic availability.

Myo-inositol-1, 2, 3, 4, 5, 6-hexakisphosphate, commonly known as phytic acid (Figure 1), is a phosphorylated

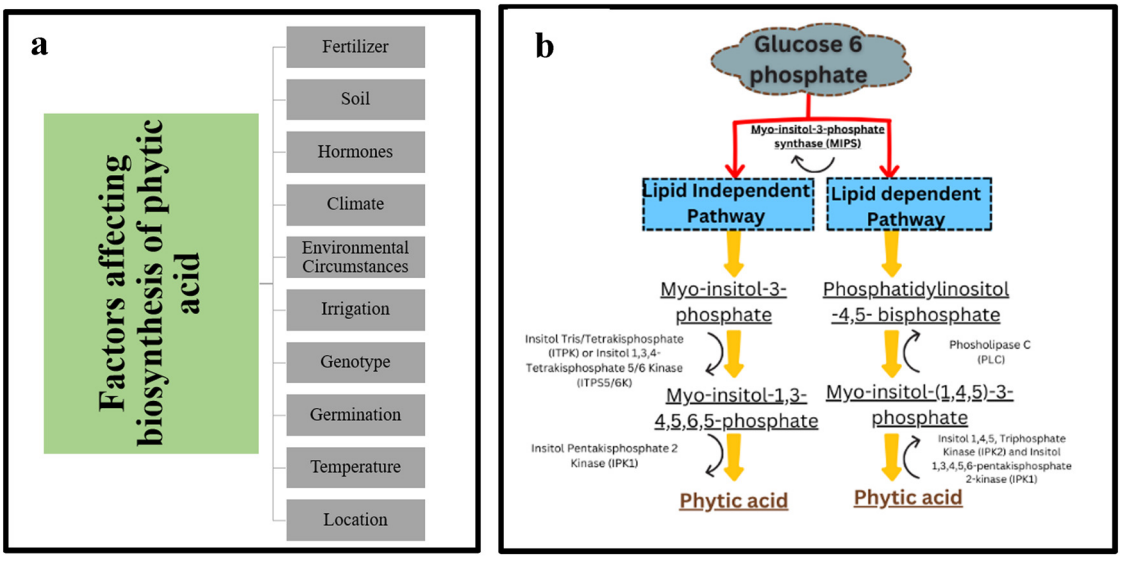


Figure 1. (a) Factors influencing phytic acid biosynthesis and (b) step in phytic acid biosynthesis, both lipid-independent versus lipid-dependent pathways for phytic acid biosynthesis.

derivative of myo-inositol (Ins) and is classified as a cyclic alcohol that provides the carbon backbones necessary for its biosynthesis (Raboy, 2003, 2009). Phytic acid possesses a molar mass of 660.04 g mol^{-1} and is represented by the molecular formula $C_6H_{18}O_{24}P_6$. X-ray crystallographic studies reveal that the phosphate groups are axially linked to carbons 1, 3, 4, 5, and 6, while they are equatorially attached to carbon 2 (Blank et al., 1971). The phytic acid molecule exhibits inertness and stability, enabling its storage in neutral or alkaline aqueous solutions for extended durations, potentially spanning months or years, as a solid before any decomposition products are generated (Graf & Eaton, 1990). Structurally, the highly phosphorylated inositol ring confers a significant negative charge to phytic acid, enabling it to form stable insoluble complexes with divalent and trivalent cations, including calcium, magnesium, zinc, iron, and copper. Structurally, the highly phosphorylated inositol ring confers a pronounced negative charge to phytic acid, enabling the formation of stable insoluble complexes with divalent and trivalent cations such as calcium, magnesium, zinc, iron, and copper (Ma et al., 2005; Pragya et al., 2023). These interactions depend on pH levels and are influenced by dietary mineral concentrations and the calcium-to-phosphorus ratio. Phytic acid chelates cations, leading to the formation of water-insoluble phytate salts (Matsuno & Fujimura, 2014). The chelating properties of phytic acid, attributable to its structure, exhibit a strong affinity for polyvalent cations, with stability decreasing in the order: $Cu^{2+} > Zn^{2+} > Ni^{2+} > Co^{2+} > Mn^{2+} > Fe^{3+} > Ca^{2+}$. Potassium ($K^+$), magnesium ($Mg^{2+}$), and calcium ($Ca^{2+}$) are the most frequently occurring monovalent and divalent cations (Kumar et al., 2010). Phytic acid interacts with starch and protein either directly or indirectly (Oatway et al., 2001). Historically, phytic acid has been considered an anti-nutrient due to its capacity to reduce mineral solubility and impede intestinal absorption in monogastric species.

Phytic acid constitutes 1 and 5% (ww^{-1}, dry weight basis) of the composition of most oilseeds, legumes, cereals, nuts, and pollen (Graf & Eaton, 1990), accounting for 50–80% of the total phosphorus content in seeds (Thavarajah et al., 2010). The phosphorus accumulation in developing seeds surpasses the requirements for standard cellular functions. Various plants use this excess phosphorus for the synthesis of phytic acid. Figure 2 presents the reported range of phytate concentrations in common

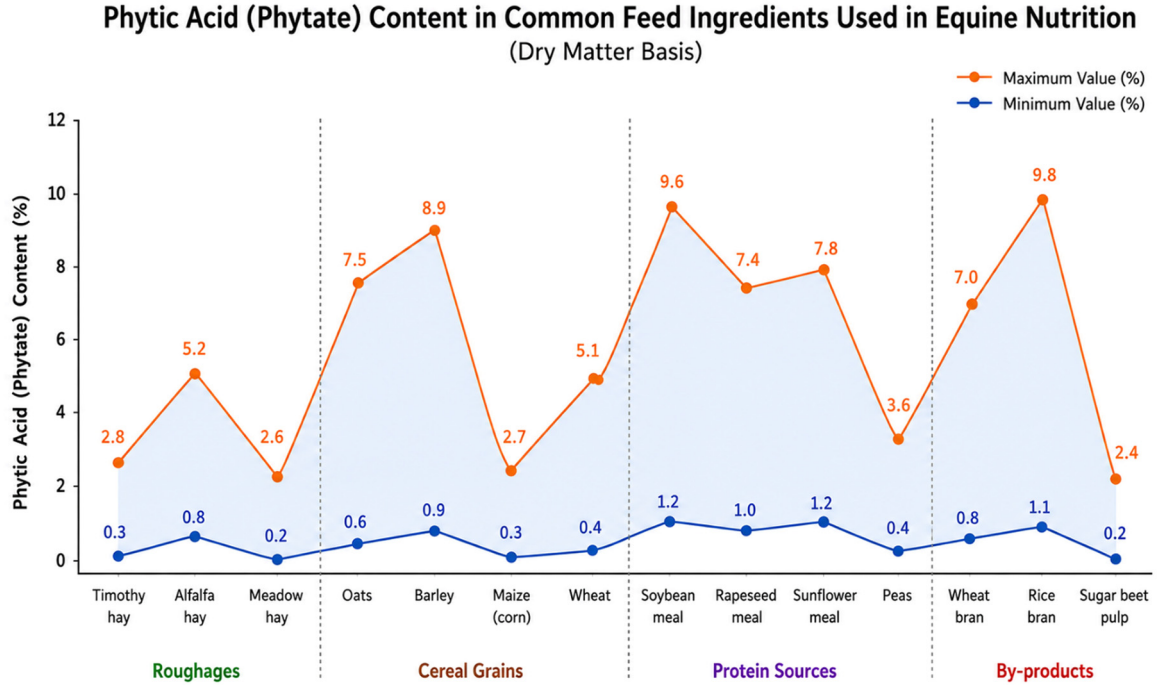


Figure 2. Variability in phytic acid concentrations among selected feed ingredients commonly used in equine nutrition and its potential relevance to phosphorus bioavailability in horses. Values represent the minimum and maximum concentrations reported on a dry matter basis for roughages, cereal grains, protein sources, and feed by-products.

Source: Adapted from Bloot et al. (2023).

feed ingredients used in equine nutrition, highlighting the significant variability in phytate-bound phosphorus among roughages, cereal grains, protein supplements, and feed by-products.

3.4 Phytate content of common equine feed ingredients

Phytic acid constitutes the primary storage form of phosphorus in various plant seeds and cereal grains. While it functions as a phosphorus reserve essential for seed germination, its potent chelating properties enable it to bind divalent cations such as calcium, magnesium, zinc, and iron, thereby reducing the bioavailability of these minerals in animal diets (Raboy, 2003; Kumar et al., 2010). Given that equine feeding systems largely rely on plant-based feedstuffs, phytate-bound phosphorus represents a significant portion of the total dietary phosphorus available to horses.

Cereal grains commonly incorporated into equine diets, such as oats, barley, maize, and wheat, contain substantial quantities of phosphorus bound as phytate. In various cereal grains, phytate accounts for approximately 50–80% of the total phosphorus content (Wang & Guo, 2021; Rodehutscord et al., 2022). Compared to other cereals, oats are regarded as one of the most popular concentrates for equine nutrition and typically exhibit modest levels of phytate. In contrast, wheat and rice bran may possess significantly higher phytate concentrations due to the presence of phytic acid in the outer layers of cereal grains. Compared to other cereals, oats are regarded as one of the most popular concentrates for equine nutrition and typically exhibit modest levels of phytate. In contrast, wheat and rice bran may possess significantly higher phytate concentrations due to the presence of phytic acid in the outer layers of cereal grains (Bloot et al., 2023; Richards et al., 2021).

Protein supplements, such as soybean meal and rapeseed meal, contribute substantial quantities of phytate-bound phosphorus to equine diets (Oliveira et al., 2008). These feed ingredients are often added to boost the protein content in the diet, which can increase both the overall phosphorus intake and the percentage of phosphorus in the phytate form. In contrast, forage feeds, such as grasses and legumes, generally possess lower phytate concentrations compared to cereal grains (Chand et al., 2022). The mineral composition of forage feeds varies based on plant maturity, soil mineral availability, and agronomic management practices (Capstaff & Miller, 2018).

The nutritional significance of phytate levels in equine diets is attributed to the limited phytase activity present in the horse's foregut. Consequently, a substantial portion of phosphorus bound to phytate may remain unavailable for absorption in the small intestine. Although hindgut microbial populations can effectively degrade phytate, the anatomical separation between the sites of hindgut fermentation and primary mineral absorption may restrict the systemic use of the phosphorus released (Van Doorn et al., 2004; Fowler et al., 2015). Diets rich in cereal grains may increase the risk of inefficient phosphorus utilization and lead to increased faecal phosphorus excretion. Understanding the phytate concentration in specific feed components is essential for evaluating phosphorus availability in equine diets. This knowledge aids in formulating nutritional strategies that improve mineral utilization and minimize environmental phosphorus losses. Phytate concentrations in commonly used equine feed components vary considerably, potentially impacting phosphorus availability in equine diets (Table 1).

Although substantial phytate degradation has been observed in horses, reaching up to 94.8%, phosphorus digestibility remains relatively low. This indicates that phytate-bound phosphorus is not being used efficiently (Brinkley-Bissinger et al., 2020; Matsui et al., 1999). Based on this observed disparity, it seems that the phosphorus released may not be adequately absorbed, even when phytate hydrolysis takes place. In horses, the hindgut serves as the principal site for phosphorus absorption, with a significant amount of phytate degradation potentially occurring after the ileum. As a result, the systemic availability of phosphorus is limited. In equine diets, the overall bioavailability of phosphorus is generally estimated to range from 30% and 45%, contingent upon the feed source and dietary composition. These findings highlight the necessity of evaluating phosphorus use in horses by considering both the site of digestion and the phytate content (Fowler et al., 2015; Matsui et al., 1999; Oliveira et al., 2008).

The anti-nutritional impact of phytic acid in equine nutrition remains a subject of ongoing discussion. Unlike swine or poultry, equines possess an extensive hindgut microbial community that can effectively degrade phytate. Numerous studies report total tract phytate disappearance rates exceeding 90% (Fowler et al., 2015). These findings warrant careful interpretation, as the degradation of phytate does not inherently lead to increased mineral bioavailability. Phytate hydrolysis predominantly takes place in the hindgut, whereas mineral absorption is primarily localized in the small intestine. This spatial separation prompts inquiries regarding the physiological relevance of phytate degradation within the hindgut (Sajid et al., 2026).

Table 1. Phytate-bound phosphorus levels in prevalent horse feed ingredients and their effects on mineral bioavailability

Feed ingredient	Typical phytate-P proportion of total P (%)	Relative phytate level	Nutritional implication in horses	References
Oats	50–65	Moderate	Common equine concentrate; moderate phytate may reduce P availability, P availability (40%)	Raboy, 2003; Wang and Guo (2021); Oliveira et al. (2008)
Barley	55–70	Moderate–high	Moderate phytate, digestion affected by microbial activity in the hindgut	Kumar et al. (2023); Oliveira et al. (2008)
Maize (corn)	60–75	High	Large proportion of P bound to phytate, low P bioavailability (30%), low intrinsic phytase; requires supplementation	Rodehutscord et al. (2022); Oliveira et al. (2008)
Wheat bran	70–80	Very high	High phytate, partial degradation due to intrinsic phytase, strong binding to minerals (Ca, Zn, Mg)	Godoy et al. (2005); Oatway et al. (2001)
Rice bran	75–85	Very high	Major phytate source; strong mineral chelation; reduced bioavailability	Godoy et al. (2005); Wang and Guo (2021)
Soybean meal	50–65	Moderate	Phytate reduces mineral digestibility, dependent on microbial degradation	Fowler et al. (2015); Kumar et al. (2022)
Rapeseed meal	50–60	Moderate	The phytate of oilseed meal limits mineral absorption, similar to SBM	Godoy et al., (2005); Gołębiewska et al. (2022)
Alfalfa hay	<20	Low	Lower phytate compared to cereals	National Research Council NRC (2007)

Source: Compiled from the references cited in the table.

Phytic acid not only chelates minerals but also inhibits protein digestion and enzymatic activity, potentially reducing overall nutrient utilization (Madhan et al., 2025; Navin Venketeish et al., 2024). However, specific evidence regarding these effects in equines is currently limited. Diets rich in phytates may influence hindgut fermentation processes, which could impact fibre digestibility and microbial ecology. Notably, phytate-bound phosphorus that remains undigested or inadequately used is excreted in manure. This contributes to phosphorus accumulation in soils, thereby increasing the potential for discharge and eutrophication in equine-managed environments (Donabédian et al., 2006; Köninger et al., 2024; Maier & Kienzle, 2024; Rogers et al., 2021).

While horses possess a superior inherent capacity to degrade phytate relative to other monogastric animals, phytic acid continues to pose a substantial nutritional and environmental challenge. The extent to which its antinutritional effects are mitigated under practical feeding conditions is not well understood, highlighting the need for more focused mechanistic investigations.

3.5 Assessment of mineral digestibility and interactions with phytic acid

Mineral digestibility in equines is a complex process involving dietary formulation, gastrointestinal physiology, mineral speciation, and intrinsic regulatory mechanisms. While most mineral absorption primarily takes place in the small intestine, the reliance of equines on hindgut fermentation introduces additional complexity to the processes of nutrient release and assimilation (Etemadi et al., 2023; Sharpe & Lawrence, 2025). As a result, metrics of apparent mineral digestibility often exhibit significant variability across different studies (Kaya & Gümüş, 2024).

Calcium and phosphorus have garnered significant attention because of their essential roles in skeletal development, hoof health, neuromuscular function, and energy metabolism. Dietary interactions, especially the calcium-to-phosphorus ratio, significantly influence the digestibility of these minerals. This effect may be intensified in diets rich in phytate. Increased calcium intake has consistently demonstrated the capacity to inhibit phosphorus absorption through the formation of insoluble complexes (Ermers et al., 2023; Garcia et al., 2022; Lawrence, 2022).

Despite the significant degradation of phytate within the equine gastrointestinal system, phosphorus digestibility throughout the tract in horses often remains low. In some instances, particularly among mature animals consuming forage-based diets, it may even exhibit

negative values (van Bömmel-Wegmann et al., 2023; Saastamoinen et al., 2020). This paradox suggests that phosphorus released from phytate may not be efficiently assimilated and could potentially be re-secreted into the gastrointestinal lumen. Age-related differences complicate interpretation, as juvenile horses typically exhibit higher phosphorus digestibility than mature horses. This is likely due to their increased physiological needs and more efficient absorption mechanisms (Fowler et al., 2015).

Trace minerals digestibility is significantly affected by interactions with phytates. Zinc, copper, and iron are particularly susceptible to chelation, a process that can adversely affect immune function, connective tissue synthesis, enzymatic activity, and overall performance when dietary phytate levels are elevated. While clinical deficiencies are uncommon in well-regulated systems, insufficient mineral availability may contribute to reduced growth efficiency, impaired hoof quality, and diminished athletic performance, especially in juvenile or high-performance equines. A recent quantitative meta-analysis concerning the metabolism of calcium, phosphorus, and magnesium in horses and ponies has demonstrated that the apparent digestibility of phosphorus is more significantly affected by mineral solubility and intake level than by the total dietary phosphorus concentration alone (Maier & Kienzle, 2024). The importance of mineral form in interpreting digestibility outcomes is highlighted by the observation that highly water-soluble inorganic phosphorus sources demonstrate greater apparent digestibility compared to other sources. Nevertheless, these factors were also linked to elevated serum phosphorus levels and enhanced renal excretion. These findings suggest that phytate-bound phosphorus, known for its low solubility, may inherently demonstrate reduced pre-cecal availability, regardless of the total tract phytate disappearance.

Overall, current evidence suggests that phytate–mineral interactions have a complex and context-dependent impact on equine mineral nutrition. Equines possess adaptive mechanisms that partially mitigate the anti-nutritional effects of phytate; however, these mechanisms do not completely remove the limitations on mineral bioavailability. This underscores the necessity for precise formulation of the ration, careful monitoring of Ca:P ratios, and continuous assessment of dietary strategies aimed at improving mineral use while minimizing excessive phosphorus excretion. Table 2 presents a summary of significant equine research evaluating dietary sources of phytate, mineral interactions, and the outcomes of apparent phosphorus digestibility.

3.6 Evidence from equine studies on phosphorus digestibility and phytate degradation

A systematic comparison of controlled experimental studies was conducted to critically evaluate the utilization of phosphorus in horses, focusing on apparent phosphorus digestibility, phytate degradation, and phytase supplementation. Table 3 presents a summary of representative equine studies conducted under diverse dietary conditions. These studies encompass digestibility trials, assessments of phytate degradation, and experiments involving phytase interventions.

The apparent total tract phosphorus digestibility in horses, as observed in controlled digestibility trials, generally ranges from approximately 2% to 45%. This variation is influenced by factors such as diet composition, physiological status, and mineral balance (Schryver et al., 1971; Fowler et al., 2015; Saastamoinen et al., 2020). Despite consistently high phytate disappearance rates, often exceeding 90%, improvements in phosphorus digestibility following exogenous phytase supplementation have not been consistently demonstrated (Lavin et al., 2013; Fowler et al., 2015; Morris-Stoker et al., 2001; Patterson et al., 2002; Van Doorn et al., 2004). The majority of experimental diets provided phosphorus levels surpassing the NRC's requirements and often exhibited elevated calcium-to-phosphorus ratios. These conditions may obscure potential phytase responses (Hainze et al., 2004). Generally, existing equine data suggest that, although there is extensive microbial phytate degradation in the hindgut (Fowler et al., 2015; Wunderlich et al., 2023), the physiological significance of this degradation for systemic phosphorus retention remains limited under typical feeding conditions (Hainze et al., 2004; Hansen et al., 2015). Table 3 presents a comprehensive overview of the primary experimental parameters and outcomes, facilitating a critical comparison of existing equine studies. The analysis includes phytate degradation rates, the calcium-to-phosphorus ratio, dietary phosphorus supply relative to requirements, and the documented effects of phytase supplementation, all of which are deemed significant.

4. Mineral deficiencies in horses: clinical and metabolic implications

Adequate mineral nutrition in horses is crucial for preserving skeletal integrity, ensuring neuromuscular

Table 2. Sources of phytate, mineral interactions, and digestive outcomes in equines

Feed ingredient/source	Approximate phytate-P proportion	Key mineral interactions	Reported digestibility/effects in horses	References
Cereal grains (oats, corn, barley, wheat)	50–80% of total P as phytate-P	Chelation of Ca, Mg, Zn, Fe; formation of insoluble phytate–mineral complexes	Significant degradation of phytate degradation (>90%) observed throughout the tract; marginal enhancement in phosphorus digestibility with exogenous phytase when dietary phosphorus exceeds nutritional requirements.	Fowler et al., (2015); Van Doorn et al., (2004); Hainze et al., (2004)
Oilseed by-products (soybean meal, rice bran, wheat bran)	Up to 70–80% phytate-P	Strong binding of Ca, Zn, and Mg; reduced mineral solubility	Increased faecal phosphorus excretion observed when fed without phytase; phytase supplementation exhibits variable effects attributable to elevated calcium-to-phosphorus ratios and adequate baseline phosphorus intake.	Patterson et al., (2002); Hainze et al., (2004)
Forage-based diets (hay, alfalfa, grass cubes)	Low phytate-P content	High Ca content may inhibit phytase activity	Phosphorus digestibility is typically low; although phytate degradation occurs, liberated phosphorus may not be efficiently assimilated as a result of hydrolysis in the hindgut.	Van Doorn et al., (2004); Fowler et al., (2015)
Mixed forage–concentrate diets	Moderate phytate-P	The Ca:P ratio strongly influences the mineral availability	Minor enhancement in phosphorus digestibility is observed with the inclusion of concentrate; The effects of phytase are frequently obscured by elevated levels of dietary phosphorus and calcium	Maier and Kienzle (2024)
Inorganic P-supplemented diets	Minimal phytate-P	Improved P availability but increased environmental excretion	Higher apparent digestibility of phosphorus accompanied by increased urinary and faecal phosphorus excretion; environmental implications emphasized	Maier and Kienzle (2024); Lavin et al. (2013)
Phytase-supplemented diets	Variable depending on feed	Improved Ca digestibility in some studies; inconsistent effects on P	Phytase rarely enhances phosphorus digestibility when phosphorus intake exceeds NRC requirements; potential advantages under conditions of phosphorus deficiency or low-calcium continue to be unstudied sufficiently.	Van Doorn et al. (2004, 2014)

Source: Compiled from the references cited in the table.

Table 3. Controlled equine studies evaluating phosphorus digestibility, phytate degradation, and phytase supplementation

Horse Type (n)	Diet type	P intake vs requirement	Ca:P ratio	Phytase dose	Phytate degradation	Effect on P digestibility	Key limitation	Interpretation	References
Ponies	Diets varying in P level	Variable	Not specified	None	Not measured	P bioavailability 30–45%	No phytate quantification	Digestibility influenced by dietary P supply	Schryver et al., (1971)
Mature horses	50% hay + 50% concentrate	~33% above NRC	Not reported	200 U/g	Not reported	No effect	Excess dietary P	High baseline P masked phytase response	Morris-Stoker et al., (2001)
Adult horses	Prairie hay + textured concentrate	>66% above NRC	2.4:1	0–900 FTU/kg	Not measured	No effect on P balance	Wide Ca:P ratio; high P intake	Excess Ca:P ratio and supra-adequate P intake likely reduced phosphorus solubility and obscured phytase response.	Patterson et al., (2002)
Yearlings	Forage + concentrates	76–164% of NRC	Not specified	1500 PU/g	Not measured	No significant effect; trend ↓ faecal P	Phytate not quantified	Partial reduction in faecal P suggests a potential conditional effect, but lack of phytate quantification limits interpretation.	Hainze et al., (2004)
Adult horses	Low-P vs phytate-rich diet	Up to 205% of NRC	~1.2:1	1000 FTU/kg	Not reported	No ↑ P digestibility; ↑ Ca digestibility	High P intake	Mineral interaction effects were observed (Ca), but excessive dietary P likely masked improvements in P retention.	Van Doorn et al., (2004)
Mature horses	Control, high-P, forage-only	31–99% above NRC	> 4.7:1	440–3400 FTU/kg	~93%	No effect on P balance	High Ca intake	Extensive degradation of hindgut phytate did not translate into improved systemic P absorption, highlighting anatomical constraints.	Lavin et al., (2013)
Yearlings vs mature	Alfalfa + timothy + concentrate	Adequate	Balanced	None	~95%	Yearlings > mature	Small sample size	Age-dependent differences indicate that physiological demand influences P utilization more than	Fowler et al., (2015)

Table 3: *Continued*

Horse Type (n)	Diet type	P intake vs requirement	Ca:P ratio	Phytase dose	Phytate degradation	Effect on P digestibility	Key limitation	Interpretation	References
								phytate disappearance alone.	
Adult horses	Forage-based diets	Variable	Variable	None	Not reported	2.7–11.1% digestibility	No phytase tested	Low apparent digestibility of P under forage diets emphasizes environmental excretion risk.	Saastamoinen et al., (2020)
Ponies	Controlled mineral diets	Adequate	Balanced	No	Endogenous P losses measured	Significant endogenous P secretion	Apparent digestibility may underestimate true absorption	Endogenous secretion substantially influences apparent digestibility, suggesting total-tract values may underestimate true absorption efficiency.	Schryver et al., (1971)
Young & aged horses	Mineral supplementation	Adequate	Variable	No	Mineral balance altered by exercise	Exercise influenced mineral retention	Physiological state affects mineral metabolism	Physiological state and training status modify mineral metabolism independent of diet composition.	Buchholz-Bryant et al., (2001)
Exercising horses	Variable Ca and P intake	Adequate	Variable	No	Ca homeostasis altered	Exercise affects mineral regulation	Physiological demand modifies absorption	The mineral balance is dynamically regulated; absorption efficiency depends on that metabolic demand.	Vervuert et al., (2006)
Growing horses	Growth-rate diets	Variable	Balanced	No	DOD risk increased with imbalanced intake	Mineral imbalance linked to orthopaedic disorders	Growth stage highly sensitive	Skeletal development is highly sensitive to Ca:P imbalance during rapid growth.	Donabédian et al., (2006)
Meta-analysis	Multiple diets	Variable	Variable	No	Quantitative Ca and P metabolism	High variability among studies	Standardization needed	Phosphorus utilization is strongly influenced by	Maier and Kienzle, (2024)

Table 3: *Continued*

Horse Type (n)	Diet type	P intake vs requirement	Ca:P ratio	Phytase dose	Phytate degradation	Effect on P digestibility	Key limitation	Interpretation	References
Weanlings	Forage based	Adequate	Balanced	No	Improved P retention in young horses	Age improves efficiency	Growth enhances absorption	Growth stage phosphorus retention efficiency under balanced diets. intake level and homeostatic regulation; standardization is needed.	Saastamoinen and Särkijärvi, (2018)

NRC = National Research Council; Ca:P = calcium-to-phosphorus ratio; DOD, developmental orthopaedic disorders; FTU = phytase units; PU = phytase units (both denote phytase enzyme activity, although assay definitions may vary among studies).

Source: Compiled from the references cited in the table.

coordination, regulating metabolism, maintaining immune competence, and supporting sustained athletic performance. Unlike ruminants, horses predominantly depend on pre-cecal enzymatic digestion for mineral absorption, which provides limited opportunities for systemic recovery of minerals released during hindgut fermentation (Clauss et al., 2007). Clinically significant outcomes may arise from both absolute deficiencies and imbalances of minerals, especially calcium (Ca), phosphorus (P), magnesium (Mg), zinc (Zn), and copper (Cu). This is particularly true during periods of increased physiological demand, such as lactation and growth (National Research Council NRC 2007; Clauss et al., 2009; Frape, 2010).

Assessing mineral adequacy necessitates consideration of the total dietary supply, bioavailability, dietary interactions (e.g., phytate binding), endocrine regulation, and physiological demand (Reddy et al., 2020). The integration of systemic mineral homeostasis and digestive dynamics provides a more precise framework for interpreting the risk of deficiency in equine nutrition.

4.1 Phosphorus deficiency and skeletal development

Phosphorus plays a crucial role in the formation of hydroxyapatite, the synthesis of ATP, cell signalling, the composition of membrane phospholipids, and the regulation of acid–base balance (Peacock, 2021; Wagner, 2024). Calcium phosphate complexes constitute the primary storage form for approximately 80–85% of total body phosphorus (Ciosek et al., 2021). To obtain optimal bone mass and facilitate endochondral ossification, horses in their growth phase require sufficient phosphorus intake (Clauss et al., 2009). Experimental evidence indicates a correlation between mineral imbalance and developmental orthopaedic disorders (DODs), including osteochondrosis and physitis (Donabédian et al., 2006; Rogers et al., 2021). Inappropriate Ca:P ratios and marginal phosphorus supply remain significant risk factors, even though despite the fact that excessive energy intake contributes to the pathogenesis of DOD. Chronic phosphorus deficiency may lead to a reduction in bone mineral density, alterations in trabecular architecture, and the activation of compensatory endocrine pathways involving PTH and vitamin D metabolites (Jacquillet & Unwin, 2019; Toribio, 2011).

Recent quantitative analyses conducted by Maier & Kienzle (2024) indicate that phosphorus retention is significantly influenced by homeostatic regulation and intake levels, rather than solely by dietary concentration. Therefore, evident dietary adequacy does not necessarily ensure optimal systemic availability, especially when a significant

portion of phosphorus intake is bound to phytate. Subclinical phosphorus insufficiency may adversely affect long-term musculoskeletal resilience and athletic longevity by hindering optimal skeletal maturation, even in the absence of explicit clinical symptoms (Frape, 2010; Rogers et al., 2020). In feeding systems abundant in cereals, which are characterized by a high inclusion of phytate, such marginal deficiencies may be particularly significant.

4.2 Calcium–phosphorus imbalance and secondary hyperparathyroidism

In equine nutrition, the clinical significance of an imbalance between calcium and phosphorus frequently surpasses that of an absolute deficiency. The recommended Ca:P ratios generally range from 1.2:1 and 2:1, depending on the physiological stage (National Research Council NRC 2007). Symptoms of nutritional secondary hyperparathyroidism, also known as big head disease, include bone demineralization, fibrous osteodystrophy, and enlargement of facial bones. This condition may result from an imbalance characterized by an excess of phosphorus relative to calcium (Toribio, 2011). Conversely, the formation of insoluble calcium–phosphate complexes can reduce the solubility and availability of phosphorus in the intestinal tract (Van Doorn et al., 2004). The manipulation of dietary calcium (Ca) and phosphorus (P) intake has significantly altered mineral homeostasis in exercising horses, as demonstrated by Vervuert et al. (2006). This finding underscores the dynamic interaction between endocrine regulation and dietary ratios.

Mineral metabolism is influenced by seasonal fluctuations. Environmental factors modulate mineral homeostasis, as evidenced by documented variations in serum vitamin D and PTH concentrations, which are linked to blanketing and sunlight exposure (Azarpeykan et al., 2016; Dosi et al., 2023). Clinical studies that examine serum levels of Ca, P, Mg, vitamin D, and PTH in disabled horses further underscore the complexity of mineral–skeletal interactions in musculoskeletal health (Etemadi et al., 2023). Specifically, when the supply of minerals nears the required thresholds, diets high in phytate may indirectly disrupt the Ca:P balance due to phytic acid's binding affinity for both calcium and phosphorus. Phytate–mineral interactions, beyond influencing mineral bioavailability, may also affect urinary mineral homeostasis and contribute to urinary tract disorders in horses. Equine urolithiasis, encompassing sabulous urolithiasis, is a condition with multiple contributing factors, including dietary mineral composition, urine characteristics, water intake, and individual predisposition. While direct evidence connecting dietary phytate to urolith formation in horses is limited, changes in the availability of calcium and phosphorus can affect urinary mineral excretion and the supersaturation of minerals implicated in calculus formation. Phytate has been documented to inhibit calcium crystallization in various species; however, similar evidence in equines is presently absent. As a result, the potential protective or adverse effects of dietary phytate on equine urolithiasis remain speculative and require further investigation (Toribio, 2011; Diaz-Espineira et al., 1995; Harris & Shepherd, 2021). Future studies should assess the impact of altering phytate consumption or supplementing with phytase on urinary phosphorus excretion, mineral balance, or the risk of urinary tract disorders in practical feeding scenarios.

4.3 Trace mineral deficiencies and connective tissue integrity

The process of collagen cross-linking, keratin synthesis, antioxidant defence, and immune function is significantly reliant on trace minerals, such as zinc and copper. Zinc deficiency has been associated with impaired keratinization and compromised hoof integrity (Burns, 2021). In equine development, copper deficiency can exacerbate skeletal abnormalities by disrupting cartilage maturation (Rogers et al., 2020, 2021). Phytic acid exhibits a strong affinity for divalent cations, including zinc, magnesium, copper, calcium, and iron. It forms stable phytate–mineral complexes, which can diminish the bioavailability of these minerals, especially in diets predominantly composed of cereal (Coenen, 2013; Zhang et al., 2022). Theoretically, the significant microbial phytase activity observed in the equine hindgut has the potential to hydrolyse phytate, thereby releasing phosphorus as well as the associated trace minerals. The extent to which minerals released during hindgut fermentation significantly affect systemic mineral status remains uncertain. As the primary locations for active mineral absorption are situated in the small intestine, minerals that are released after the digesta has reached the cecum and colon are likely to be absorbed as efficiently as those released before reaching the cecum (Coenen, 2013; Toribio, 2011; Wilkens & Muscher-Banse, 2020). Although hindgut phytate degradation often surpasses 90%, this substantial microbial hydrolysis does not invariably result in corresponding enhancements in the bioavailability of zinc, magnesium, or other trace minerals (Sajid et al., 2026). At present, there is a paucity of direct experimental evidence assessing the impact of hindgut

phytate hydrolysis on trace mineral absorption in horses. This represents a significant knowledge gap that necessitates further research (Fowler et al., 2015; Maier & Kienzle, 2024). While equine-specific data on the interactions between phytate and trace minerals are limited, evidence from other monogastric species indicates that zinc absorption is considerably diminished under high-phytate conditions (Philippi et al., 2023). Horses may undergo similar interactions, especially when subjected to high-concentrate feeding regimens, owing to structural and metabolic similarities in their mineral absorption pathways. Recent assessments of mineral requirements for performance horses indicate that biochemical demands during training may exceed baseline maintenance estimates (Best et al., 2023). This suggests that marginal bioavailability could have clinical significance in athletic populations.

4.4 Magnesium deficiency and neuromuscular regulation

Magnesium plays a significant role in influencing ATP-dependent metabolic pathways, enzyme activation, and neuromuscular transmission. In equines consuming diets primarily composed of balanced forage, overt magnesium deficiency is uncommon. Nevertheless, suboptimal magnesium levels have been linked to modifications in stress response and heightened neuromuscular excitability. Their relationship between calcium metabolism and magnesium homeostasis is closely interconnected. The interactions between magnesium and calcium can significantly influence mineral homeostasis, especially under conditions of transport stress, intensive exercise, or dietary imbalance (Frape, 2010; Latham et al., 2021). Quantitative analyses demonstrate that the efficiency of magnesium absorption is significantly affected by both the level of ingestion and regulatory adaptation (Maier & Kienzle, 2024). Similarly, phosphorus exhibits comparable characteristics. Table 4 provides a summary of the primary physiological functions, risk factors, and potential interactions between mineral deficiencies and dietary phytate in horses.

4.5 Performance and long-term implications

The performance of athlete horses is strongly linked to their mineral adequacy. Trace minerals play a crucial role in oxygen transport, antioxidant capacity, immune resilience, and recovery following exercise. Additionally, calcium and phosphorus are vital for skeletal loading and bone remodelling during training (Heffernan et al., 2019; Latham et al., 2021; Urschel & McKenzie, 2021). Research indicates that the performance of Thoroughbred racehorses is affected by nutritional management during their maturation. This underscores the significance of maintaining a balanced mineral supply over the long term (Frape, 2010).

High-performance athletes and growing horses represent physiologically sensitive populations due to their increased mineral demand and skeletal turnover. Even slight deficiencies in phosphorus use can affect the development of optimal bone mass, metabolic resilience, and long-term health. Although extensive total tract phytate degradation observed in equine studies must be remembered (Van Doorn et al., 2004; Lavin et al., 2013; Fowler et al., 2015), it does not guarantee systemic mineral recovery. The anatomical separation between hindgut phytate hydrolysis and small intestinal mineral absorption may limit the effective use of liberated phosphorus and associated cations. Therefore, the optimal bioavailability of certain minerals is not assured merely by their apparent sufficiency in the overall dietary mineral content.

5. Phytase supplementation in horses: mechanisms and experimental evidence

In equine diets that primarily consist of cereals, a substantial proportion of the total phosphorus is in the form of phytate-bound phosphorus. Phytic acid exhibits strong chelating properties, which can reduce the solubility and pre-cecal absorption of minerals by forming insoluble complexes with calcium, magnesium, zinc, iron, and proteins (Zhang et al., 2022; Marolt & Kolar, 2020). Exogenous microbial phytase supplementation consistently enhances mineral retention, decreases faecal phosphorus excretion, and increases phosphorus digestibility in monogastric livestock species, such as poultry and swine (Humer et al., 2015; Philippi et al., 2023; Yang et al., 2020). Simultaneously, while the mechanistic plausibility of phytase supplementation in horses is established, empirical evidence regarding its efficacy remains inconsistent.

The hydrolysis of phytic acid is progressively catalysed by phytase (myo-inositol hexakisphosphate phosphohydrolase), resulting in the release of inorganic phosphate and lower inositol phosphates with diminished chelating capacity (Gerke, 2015). Although horses exhibit limited endogenous pre-cecal phytase activity, significant microbial phytate degradation takes place in the hindgut (Lavin

Table 4. Clinical and functional consequences of mineral deficiencies in horses

Minerals	Physiological role	Deficiency manifestations	Performance implications	Risk conditions	Potential interaction with phytate	References
Phosphorus	Bone mineralization, ATP synthesis, cellular signalling, acid–base regulation	Reduced bone mineral density, impaired endochondral ossification, secondary hyperparathyroidism	Reduced skeletal durability, increased fracture risk, compromised growth	Rapid growth, marginal dietary P supply, imbalanced Ca:P ratio	Phytate-bound P may limit pre-cecal availability; hindgut hydrolysis may not ensure systemic absorption	Schryver et al. (1971); Toribio (2011); Fowler et al. (2015); Peacock (2021); Rogers et al. (2021)
Calcium	Skeletal integrity, neuromuscular transmission, enzyme activation	Fibrous osteodystrophy, altered mineral homeostasis	Reduced bone strength under training load	High dietary phosphorus, cereal-rich diets	Phytate binds Ca, potentially reducing solubility and affecting Ca:P equilibrium	Van Doorn et al. (2004); National Research Council NRC (2007)
Ca:P imbalance	Regulation of mineral homeostasis and endocrine control	Nutritional secondary hyperparathyroidism (“big head disease”)	Structural weakness, impaired remodelling	Excess P or disproportionate Ca supplementation	High phytate diets may exacerbate imbalance under marginal mineral supply	Toribio (2011)
Zinc	Keratinization, immune competence, antioxidant defence	Poor hoof horn quality, impaired wound healing	Reduced hoof resilience, immune suppression	High cereal inclusion, rapid growth	Strong chelation by phytate reduces Zn bioavailability	Burns (2021); Philippi et al. (2023)
Copper	Collagen cross-linking, cartilage development	Cartilage defects, skeletal abnormalities	Increased DOD susceptibility	Imbalanced trace mineral supply in growing horses	Phytate may reduce Cu absorption under high-grain feeding	Rogers et al. (2020)
Magnesium	Neuromuscular regulation, enzyme cofactor in energy metabolism	Increased excitability, altered stress response	Variability in performance consistency	Transport stress, high-performance training	Phytate may bind Mg, reducing absorption efficiency	Frape, (2010)

Ca:P, calcium-to-phosphorus ratio; DOD, developmental orthopaedic disorders; ATP, adenosine triphosphate.

Source: Compiled from the references cited in the table.

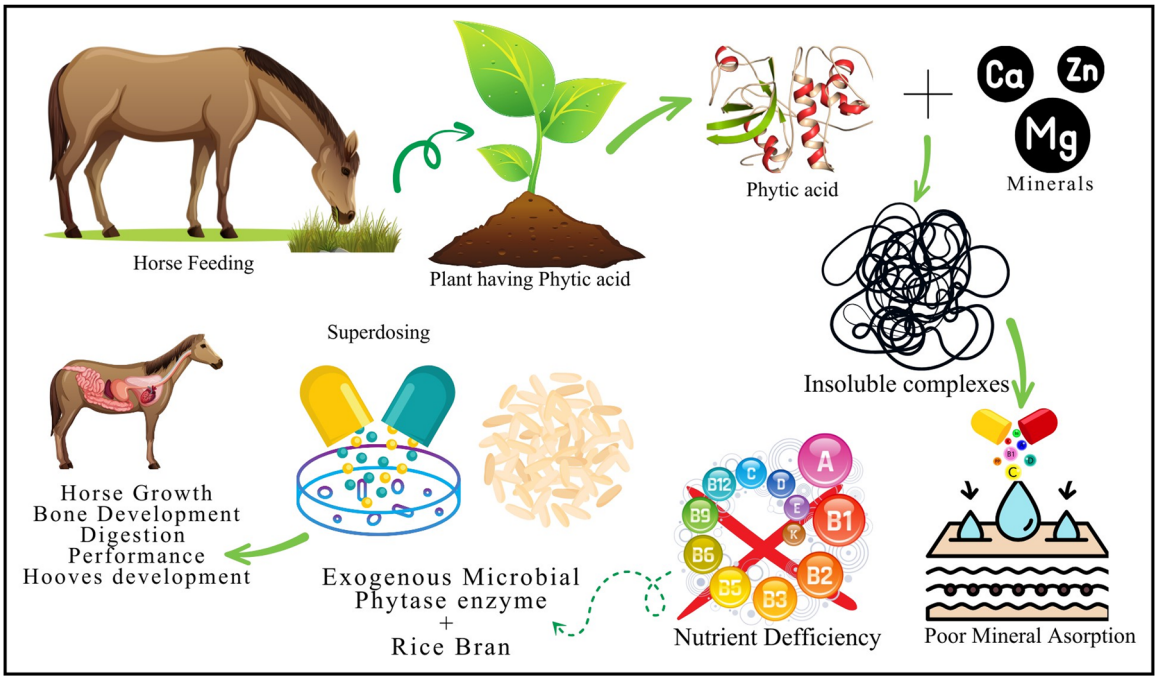


Figure 3. Dietary phytic acid in equine feeds, its effects on mineral bioavailability, and the potential role of exogenous microbial phytase.

et al., 2013; Rimbach et al., 2008). The physiological characteristic that distinguishes horses from other monogastric species is likely responsible for the variability observed in equine phytase trails.

Phytase is extensively employed in monogastric species to improve the bioavailability of phosphorus (P) linked with phytic acid. Nevertheless, its effectiveness in equine nutrition remains unestablished (Oliveira et al., 2008). Horses frequently consume forages and cereal grains that are rich in phytic acid. This compound can chelate essential minerals, including calcium (Ca), zinc (Zn), and magnesium (Mg), leading to the formation of insoluble complexes and subsequent reduction in mineral bioavailability (Van Doorn et al., 2004). These interactions can negatively impact growth, skeletal mineralization, metabolic processes, overall performance, and hoof health (Patterson et al., 2002). The use of exogenous microbial phytase offers the potential to hydrolyse phytic acid, which in turn releases bound minerals and improves nutrient utilization. Nevertheless, studies conducted on equine subjects have yielded inconsistent results. To address this issue, exogenous microbial phytase enzymes, commonly included in diets alongside rice bran, can be employed to degrade phytic acid. This process enhances the release of bonded minerals, thereby increasing their bioavailability (Figure 3). Ensuring adequate growth and development in horses necessitates appropriate supplementation, which is crucial for supporting essential physiological processes.

5.1 Mechanistic considerations

In equines, the small intestine serves as the principal location for mineral absorption. This process is modulated by vitamin D, PTH, and FGF23, utilizing both passive diffusion and active transport mechanisms (Peacock, 2021; Wagner, 2024). Conversely, hindgut fermentation leads to significant hydrolysis of phytate. The anatomical differences between phytate degradation and absorptive capacity may lead to inefficient systemic assimilation of phosphorus following its post-ileal release. Previous investigations have demonstrated that the release of phosphorus bound to phytate may occur distal to the primary absorptive sites, as indicated by the tracking of phytate and phosphorus movement within the equine gastrointestinal tract (Fowler et al., 2015). This spatial dissociation is substantiated. Additionally, a recent quantitative assessment of the metabolism of calcium, phosphorus, and magnesium in horses and ponies further corroborates this concept. A

meta-analysis conducted in 2024 by Maier & Kienzle demonstrates that the efficacy of phosphorus is more significantly affected by mineral solubility and the level of ingestion than by the total dietary phosphorus content alone. Highly soluble phosphorus sources elevated serum phosphorus levels and were concurrently linked to enhanced renal excretion, underscoring the significance of homeostatic regulation. The findings suggest that increasing luminal phosphorus availability via phytase may not improve retention if systemic regulatory mechanisms are already optimized.

5.2 Evidence from controlled equine trials

Controlled studies on equine phytase have generally indicated either neutral or conditional outcomes. Morris-Stoker et al. (2001) reported no enhancement in phosphorus digestibility in mature horses consuming a mixed forage–concentrate diet supplemented with phytase at a concentration of 200 U/g. Dietary phosphorus levels surpassed the recommended thresholds. Consistent with the findings of Patterson et al. (2002), the phosphorus balance in adult horses consuming prairie forage and concentrate remained unaffected by the inclusion of phytase at levels ranging from 0 to 900 FTU/kg. The dietary calcium-to-phosphorus ratio of 2.4:1 may exhibit limited phosphorus solubility. Hainze et al. (2004) determined that supplementation with phytase at a concentration of 1500 PU/g did not significantly enhance the apparent phosphorus digestibility in yearling geldings. A trend indicating reduced faecal phosphorus excretion was observed in sweet-feed diets. In a more controlled study comparing phytate-rich and low-phytate diets with the inclusion of phytase at 1000 FTU/kg, Van Doorn et al. (2004) reported no improvement in phosphorus digestibility. They observed an increase in calcium digestibility and a reduction in calcium excretion, which indicates interactive mineral dynamics. The reduction in model sensitivity was likely due to dietary phosphorus concentrations surpassing the necessary level.

Lavin et al. (2013) demonstrated that total tract phytate degradation surpassed 90%, irrespective of phytase supplementation. This finding suggests that intrinsic microbial hydrolysis was extensive. Fowler et al. (2015) observed that yearlings and mature horses demonstrated a similar disappearance rate of phytate, approximately 95%. However, the apparent digestibility of phosphorus was higher in developing animals. These findings suggest that the regulation of net phosphorus use is primarily governed by physiological demand, rather than solely by the process of phytate hydrolysis. Recent research examining the dietary composition and phosphorus excretion further substantiates this interpretation. In diets based on forage, the apparent digestibility of phosphorus is often low, ranging from 2.7% to 11.1%. Additionally, significant faecal and urinary phosphorus losses, amounting to 20 g/day, have been documented (Saastamoinen et al., 2020). Environmental monitoring has confirmed that equine manure contributes to the accumulation of soil phosphorus and increases the risk of phosphorus discharge (Aronsson et al., 2022). This finding suggests that inefficiencies in phosphorus use continue to exist, even with consistent responses to phytase.

5.3 Determinants of conditional phytase response

A variety of physiological and experimental factors collectively obscure the measurable efficacy of phytase in equines: (1) Dietary phosphorus intake often surpasses the required thresholds (National Research Council NRC 2007); (2) elevated Ca:P ratios reduce phosphorus solubility through the formation of insoluble complexes; (3) inconsistent quantification of dietary phytate burden in studies; (4) extensive endogenous degradation of phytate in the hindgut; (5) phosphorus retention, when adequately supplied, is limited by stringent endocrine regulation of phosphorus homeostasis.

The biological significance of age-related variation is apparent. Young horses exhibit a higher apparent phosphorus digestibility as compared to mature animals (Fowler et al., 2015). It reflects the increased skeletal accretion and adaptive hormonal regulation (Toribio, 2011). Furthermore, clinical assessments of serum calcium, phosphorus, magnesium, vitamin D, and PTH concentrations underscore the dynamic regulation of mineral metabolism in musculoskeletal health (Etemadi et al., 2023). Dosi et al. (2023) and Hurst et al. (2020) have documented the seasonal effects on vitamin D and PTH, indicating that the environment influences mineral homeostasis. A few studies have assessed the efficacy of phytase supplementation under conditions of restricted or marginal dietary phosphorus. The inconsistent responses to phytase under conditions of adequate phosphorus feeding should not be interpreted as evidence of ineffectiveness. Instead, this suggests that the experimental models may accurately represent situations in which phytase could exert a measurable impact.

5.4 Strategic research priorities

Future research should prioritize the following to clarify the role of phytase in equine nutrition: (a) quantification

and regulation of phytate inclusion levels in the diet; (b) standardization of Ca:P ratios within physiologically optimal ranges; (c) development of experimental models that incorporate marginal phosphorus supply; (d) differentiation between pre-cecal and total-tract digestibility; (e) integration of endocrine biomarkers (FGF23, vitamin D metabolites, PTH); (f) assessment of environmental phosphorus fractions in manure distinguishing between soluble and bound forms.

The effectiveness of phytase supplementation in horses should be considered as context dependent, as it is affected by dietary composition, physiological demands, and mineral regulatory mechanisms, pending the availability of relevant data. Nonetheless, the persistent documentation of environmental phosphorus losses and inefficiency highlights the need to optimize the dynamics of phytate phosphorus in equine nutrition systems. Future investigations into phytase efficacy should utilize experimental diets with marginal phosphorus deficiency, to enhance the likelihood of observing biologically significant responses while ensuring animal welfare. Current evidence suggests that dietary phosphorus concentrations of approximately 80–90% of the established requirement recommendations (National Research Council NRC 2007) would serve as a more suitable experimental model compared to diets with adequate or excessive phosphorus. These diets should be formulated with precisely quantified phytate concentrations, standardized calcium-to-phosphorus ratios (approximately 1.5:1–2.0:1), and specified phytase inclusion levels. Simultaneous assessment of phosphorus digestibility, mineral retention, endocrine biomarkers, and faecal phosphorus excretion would offer a more comprehensive evaluation of phytase efficacy under nutritionally relevant conditions.

6. Meta-synthesis of equine phosphorus digestibility and phytase evidence

A synthesis of controlled equine studies reveals a biologically coherent yet mechanistically complex pattern concerning phosphorus digestibility, phytate degradation, mineral balance, and phytase supplementation. The apparent total tract phosphorus digestibility in horses generally ranges from approximately 2% to 45% across various experiments. Notably, higher digestibility values are consistently observed in growing animals and when calcium-to-phosphorus (Ca:P) ratios are more balanced (Schryver et al., 1971; Vervuert et al., 2006; Fowler et al., 2015; Saastamoinen et al., 2020). The total disappearance of phytate in the tract frequently exceeds 90% (Van Doorn et al., 2004; Lavin et al., 2013; Fowler et al., 2015). However, this extensive hydrolysis does not consistently lead to proportional improvements in systemic phosphorus retention. This apparent paradox underscores the necessity of distinguishing between physiologically meaningful phosphorus absorption and gastrointestinal phytate degradation (Fowler & Lawrence, 2019).

A recent quantitative meta-analysis on the metabolism of calcium, phosphorus, and magnesium in horses and ponies significantly clarifies the discrepancy (Maier & Kienzle, 2024; Van Doorn et al., 2014). The analysis demonstrated that phosphorus absorption efficiency is more substantially influenced by mineral solubility and the quantity of phosphorus intake than by the overall phosphorus concentration in the diet. Hainze et al. (2004) demonstrated that highly water-soluble inorganic phosphorus sources exhibit greater digestibility. However, these sources are also associated with elevated serum phosphorus concentrations and increased renal excretion, highlighting the fundamental role of homeostatic regulation. These findings support the conclusion that extensive hydrolysis of hindgut may not enhance systemic phosphorus retention when intestinal transporters and renal pathways are already regulated to maintain mineral balance.

Anatomical considerations further clarify the discrepancy between phosphorus use and phytate degradation. In equines, the small intestine serves as the principal location for mineral absorption. This process is regulated by vitamin D, PTH, and FGF23 via both active and passive transport mechanisms (Peacock, 2021; Wagner, 2024). Conversely, microbial fermentation in the hindgut leads to substantial phytate hydrolysis. The liberation of phosphorus bound to phytate often takes place distal to primary absorptive sites, as demonstrated by prior studies that tracked the movement of phytate and phosphorus within the equine gastrointestinal tract (Vervuert et al., 2006). As a result, phosphorus released post-ileally may not be efficiently assimilated and is likely to be excreted in faeces. The anatomical separation between absorption and hydrolysis represents a fundamental physiological constraint.

Inconsistent responses to phytase are likely attributable to factors related to the experimental design. The majority of equine phytase trials have been conducted with dietary phosphorus intake levels that meet or exceed the recommendations of National Research Council NRC (2007) (Morris-Stoker et al., 2001; Patterson et al., 2002; Van Doorn et al., 2004). Enhancements in measurable retention are limited by adaptive intestinal absorption and renal

excretion when phosphorus levels are adequate or excessive (Wilkens & Muscher-Banse, 2020). The potential effect of phytase may have been obscured by the formation of insoluble calcium-phosphate complexes, which could further reduce phosphorus solubility (Van Doorn et al., 2004). Elevated Ca:P ratios (>2:1), as reported in numerous experiments, may have contributed to this phenomenon. Additionally, the inconsistent quantification of dietary phytate inclusion in studies hinders cross-study comparability and limits mechanistic interpretation.

The physiological demand is a significant modifier. The apparent digestibility of phosphorus in growing horses consistently exceeds that in mature animals (Fowler et al., 2015), likely due to increased skeletal accretion and endocrine modulation (Toribio, 2011). Furthermore, clinical investigations assessing serum calcium, phosphorus, magnesium, vitamin D, and PTH concentrations highlight the dynamic endocrine regulation of mineral metabolism in maintaining equine musculoskeletal health (Etemadi et al., 2023). Environmental modulation of mineral homeostasis is evidenced by documented seasonal influences on vitamin D and PTH concentrations (Vervuert et al., 2006). Collectively, these data suggest that phytase efficacy is most likely detectable under conditions of marginal phosphorus supply or increased physiological demand, although there is a lack of well-controlled trials conducted under these conditions (Hainze et al., 2004).

In addition to digestive physiology, the environmental impact of phosphorus inefficiencies is measurable. Forage-based diets exhibit low apparent phosphorus digestibility, typically ranging between 2.7% and 11.1%, leading to significant faecal and urinary losses (Saastamoinen et al., 2020). Aronsson et al. (2022) have verified that phosphorus losses from manure deposited in paddocks contribute to soil phosphorus accumulation and increase runoff risk. Additionally, surveys of horse paddocks in Sweden indicate a significant rise in soil P levels linked to equine management practices (Parvage et al., 2013, 2015). Consequently, the environmental aspect of equine phosphorus nutrition remains significant in the absence of consistent phytase responses.

Overall, the data do not indicate that phytase supplementation universally benefits horses. Its effects are conditional and highly dependent on factors such as dietary phosphorus concentration, the Ca:P ratio, quantified phytate burden, physiological stage, and experimental design (Patterson et al., 2002; Maier & Kienzle, 2024). Predicting systemic phosphorus retention based solely on high total tract phytate degradation is inadequate. Future research should focus on controlled phytate inclusion levels, standardized Ca:P ratios within physiologically optimal ranges, dietary phosphorus supply aligned with requirement thresholds, and site-specific assessment of mineral absorption linked to endocrine biomarkers of phosphorus regulation. Phytase supplementation in horses should be viewed as a context-dependent nutritional strategy rather than a universally applicable solution until such controlled data are available. Concurrently, the consistent documentation of phosphorus inefficiency and associated faecal losses underscores the ongoing nutritional and environmental significance of optimizing phytate–phosphorus dynamics in equine feeding systems.

7. Critical interpretation and conceptual framework

The supplementation of phytase and the utilization of phytate-bound phosphorus in equine studies demonstrate a pattern characterized by both mechanistic complexity and biological consistency. In controlled trials, the degradation of phytate in the total tract of horses often exceeds 90% (Van Doorn et al., 2004; Lavin et al., 2013; Fowler et al., 2015). Nevertheless, there are inconsistent findings regarding improvements in apparent phosphorus digestibility, retention, or systemic mineral balance. This apparent paradox underscores the necessity of distinguishing physiologically meaningful assimilation and the mere disappearance of phytate within the gastrointestinal tract. Extensive phytate hydrolysis does not inherently lead to increased systemic phosphorus availability. As noted by Maier & Kienzle (2024), the robust homeostatic regulation of phosphorus metabolism, which includes adaptive renal excretion and modulation of intestinal transporters, may further diminish detectable phytase responses under conditions where adequate is adequate.

The equine digestive system is anatomically and functionally structured to serve as a fundamental explanatory mechanism. In horses, the absorption of mineral is primarily regulated by vitamin D, PTH, and fibroblast growth factor 23, which facilitates active and passive transport processes in the small intestine (Peacock, 2021; Wagner, 2024). Conversely, phytate hydrolysis is markedly increased during microbial fermentation in the hindgut. Previous research on the movement of phytate and phosphorus within the equine gastrointestinal tract has demonstrated that the release of phytate-bound phosphorus often occurs distal to the primary absorptive regions (Fowler et al., 2015; Oliveira et al., 2008; Matsui et al., 1999). Consequently, phosphorus released post-ileally may not be efficiently assimilated systemically and may instead be excreted in faeces. Maier and Kienzle

(2024) further support the notion that phosphorus absorption efficacy is significantly influenced by ingestion level and homeostatic control, rather than solely by substrate availability. Recent quantitative evaluations of calcium, phosphorus, and magnesium metabolism in horses provide additional support for this assertion. These findings collectively indicate that systemic phosphorus retention is not necessarily enhanced by the extensive degradation of phytate in the hindgut.

Differences in reported phytase responses are significantly influenced by factors related to experimental design. Numerous equine phytase trials have been conducted with dietary phosphorus intakes that meet or exceed the recommendations of the National Research Council NRC (2007) (Morris-Stoker et al., 2001; Patterson et al., 2002; Van Doorn et al., 2004). Under conditions of inadequate or excessive phosphorus, intestinal transporters and renal excretion pathways are already adapted to maintain mineral homeostasis (Wilkens & Muscher-Banse, 2020). As a result, the probability of observing measurable improvements in phosphorus retention due to phytase supplementation is reduced. The formation of insoluble calcium phosphate complexes can further limit phosphorus solubility, potentially masking the effects of phytase, as evidenced by the elevated calcium-to-phosphorus ratios (> 2:1) reported in these studies (Van Doorn et al., 2004). Additionally, the availability of substrate for exogenous phytase may be insufficient to produce detectable changes in digestibility metrics when experimental diets contain relatively low levels of phytate.

The effectiveness of phosphorus utilization is notably affected by the physiological state of the organism. Research indicates that the apparent digestibility in growing horses consistently surpasses that in mature animals (Fowler et al., 2015). This phenomenon is likely attributable to enhanced skeletal accretion and endocrine regulation of mineral metabolism (Toribio, 2011). These observations suggest that the effectiveness of phytase may be more pronounced under conditions of increased physiological demand or limited phosphorus supply. Nevertheless, there is a lack of controlled trials specifically designed to assess phytase supplementation in phosphorus-restricted environments (Hainze et al., 2004). Therefore, inconsistent responses to phytase observed in existing studies should be cautiously interpreted, considering regulatory adaptation and dietary formulation.

Phosphorus inefficiency in horses has significant environmental implications, alongside its effects on nutritional physiology. In forage-based diets, the apparent digestibility of phosphorus may remain low (2.7–11.1%) despite extensive phytate degradation, as indicated by substantial faecal and urinary phosphorus losses (Saastamoinen et al., 2020). Equine manure has been identified as a contributor to soil phosphorus accumulation and discharge, particularly when faecal phosphorus contains soluble fractions prone to leaching, as demonstrated by environmental monitoring studies (Aronsson et al., 2022). Therefore, the environmental significance of inefficiencies in phosphorus utilization remains unaffected by inconsistent phytase responses. Several interrelated nutritional, physiological, and intestinal factors influence phosphorus utilization in horses. The factors and their respective implications are summarized in Table 5.

Table 5 outlines the interconnected aspects of digestive physiology, dietary composition, mineral balance, physiological demand, and phosphorus utilization in horses, indicating that these factors are not solely determined by a single dietary component. The anatomical separation between the primary site of mineral absorption and the site of phytate breakdown presents a significant limitation impacting phosphorus efficiency in horses. Table 5 summarizes the key factors influencing phosphorus utilization in horses, whereas Figure 4 illustrates a conceptual integration of these processes.

Figure 4 illustrates the integrated effects of environmental and physiological factors. The framework indicates that phosphorus release distal to primary absorptive regions results from extensive microbial degradation in the hindgut and limited phytate hydrolysis in the small intestine. High dietary phosphorus intake, elevated Ca:P ratios, or low dietary phytate inclusion may obscure measurable phytase responses. Conversely, the nutritional importance of enhanced phytate utilization may be evident in conditions characterized by marginal phosphorus intake, rapid skeletal growth, or compromised mineral status. Inefficient phosphorus utilization leads to faecal excretion and potential soil phosphorus accumulation, irrespective of phytase response, thus highlighting the environmental aspect of equine nutrition and the risk of eutrophication. Notably, phytase supplementation has been assessed in only a limited number of studies under phosphorus-deficient or peripheral conditions (Hainze et al., 2004).

The figure elucidates the nutritional and environmental impact of phytate-bound phosphorus in horses upon digestion. *Panel A* delineates the digestive processes in equines, highlighting the limited hydrolysis of phytate in the small intestine, extensive microbial degradation in the hindgut, and subsequent excretion of faecal phosphorus. *Panel B* summarizes the experimental conditions frequently encountered in equine phytase trials, such as elevated Ca:P ratios, low dietary phytate levels, and high dietary phosphorus intake, which may obscure potential phytase effects.

Table 5. Principal factors influencing phosphorus utilization in horses and its nutritional and environmental implications

Factor	Mechanism	Effect on phosphorus utilization	Practical implication in horses	Key references
Dietary phosphorus level	Intake relative to requirement regulates absorption and excretion	High intake ↓ fractional absorption; ↑ urinary excretion	Excess P masks phytase effects and increases environmental losses	National Research Council NRC (2007); Maier and Kienzle, (2024)
Phytate content in feed	Phytate binds phosphorus and minerals, limiting availability	↓ Pre-cecal P availability; ↑ faecal P excretion	High cereal diets reduce effective P utilization	Raboy, (2003); Wang and Guo, (2021)
Site of phytate degradation	Majority of phytate hydrolysis occurs in hindgut	Released P may not be absorbed efficiently	Explains disconnection between phytate degradation and absorption	Van Doorn et al., (2004); Fowler et al., (2015)
Calcium-to-phosphorus ratio	High Ca forms insoluble Ca–P complexes	↓ P solubility and absorption	Imbalanced diets reduce mineral efficiency	Vervuert et al., (2006); Van Doorn et al., (2004)
Age and physiological stage	Growth and lactation increase mineral demand	↑ P retention in young horses	Young horses respond differently than adults	Fowler et al., (2015); Rogers et al., (2021)
Endogenous phosphorus losses	Saliva and digestive secretions contribute P to gut	Apparent digestibility underestimates true absorption	Must interpret digestibility data cautiously	Nielsen et al., (1998)
Hindgut microbial activity	Microbial phytase degrades phytate post-ileum	Limited systemic benefit despite high degradation	Explains weak phytase responses in horses	Lavin et al., (2013); Fowler et al., (2015)
Phytase supplementation	Enzymatic hydrolysis of phytate	Conditional improvement depending on diet	More effective under low P or high phytate conditions	Hainze et al., (2004); Patterson et al., (2002)
Diet composition (forage vs concentrate)	Influences phytate level and mineral balance	Forage diets → lower phytate; concentrate diets → higher phytate	Impacts digestibility and excretion patterns	Saastamoinen et al., (2020)
Environmental excretion	Unabsorbed P excreted in faeces and urine	↑ Risk of soil P accumulation and runoff	Important for sustainable horse management	Aronsson et al., (2022)

↓: decreases; ↑: increases.

Source: Compiled from the references cited in the table.

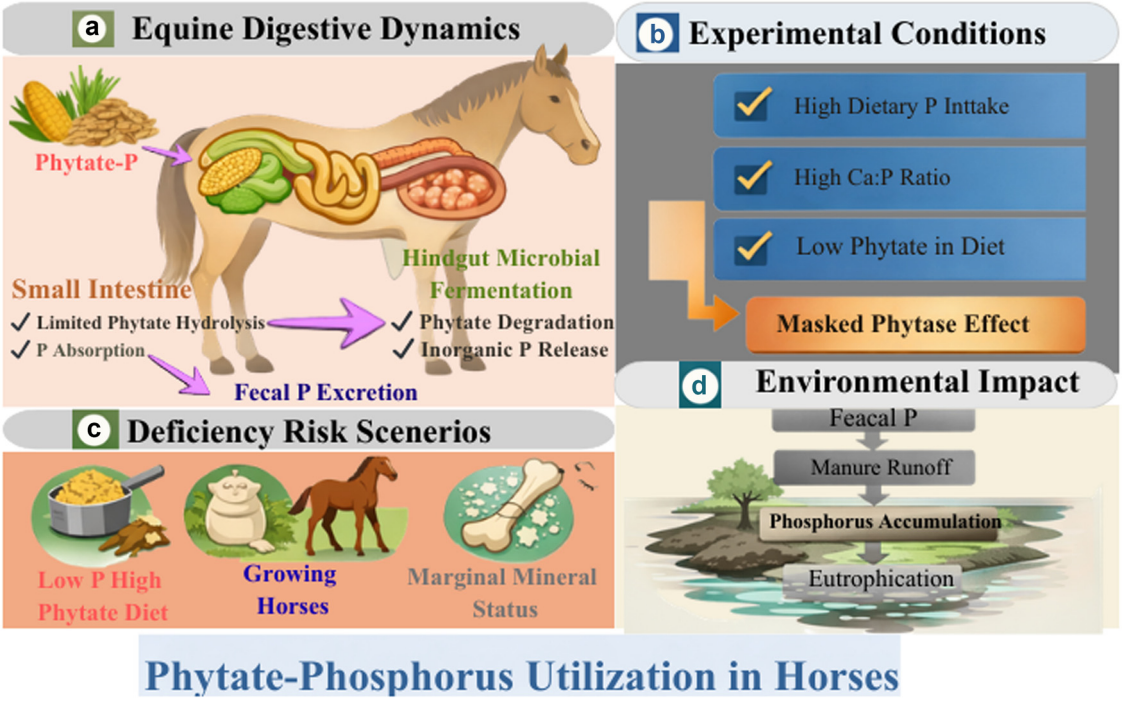


Figure 4. Conceptual framework of phytate–phosphorus utilization, masked phytase effects, deficiency risk scenarios, and environmental phosphorus dynamics in horses.

Panel C identifies physiological scenarios conducive to enhanced phytate utilization, including growing horses, low phosphorus diets, and marginal mineral status. *Panel D* illustrates the environmental pathway of unabsorbed phosphorus, emphasizing the risk of eutrophication, soil accumulation, and faecal soluble phosphorus.

Overall, the evidence indicates that phytase supplementation in horses does not exhibit universal efficacy, but rather conditional influences by dietary composition, physiological state, and regulatory mineral homeostasis. Future research should focus on the following priorities: establishing controlled and quantified levels of dietary phytate inclusion, maintaining standardized Ca:P ratios within physiologically optimal ranges, utilizing experimental models that incorporate marginal phosphorus supply, conducting site-specific assessment of mineral absorption along the gastrointestinal tract, and the integrating endocrine biomarkers, such as PTH, vitamin D metabolites, and FGF23, to evaluate systemic calcium regulation. Phytase supplementation in horses should be considered a context-dependent nutritional strategy rather than a universally applicable solution until rigorously controlled data become available. Additionally, the persistent inefficiencies in phosphorus utilization and the associated faecal losses highlight the ongoing nutritional and environmental importance of optimizing phytate phosphorus dynamics in equine feeding systems.

7.1 Nutritional strategies to reduce phosphorus excretion in horses

In light of the increasing environmental concerns related to phosphorus (P), due to its limited global reserves and its contribution to nutrient pollution, the formulation of strategies to reduce P excretion has become a central focus in animal nutrition. Three main strategies have been identified to mitigate phosphorus losses: (1) the use of low phytic acid crop genotypes or genetically modified crops (GMOs) engineered to co-express fungal phytase, (2) precise ration formulation to minimize dietary phytate-P and avoid excessive inorganic phosphorus supplementation, and (3) the inclusion of exogenous microbial phytase in feed, as documented by Knowlton et al. (2004), Ray and Knowlton (2015), and Manopriya et al. (2022). Crops with reduced phytic acid levels, such as maize, wheat, rice, barley, and soybean, demonstrate decreased phytic acid concentrations and increased inorganic phosphorus levels while maintaining overall phosphorus content (Lawrence, 2022; Raboy, 2003, 2009). While these crops can enhance mineral

uptake and reduce phosphorus excretion in animals, their agronomic performance may suffer due to reduced seed vigour, lower yields, and decreased tolerance to stress (Reddy et al., 2020). GMOs expressing fungal phytase have demonstrated significant potential; they enhance endogenous phytase activity without reducing phytate levels. Research involving poultry indicates that their nutritional benefits are comparable to those obtained through exogenous phytase supplementation (Ndiaye et al., 2020; Prasad et al., 2015). At present, no commercially available cultivars expressing phytase exist, and public concerns regarding genetically modified organisms may hinder their widespread adoption (Li et al., 2016).

A practicable and widely applicable strategy to reduce phosphorus excretion involves the formulation of precise rations. Excessive phosphorus supplementation often occurs due to inconsistencies in feed labelling, the use of high phytate by-products such as wheat bran and rice bran, and a general tendency to over-supplement phosphorus as a precaution (Schryver et al., 1971). These by-products elevate dietary phytate-P levels, as phytic acid is predominantly concentrated in the aleurone layer of cereals (Raboy, 2009), frequently leading to unnecessary supplementation of inorganic phosphorus. Nutrient efficiency can be enhanced by selecting feed ingredients with reduced phytate P content, reducing reliance on high-phytate by-products, and accurately meeting the phosphorus requirements of each physiological stage without exceeding them. The inclusion of exogenous phytase improves the bioavailability of phosphorus bound to phytate, thereby decreasing the need for additional inorganic phosphorus supplementation and reducing the excretion of soluble phosphorus into the environment. Collectively, these strategies provide a comprehensive approach to minimizing phosphorus waste, improving nutrient utilization, and mitigating the environmental impact associated with equine manure.

8. Discussion

This study compiles data specific to horses concerning phosphorus digestibility, phytate breakdown, mineral homeostasis, and phytase supplementation in the context of equine digestive physiology. The aggregated data suggest that the primary factors affecting phosphorus utilization in horses include dietary intake, calcium-to-phosphorus ratio, physiological stage, endogenous secretion, and endocrine regulation, rather than solely phytate degradation. In controlled equine trials, a recurring observation is the apparent discrepancy between extensive total tract phytate disappearance and inconsistent improvements in phosphorus retention (Van Doorn et al., 2004; Lavin et al., 2013; Fowler et al., 2015). The anatomical configuration of the equine gastrointestinal tract accounts for the mechanics of this pattern. While substantial phytate hydrolysis occurs during hindgut fermentation, mineral absorption predominantly takes place in the small intestine. Therefore, the systemic effects of phytate degradation beyond the cecum may be limited due to the inefficient absorption of phosphorus released distal to the ileum.

The dietary context plays a crucial role in determining the digestibility of phosphorus. When phosphorus intake approaches or exceeds the recommended levels (National Research Council NRC 2007), homeostatic mechanisms adjust absorption efficiency and renal excretion to maintain plasma mineral balance (Maier & Kienzle, 2024). Under such conditions, the capacity to detect improvements following phytase supplementation is inherently limited. Numerous studies on horse phytase have been conducted in scenarios where phosphorus intake was either above adequate level or the Ca:P ratio was elevated (Morris-Stoker et al., 2001; Patterson et al., 2002; Van Doorn et al., 2004). These conditions are likely to reduce mineral solubility and obscure the effects of supplements.

Age and physiological demand are significant factors in the regulation of phosphorus utilization. The efficacy of phosphorus retention in growing horses consistently surpasses that in mature animals (Fowler et al., 2015; Saastamoinen & Särkijärvi, 2018), reflecting increased skeletal accretion and endocrine adaptation. Exercise impacts mineral metabolism and calcium homeostasis (Vervuert et al., 2006), highlighting the importance of considering physiological condition when analysing digestibility results. Additionally, heterogeneity is intensified by methodological variation. Direct comparison of studies is challenging due to variations in dietary formulation, phytate quantification, adaptation duration, and methodologies for assessing digestibility. Apparent digestibility values may underestimate actual absorption because of endogenous phosphorus secretion (Fowler et al., 2020). Additionally, few studies differentiate between pre-cecal and total tract mineral utilization. Inefficiencies in phosphorus utilization are environmentally significant, irrespective of the phytase response. Forage-based diets can lead to substantial faecal excretion, resulting in relatively low apparent phosphorus digestibility (Saastamoinen et al., 2020). Certain management practices may cause phosphorus accumulation in equine-managed systems, as evidenced by soil monitoring studies (Aronsson et al., 2022). Therefore, optimizing phosphorus nutrition is crucial for both environmental sustainability and skeletal bone health.

The current body of evidence does not consistently demonstrate a universal benefit of phytase supplementation in horses. Instead, responses are conditional, depending on physiological demand, phosphorus intake relative to requirement, Ca:P ratio, and dietary phytate concentration. The limited number of controlled trials conducted under conditions of marginal phosphorus supply highlights a significant knowledge gap. Future research is required, employing standardized phytate quantification, controlled Ca:P ratios, optimal phosphorus models, and endocrine biomarkers, to improve understanding of the environmental and nutritional implications of phytase use in equine systems.

9. Future directions in phosphorus nutrition and sustainability

Future research should focus on the digestion of phytate-P in growing horses, as current studies predominantly address mature horses. It is crucial to examine the efficiency of younger horses, particularly long-yearlings, in degrading phytate-P due to their heightened nutritional requirements during growth. This investigation will improve phosphorus supplementation strategies, particularly by reducing dependence on inorganic phosphorus sources. Examining phosphorus requirements across various physiological stages, including growth, lactation, and exercise, is crucial for providing precise and tailored recommendations. This strategy would mitigate over-supplementation and decrease phosphorus excretion, then reducing environmental pollution (Parvage et al., 2013). Further research is necessary to identify alternative phytate-rich feed components that enhance nutrient efficiency and support sustainability (Sajid et al., 2023). Feedstuffs that inherently enhance phosphorus bioavailability throughout different life stages would enable more efficient diet formulation. Recent advancements in phytase supplementation indicate significant potential. Future research should focus on developing more stable and active phytase variants that are optimized for efficient functionality within the equine gastrointestinal tract. Reassessing the potential of GMOs engineered to express phytase, despite prevailing concerns regarding GMOs, may offer an innovative and sustainable strategy to improve phosphorus bioavailability.

In summary, considering phosphorus is a limited resource and a significant environmental pollutant, future efforts should prioritize sustainable phosphorus recycling methods. Investigating strategies to mitigate phosphorus runoff from equine facilities, particularly through advancements in manure management and phosphorus extraction technologies, can significantly reduce environmental impacts. Implementing effective recycling strategies, such as composting manure for use as fertilizer, enhances environmental sustainability and addresses the challenges of resource depletion linked to phosphorus in equine nutrition.

10. Conclusion

Equine phosphorus nutrition is characterized by a complex interaction of feed composition, specialized digestive sites, mineral solubility, physiological demands, and hormonal regulation. The distinction between hindgut fermentation and small-intestinal absorption indicates that, although significant phytate breakdown occurs in the horse's gastrointestinal tract, this does not necessarily enhance systemic phosphorus retention. Current data suggest that phytase supplementation in horses yields context-dependent effects rather than consistent improvements in phosphorus digestibility.

Therefore, it is more accurate to attribute mineral insufficiency in horses to physiological regulation and nutritional equilibrium rather than merely the total phosphorus content. Future research should prioritize equine-specific, controlled mineral balance studies with restricted phosphorus supply, standardized calcium-to-phosphorus ratios, and quantified phytate inclusion. Such studies are essential to clarify the role of phytase in enhancing mineral bioavailability and reducing environmental phosphorus losses.

Funding information

The article is part of a PhD dissertation titled "The effect of phytic acid on mineral absorption in horses and the enhancement of phytic phosphorus digestibility through exogenous microbial phytase supplementation", prepared during the Doctoral School at the Wrocław University of Environmental and Life Sciences. The APC is financed by Wrocław University of Environmental and Life Sciences, Poland.

Author contributions

Conceptualization, Q.U.A.S. and M.K.; Methodology, M.U.A. and Q.U.A.S.; Investigation, M.U.A., and Q.U.A.S.; Literature

collection and data curation, M.U.A., and Q.U.A.S.; Visualization, M.U.A.; Writing – original draft, Q.U.A.S.; Writing – review and editing, M.U.A., P.W., B.K., and M.K.; Supervision, M.K., B.K., and Project administration, M.K.

Conflict of interest statement

The authors declare no conflict of interest.

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