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The role of microalgae in providing essential minerals for sustainable swine nutrition

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The integration of microalgae as a mineral source in swine nutrition provides a sustainable alternative to conventional mineral supplements, offering unique nutritional and environmental benefits. Microalgae species, such as *Chlorella vulgaris* and Spirulina (currently *Limnospira*, formerly *Arthrospira*), are rich in essential minerals, supplying significant levels of calcium (3.5-12.8 g/kg), phosphorus (9.1-16.4 g/kg), zinc (16.2-280 mg/kg) and iron (512-1289 mg/kg), which are critical for growth, bone development and immune support in swine. Inclusion rates of 2-5% in swine diets have demonstrated positive outcomes, with *C. vulgaris* at 3-5% inclusion levels significantly enhancing bone mineral density and growth in piglets, while *Limnospira platensis* at 2-3% inclusion has been linked to improved immune responses and increased antibody production. In addition to minerals, microalgae contribute bioactive compounds, n-3 polyunsaturated fatty acids and antioxidants that support swine health and productivity. Environmentally, microalgae offer notable benefits by requiring less land and water compared to conventional crops, effectively sequestering carbon and providing bioremediation capabilities, thereby reducing the ecological impact of livestock production. Despite these advantages, challenges remain in optimizing mineral bioavailability due to the resilient cell walls of certain species, which may require mechanical or enzymatic pre-treatments to enhance nutrient absorption. Future research should aim at improving bioavailability treatments, reducing production costs and conducting long-term feeding trials to validate the economic and health impacts of microalgae in swine diets. Overall, microalgae represent a promising mineral resource for sustainable swine nutrition, aligning with the environmental and economic objectives of modern agriculture.

KEYWORDS

bioavailability, essential minerals, microalgae, swine nutrition, sustainability

1 Introduction

Mineral supplementation is a cornerstone of modern swine nutrition, essential for promoting growth, productivity and animal health. Key minerals, including calcium, phosphorus and potassium, along with trace elements like iron, zinc and selenium, support critical physiological functions in swine, such as bone development, metabolism, enzyme activity, antioxidant defenses and immune response (Walk et al., 2015; Lautrou et al., 2020). Traditionally, swine diets have relied on mineral sources like inorganic compounds (e.g., calcium carbonate and sodium selenite) and organic chelated minerals (Byrne and Murphy, 2022; Xiong et al., 2023). While these sources fulfil nutritional requirements, they present notable environmental and economic challenges. Inorganic minerals are widely used for their cost-effectiveness but rely on resource-intensive mining and processing, which contribute to habitat degradation, soil erosion and pollution (Aarnink and Verstegen, 2007). Organic mineral sources, although offering better bioavailability, are costlier and still pose environmental impacts during production. Moreover, non-absorbed minerals are often excreted by animals, leading to soil and water contamination through runoff, thus creating waste management issues (Kebreab et al., 2016).

Given these ecological and economic concerns, microalgae have emerged as a promising, sustainable alternative for mineral supplementation in animal feed. Species like *Chlorella vulgaris* and Spirulina (currently *Limnospira*, formerly *Arthrospira*) are nutrient-dense, providing significant levels of essential minerals, high-quality proteins, n-3 polyunsaturated fatty acids (PUFA) and bioactive compounds that contribute to both nutrition and health (Safi et al., 2014; Kose et al., 2017). Microalgae cultivation is environmentally advantageous, requiring minimal land and water, and it can even aid in wastewater treatment by recycling nutrients from water sources (Khan et al., 2018). This reduces the environmental footprint associated with traditional mineral production. The structural and biochemical characteristics of microalgae also make them particularly suitable for animal nutrition. For example, while *Chlorella* has a rigid cell wall that necessitates pre-treatment to release nutrients effectively, Spirulina has a more digestible structure that naturally facilitates nutrient absorption (Canelli et al., 2021).

Despite their advantages, the incorporation of microalgae into swine diets presents challenges. A primary factor is mineral bioavailability, which is influenced by the cell wall composition unique to each species. Additionally, the economic feasibility of large-scale production and the practical impact on swine growth, health and productivity must be considered to fully assess their utility. Research has shown positive results at inclusion rates of 2-5% for *Chlorella* and Spirulina, with benefits such as improved immune responses and enhanced bone mineral density in piglets, but large-scale applications remain costly (Furbeyre et al., 2017; Coelho et al., 2020b).

This review provides an in-depth analysis of these factors, exploring the nutritional profile of microalgae, mechanisms to enhance mineral bioavailability, impacts on swine health and the environmental and economic considerations of integrating microalgae into animal feed. By addressing these elements, we aim to offer a comprehensive overview of how microalgae could support sustainable and efficient swine production, potentially replacing or complementing traditional mineral sources while aligning with the environmental goals of modern agriculture.

2 Nutritional profile of microalgae

Microalgae are recognized for their dense nutritional profile, rich in essential minerals, high-quality proteins, vitamins and various bioactive compounds (Martins et al., 2021; Costa et al., 2023a). These characteristics make microalgae a promising alternative to conventional mineral supplements in animal nutrition, particularly in swine diets where balanced nutrition is essential for growth, health and productivity. Commonly studied species include *Chlorella vulgaris*, *Isochrysis galbana*, *Porphyridium cruentum*, *Schizochytrium* sp. and Spirulina, each offering a unique composition to support diverse nutritional needs in swine (Martins et al., 2021; Costa et al., 2023a). Not only do these species supply essential minerals required for swine, but they also enhance the overall dietary profile, making them effective for enriching feed formulations sustainably.

2.1 Mineral composition of microalgae

Minerals are fundamental in swine physiology, supporting critical functions like bone development, metabolic processes and immune defenses (Upadhaya and Kim, 2020; Stefanache et al., 2023). Microalgae provide a concentrated source of these essential macrominerals and trace elements, including calcium, phosphorus, potassium, iron, zinc, magnesium and selenium, often in higher concentrations than many plant-based feed ingredients, which highlights their appeal as nutrient-dense supplements for swine diets (Kusmayadi et al., 2021; Valente et al., 2021).

Calcium and phosphorus, crucial for bone formation and muscle function, are abundant in species like *Chlorella*, making it valuable for promoting skeletal growth in young pigs and maintaining bone integrity in adult swine (Costa et al., 2022). Potassium and magnesium, present in substantial amounts across various microalgae species, significantly contribute to muscle and nerve functions necessary for the activity levels of swine. Magnesium, specifically, plays an important role in activating enzymes that support metabolic and digestive processes.

Trace elements such as iron, zinc, manganese and selenium are also plentiful in microalgae and play integral roles in immune function, enzymatic reactions and antioxidant defenses. *Chlorella* and Spirulina are especially notable for their high iron content, essential for hemoglobin synthesis and oxygen transport, both vital for growth and energy production (Mišurcová et al., 2011). Additionally, zinc, manganese and selenium in these microalgae species contribute to robust antioxidant defenses and enzymatic activities, supporting disease resistance and overall health in swine (Ghazi et al., 2021; Kusmayadi et al., 2021).

Swine requires a balanced intake of essential nutrients, including macrominerals, trace elements, proteins, vitamins and energy, to support growth, reproductive performance, and overall health. These nutrient requirements vary depending on factors such as age, weight and production stage. The National Research Council (NRC) has provided comprehensive guidelines for swine nutrition in its *Nutrient Requirements of Swine* report (11th revised edition), which remains a key reference for establishing dietary needs across different life stages and production types (Council, 2012). Additionally, the National Academies of Sciences, Engineering and Medicine is currently developing the 12th revised edition, which will incorporate recent scientific advancements in swine nutrition to refine these requirements further.

For growing and finishing pigs weighing between 50-120 kg, the NRC outlines specific mineral requirements to support optimal health and productivity. Calcium is required at 5.5-8.0 g/kg of feed to support skeletal development and muscle function, while phosphorus is needed at 4.0-6.5 g/kg to maintain bone strength, energy metabolism and cellular processes. Zinc, recommended at 50-100 mg/kg, aids immune response, skin health and overall growth. Iron, essential for preventing anemia, supporting oxygen transport and boosting immune function, should be included at 80-100 mg/kg. Magnesium, necessary for nerve function, muscle contraction and enzyme activation, should be present at 400-500 mg/kg. Selenium, required at 0.15-0.30 mg/kg, supports antioxidant defense and immune health.

The mineral content in microalgae varies across species, providing a broad spectrum of nutrients essential for swine growth and productivity (Costa et al., 2023a). Table 1 compares the mineral content in microalgae with swine nutritional requirements, highlighting their potential to meet or exceed dietary needs.

2.2 Other nutritional benefits

Beyond minerals, microalgae such as *Chlorella* and Spirulina offer high protein content, often exceeding 50% of their dry weight, with a complete profile of essential amino acids (Niccolai et al., 2019; Martins et al., 2021). This makes them an excellent protein source, supporting muscle growth and overall swine health (Costa et al., 2023a). Microalgae are also rich in vitamins, including B12, crucial for nerve function and blood formation, and they contain n-3 PUFA, which provide anti-inflammatory benefits valuable for animal welfare (Ramos-Romero et al., 2021). Additionally, bioactive compounds like chlorophylls and carotenoids in microalgae support antioxidant defenses, potentially reducing oxidative stress and enhancing disease resilience in pigs (Mavrommatis et al., 2023).

2.3 Tailoring nutritional profiles through cultivation techniques

The nutrient composition of microalgae can be optimized through targeted cultivation techniques, allowing producers to tailor the mineral and vitamin profiles to specific dietary needs. Factors such as light intensity, nutrient availability and salinity can be adjusted to enhance particular nutrients in microalgae, a process known as biofortification (Kusmayadi et al., 2021). For example, increasing the iron concentration in the growth medium has been shown to elevate iron levels in *Chlorella*, making it more suitable for addressing mineral deficiencies in swine diets (Gao et al., 2019). Such methods improve the practical application of microalgae in animal feed, ensuring that the final product aligns more closely with the nutritional requirements of swine.

3 Bioavailability of microalgal minerals

3.1 Microalgal cell wall structure and mineral absorption in swine

Microalgal cell walls vary significantly across species, affecting their digestibility and the subsequent release of essential minerals in swine and other monogastric animals. For example, *Chlorella* species possess rigid cell walls that limit nutrient release and require processing to improve bioavailability. In contrast, Spirulina has a more digestible cell structure that naturally facilitates greater nutrient absorption without extensive processing (Kose et al., 2017; Canelli et al., 2021). These structural differences highlight the need to consider the cell wall characteristics of each microalgal species when developing swine feed.

Research demonstrates that the structural resilience of microalgal cell walls can restrict the absorption of minerals, such as calcium, iron and zinc, in animals consuming microalgae-enriched diets (Coelho et al., 2020a; Spínola et al., 2022). Studies in swine and other monogastric animals suggest that, without adequate pre-treatment, a significant proportion of these minerals may remain inaccessible. For example, *Chlorella* in swine diets has shown improved mineral absorption following cell wall disruption, making key elements like iron and zinc more bioavailable and supporting essential physiological functions such as hemoglobin synthesis and immune health (Coelho et al., 2020b; Costa et al., 2022).

3.2 Pre-treatment strategies to enhance bioavailability

Various mechanical pre-treatment techniques have been developed to improve mineral bioavailability by breaking down microalgal cell walls (Costa et al., 2023b; Spínola et al., 2023). High-pressure homogenization, bead milling and extrusion are effective methods for enhancing nutrient accessibility. Bead milling, for instance, effectively disrupts cell walls in species like *Chlorella* and Spirulina, leading to increased mineral release and absorption in swine. Extrusion has also proven beneficial, reducing protein solubility in Spirulina, thereby enhancing protein bioavailability and indirectly could support mineral uptake through improved overall digestibility (Safi et al., 2014).

Enzymatic treatments are another approach to enhance bioavailability, using enzymes such as lysozyme and amylase to

TABLE 1 Macrominerals (g/kg dry matter) and microminerals (mg/kg) of key microalgae species used in animal nutrition, and selected mineral requirements for growing and finishing pigs weighing between 50-120 kg (g/kg and mg/kg feed for macro and microminerals, respectively).

Mineral	*Chlorella* sp.	*Isochrysis* sp.	*Porphyridium* sp.	*Schizochytrium* sp.	Spirulina	Swine requirements
Ash (%)	10.7 ± 5.4	18.7 ± 6.14	23.1 ± 7.62	7.37 ± 2.35	9.87 ± 6.00	–
Macrominerals						
Calcium (Ca)	9.32 ± 16.8	9.37 ± 3.08	12.8 ± 5.17	3.53	3.45 ± 3.78	5.5 - 8.0
Magnesium (Mg)	5.56 ± 5.69	6.07 ± 3.03	7.41 ± 3.61	–	2.72 ± 1.20	0.4 - 0.5
Phosphorus (P)	16.4 ± 7.37	15.5 ± 11.0	10.5 ± 6.39	4.88	9.10 ± 4.25	4.0 - 6.5
Potassium (K)	23.6 ± 41.6	10.4 ± 4.22	11.2 ± 2.69	5.71	18.1 ± 5.84	1.5 - 2.5
Sodium (Na)	5.67 ± 6.81	18.4 ± 8.26	29.5 ± 27.4	1.04	25.8 ± 26.0	1.5 - 2.5
Sulphur (S)	0.12	–	11.9 ± 4.76	7.68	–	- *
Microminerals						
Copper (Cu)	24.3 ± 35.4	14.5 ± 9.75	17.0 ± 15.9	2.08	4.32 ± 6.54	5 - 10
Iron (Fe)	1289 ± 1702	880 ± 1007	2682 ± 4708	13.5	512 ± 357	80 - 100
Manganese (Mn)	269 ± 406	272 ± 379	81.1 ± 100	–	87.1 ± 174	2 - 4
Selenium (Se)	0.22	0.04	0.5	–	0.4	0.15- 0.30
Zinc (Zn)	131 ± 173	280 ± 443	199 ± 176	37.4	16.2 ± 11.4	50 - 100

Contents of microalgae are expressed as average ± standard deviation, and values for swine nutrient requirements as minimum - maximum.
*Generally provided through proteins.
Sources: (Council, 2012; Wild et al., 2018; Dineshbabu et al., 2019; Kusmayadi et al., 2021; Nagarajan et al., 2021; Valente et al., 2021; Xu et al., 2021; Costa et al., 2023a, 2024).

partially degrade the microalgal cell wall (Coelho et al., 2019, 2020a). This degradation facilitates the release of minerals and other nutrients during digestion. Studies have shown that treating Spirulina with lysozyme and α-amylase improves the release of calcium, magnesium and fatty acids (Coelho et al., 2020a). Similarly, enzyme cocktails targeting specific cell wall components in *Chlorella* have increased mineral bioavailability without altering the nutrient profile, highlighting the potential of enzymatic methods to optimize nutrient accessibility (Coelho et al., 2019).

Both mechanical and enzymatic pre-treatments show strong potential for improving the bioavailability of minerals from microalgae, establishing them as a viable mineral source for swine diets. These treatments not only enhance mineral release but also increase overall digestibility and nutritional value, supporting better growth, health and productivity in swine production. Continued research is focused on identifying optimal combinations of these pre-treatments to maximize the efficiency and economic viability of microalgae as a mineral-rich feed component in sustainable animal agriculture.

4 Impact on swine health and growth performance

4.1 Growth rate and bone health

Minerals like calcium, phosphorus and magnesium are essential for bone development and structural integrity in swine. *Chlorella* and Spirulina, rich in these minerals, offer bioavailable sources that support skeletal growth. Becker et al. (2020) demonstrated that piglets fed a diet with 5% *Chlorella vulgaris* showed a 12% increase in growth rate and a significant improvement in bone mineral density compared to piglets on a standard mineral diet. This enhancement in skeletal strength was attributed to *Chlorella*'s high calcium (9.3 g/kg) and phosphorus (16.4 g/kg) levels, which facilitate effective bone mineralization. In a related study, Schlegel and Gutzwiller (Schlegel and Gutzwiller, 2020) found that weaned piglets supplemented with 2% Spirulina exhibited a 9% increase in weight gain and improved bone development, highlighting the efficacy of microalgae in promoting growth and structural health in swine.

However, while these studies affirm microalgae's benefits for bone health, they also underscore the need for balanced inclusion rates. Excessive levels of specific minerals, particularly calcium and iron, can lead to imbalances or toxicity (Costa et al., 2024). Properly calibrated inclusion levels ensure nutritional adequacy without risking mineral excess.

4.2 Immune function and disease resistance

Trace elements like zinc, iron and selenium play a critical role in immune function, supporting resistance to disease in swine (Nagarajan et al., 2021). Spirulina, rich in these elements, has shown positive effects on immune responses. In a study by Furbeyre et al (Furbeyre et al., 2017), diets enriched with 3% Spirulina led to a 15% increase in leukocyte counts and a 20% elevation in antibody production in pigs, which enhanced disease resistance. The high zinc content in Spirulina (16.2 mg/kg) was associated with improved immune cell function, while selenium's antioxidant properties supported protection against cellular oxidative stress. Martins et al. (2022) corroborated these findings, noting that a diet with 5% *Chlorella* supplementation reduced disease incidence by 18% and enhanced resilience to infections. This study highlights microalgae's potential to bolster immune health, particularly during growth stages when swine are more susceptible to infections.

Despite these advantages, the immune-boosting effects of microalgae depend on species composition and mineral bioavailability, which can vary significantly. Therefore, while effective as an immune supplement, microalgae-based diets should be monitored for nutrient consistency to prevent variability in immune responses across swine populations.

4.3 Meat quality and productivity

Although the primary focus of this study is on the role of microalgae in mineral supplementation, this section is included to address concerns about potential impacts of microalgae inclusion on meat quality. The findings discussed here demonstrate that microalgae not only provide nutritional benefits but also maintain or enhance meat quality characteristics. Microalgae's inclusion in swine diets has also been associated with enhanced meat quality, especially through improvements in the fatty acid profile. Species like *Isochrysis galbana* and *Porphyridium cruentum* are rich in n-3 PUFA, which contribute to healthier meat profiles. In a study by De Tonnac and Mourot (de Tonnac and Mourot, 2018), a 2% *Isochrysis* supplementation increased n-3 PUFA levels in muscle tissues by 25%, resulting in an improved n-6 to n-3 PUFA ratio. This shift not only enhanced the nutritional value of the pork but also improved sensory qualities, including tenderness and juiciness. Similarly, Kalbe et al. (2019) found that a 1.5% *Porphyridium* inclusion reduced lipid oxidation by 15%, extending shelf life and preserving meat quality. Xu et al. (2021) reported that a 3% microalgae inclusion improved overall productivity metrics, increasing feed conversion ratios by 10% and average daily gain by 8%, indicating a positive impact on swine performance and product value.

These studies suggest that microalgae can significantly enhance meat quality and productivity. However, high PUFA content may require careful monitoring, as excessive PUFA can impact lipid stability, affecting meat storage if not balanced with antioxidants.

4.4 Optimal inclusion rates and role as ingredient or additive

Determining the optimal inclusion rate of microalgae in swine diets is essential for maximizing health benefits while maintaining cost-effectiveness. Research generally supports inclusion rates of 2-5% for species like *Chlorella* and Spirulina, which have shown favorable impacts on growth, bone health and immunity without substantial cost increases (Valente et al., 2021; Costa et al., 2023a). Studies indicate that a 3% inclusion rate often provides the best balance, enhancing growth and immunity, while rates above 5% may lead to diminishing returns due to increased feed costs and potential mineral imbalances.

Microalgae can serve as both an ingredient and an additive in swine nutrition. When used as an ingredient, microalgae may replace conventional mineral sources, such as calcium carbonate or zinc oxide, offering a sustainable mineral alternative and reducing the environmental impacts of mineral mining and processing (Becker et al., 2020; Valente et al., 2021). Microalga species belonging to the genera *Chlorella* and Spirulina, known for their mineral and protein-rich profiles, hold promise in this role by supporting bone and immune health.

However, due to current production costs and nutrient variability, microalgae are more feasible as a dietary additive rather than a full ingredient replacement. At inclusion rates of 2-5%, microalgae serve as a supplementary source, enhancing the nutritional value of the diet with bioavailable minerals, vitamins, n-3 PUFA and antioxidants. This additive role allows for improved growth, immunity and meat quality without fully displacing existing mineral ingredients (Kusmayadi et al., 2021; Costa et al., 2023a).

Future research should focus on strategies to reduce production costs and standardize nutrient profiles, which could enable microalgae to transition from an additive to a primary ingredient in swine diets. As production technologies advance, microalgae may eventually support both roles, serving as a sustainable dietary additive and potentially as a full mineral source replacement, contributing to improved productivity and environmental sustainability in swine production.

Table 2 provides an overview of the primary minerals available in different microalgae species, their physiological roles in swine, and the specific benefits observed through supplementation in swine health and growth performance.

5 Environmental sustainability of microalgae cultivation

Microalgae cultivation offers unique environmental advantages, particularly in the context of sustainable swine mineral nutrition. Compared to traditional mineral sources, microalgae production requires significantly less land and water, while their rapid growth rates make them a renewable resource (Khan et al., 2018; Kusmayadi et al., 2021). The carbon sequestration capabilities of microalgae further enhance their sustainability, as they can absorb up to 1.8 kg of carbon dioxide per kilogram of biomass produced, reducing the overall carbon footprint of swine production systems (Singh and Ahluwalia, 2013). Additionally, microalgae's bioremediation potential allows them to recycle nutrients from wastewater, minimizing agricultural runoff and preventing eutrophication in surrounding ecosystems (Sydney et al., 2011; Díez-Montero et al., 2020). These attributes make microalgae a promising alternative for addressing the environmental challenges associated with conventional mineral supplementation in swine nutrition.

TABLE 2 Potential role and benefits of key microalgae as a source of minerals in swine nutrition.

Mineral	Microalgae source	Physiological role	Benefits
Macrominerals			
Calcium (Ca)	*Chlorella*, *Isochrysis* *Porphyridium*	Supports bone development and muscle function, especially in young pigs	Higher bioavailability from microalgae can improve skeletal health and growth rates in swine
Magnesium (Mg)	*Chlorella*, *Isochrysis* *Porphyridium*	Vital for enzyme activation, nerve function and muscle health	Contributes to muscle activity and overall metabolic function, reducing cramps and enhancing feed efficiency
Phosphorus (P)	*Chlorella*, *Isochrysis*	Essential for energy production, cell signaling and bone mineralization	Enhanced bioavailability promotes energy metabolism and bone health
Potassium (K)	*Chlorella*, Spirulina	Maintains electrolyte balance and supports nerve and muscle function	Supports muscular and neural functions, crucial for the health of actively growing pigs
Sodium (Na)	*Porphyridium*, Spirulina	Maintains osmotic balance, hydration and proper nerve transmission	Helps regulate fluid balance, supports cellular hydration and aids nerve function
Sulphur (S)	*Porphyridium*, *Schizochytrium*	Necessary for amino acid synthesis and antioxidant defense mechanisms	Aids in protein synthesis, supports antioxidant defenses and enhances detoxification
Microminerals			
Copper (Cu)	*Chlorella*, *Isochrysis* *Porphyridium*	Critical for immune function, enzymatic reactions and antioxidant defenses	Bioavailable copper from microalgae supports redox balance, boosts immunity and enhances resilience
Iron (Fe)	*Chlorella*, *Porphyridium*	Critical for hemoglobin synthesis and oxygen transport	Bioavailable iron from microalgae supports blood health and reduces anemia risk, enhancing growth and energy levels
Manganese (Mn)	*Chlorella*, *Isochrysis*	Cofactor in metabolic reactions and essential for bone formation	Enhances enzyme function and bone development, aiding metabolism and skeletal growth in young pigs
Selenium (Se)	*Porphyridium*, Spirulina	Functions as an antioxidant and supports immune and thyroid health	Enhances antioxidant defenses and immune response, reducing disease risk and oxidative stress
Zinc (Zn)	*Isochrysis* *Porphyridium*	Integral to immune function, skin health, and reproductive performance	Bioavailable zinc strengthens immune defenses, skin integrity, and growth, improving overall health resilience

Sources: (Council, 2012; Walk et al., 2015; Furbeyre et al., 2017; Khan et al., 2018; Wild et al., 2018; Lautrou et al., 2020; Schlegel and Gutzwiller, 2020; Kusmayadi et al., 2021; Saadaoui et al., 2021; Valente et al., 2021; Costa et al., 2022; Martins et al., 2022; Costa et al., 2023a; Mavrommatis et al., 2023; Costa et al., 2024).

6 Economic viability and practical considerations

The economic feasibility of microalgae as a mineral source for swine nutrition is influenced by production costs, scalability, and market acceptance. While current cultivation systems, such as photobioreactors, incur higher costs compared to traditional mineral supplements, ongoing advancements in technology, such as modular systems and solar-powered drying techniques, are reducing these expenses (Barros et al., 2015; Vigani et al., 2015). The nutrient consistency of microalgae, which can vary based on environmental factors, is being addressed through standardized cultivation protocols and biofortification methods, enhancing their reliability as a mineral source (Wild et al., 2018; Kusmayadi et al., 2021). Additionally, consumer demand for sustainable pork products provides an opportunity for producers to offset costs by marketing eco-friendly practices (Ahmad et al., 2022). Despite existing barriers, the integration of microalgae as a mineral source aligns with the economic and environmental goals of modern swine production, offering a viable solution for long-term sustainability.

7 Safety and regulatory considerations

7.1 Potential risks and contaminants

Microalgae can absorb contaminants, including heavy metals like arsenic, cadmium, lead and mercury, from their cultivation environments, which could pose risks to animal and human health if these contaminants accumulate in animal tissues (Markou et al., 2018; Mustafa et al., 2021). For instance, cadmium and lead are known to bioaccumulate, leading to toxic effects when consumed. The risk of contamination is higher for microalgae grown in open ponds or in environments exposed to untreated wastewater, which increases exposure to environmental pollutants.

Additionally, some microalgae species are capable of producing harmful toxins. For example, certain cyanobacteria (blue-green microalgae) can produce microcystins, hepatotoxic compounds that can cause liver damage in both animals and humans (Mustafa et al., 2021). While commercially cultivated species like *Chlorella* and Spirulina, widely used in animal feed, are generally non-toxic, contamination risks persist, especially when these species

TABLE 3 Current limitations of microalgae as a source of minerals in swine nutrition.

Limitation	Description	Implications
High production costs	Cultivation, harvesting and processing of microalgae are resource-intensive, requiring controlled environments and advanced technology (e.g., photobioreactors and precise nutrient media)	Higher costs limit accessibility, making microalgae less economically feasible compared to traditional mineral sources
Risk of contamination	Microalgae can absorb environmental contaminants such as heavy metals (e.g., arsenic, cadmium, lead and mercury) and produce toxins (e.g., microcystins) under certain conditions	Potential health risks to swine and humans if contaminants bioaccumulate and enter the food chain; requires stringent monitoring and quality control
Nutrient variability	The nutrient profile of microalgae can vary significantly based on environmental factors like light, temperature and nutrient availability	Variability affects reliability and consistency in meeting specific mineral requirements for swine, necessitating controlled cultivation and standardization
Lack of established supply chains	Limited infrastructure and partnerships with traditional agricultural networks hinder large-scale distribution and market accessibility	Smaller producers may face difficulties sourcing microalgae-based ingredients, impacting the feasibility of widespread adoption
Regulatory and compliance challenges	Regulatory frameworks for microalgae as feed ingredients are evolving and may require extensive safety documentation, contaminant testing and quality assurance measures	Compliance can be time-consuming and costly, potentially limiting smaller producers from entering the market
Consumer and industry acceptance	Limited awareness and acceptance of microalgae as a feed ingredient may lead to reluctance in adoption by producers and consumers	Reduced demand can impact economies of scale, preventing cost reductions and broader adoption

Sources: (van der Spiegel et al., 2013; Vigani et al., 2015; Markou et al., 2018; Wild et al., 2018; Yarnold et al., 2019; Mustafa et al., 2021; Cruz and Vasconcelos, 2024).

are grown in non-sterile or open systems. Therefore, selecting non-toxic strains and cultivating them under controlled conditions are vital to minimize these risks (Markou et al., 2018).

Regular monitoring and stringent quality controls are essential to ensure the safety of microalgae-based feed products. This includes routine screening for heavy metals and toxic compounds and ensuring that microalgae products meet the regulatory standards for contaminant levels. Pre-treatment methods, such as washing and filtration, are often employed to remove potential contaminants from microalgal biomass, further enhancing safety before they are incorporated into animal diets (Brennan and Owende, 2010).

7.2 Safety and regulatory standards

To ensure the safe inclusion of microalgae in swine feed, regulatory agencies, such as the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA), have established stringent guidelines for contaminants in animal feed. These guidelines specify permissible levels for heavy metals, microbial pathogens and other toxic compounds (Mustafa et al., 2021). For instance, the EFSA mandates maximum levels of cadmium and lead in feed materials and requires that any novel feed ingredient, including microalgae, undergo safety assessments to ensure contaminant levels are within allowable limits (EFSA, accessible at https://www.efsa.europa.eu/en/publications).

Producers are responsible for demonstrating compliance with these regulations by providing documentation that verifies their products' safety. In addition to contaminant limits, regulations in the EU, U.S., and other regions mandate testing for digestibility, nutrient composition and potential allergens for any new feed ingredient to confirm both safety and efficacy in animal nutrition (van der Spiegel et al., 2013). By adhering to these standards, microalgae-based products can ensure both safe consumption and effective nutritional contribution to swine diets.

Quality management systems, such as Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Points (HACCP), are also essential for minimizing risks associated with microalgae production and processing. GMP ensures consistent quality by controlling production processes, while HACCP identifies and manages potential contamination points. Together, these protocols offer a systematic approach to maintaining quality and minimizing contamination risks throughout the supply chain, from cultivation to final processing (van der Spiegel et al., 2013).

7.3 Quality control and labeling practices

Maintaining strict quality control is essential for building and sustaining confidence in microalgae as a safe and reliable feed ingredient. Effective quality control involves regular testing for contaminants, ensuring batch traceability and providing clear labeling of nutritional content and production methods (Cruz and Vasconcelos, 2024). Routine testing for heavy metals, toxins and pathogens is critical to verify that each batch complies with regulatory standards, as even minor deviations can have significant health implications.

Batch traceability practices, such as assigning unique batch numbers, allow for rapid identification and recall of contaminated products, providing an important safeguard in case of safety concerns. Traceability is particularly valuable for maintaining consistency in feed quality, helping producers and consumers feel confident in the product's safety (Cruz and Vasconcelos, 2024).

Transparent labeling is equally crucial for consumer assurance and informed decision-making. Labels should display nutrient content, origin, and any pre-treatment techniques, such as enzymatic or mechanical processing, used to improve bioavailability. For example, if a microalgae product has undergone enzymatic treatments to enhance mineral absorption, this information should be stated on the label. Accurate labeling not only ensures that producers are transparent about their practices but also helps consumers understand the product's composition and nutritional value, fostering trust in microalgae-based feed ingredients (van der Spiegel et al., 2013) (Table 3).

8 Conclusion and future perspectives

The integration of microalgae as a mineral source in swine nutrition represents a promising step toward more sustainable livestock production. With their rich content of essential minerals, proteins, n-3 PUFA and bioactive compounds, microalgae offer a valuable alternative or supplement to traditional mineral sources. The review highlights that, at inclusion rates of 2-5%, microalgae, such as *Chlorella* and Spirulina, can enhance growth, immune function and meat quality in swine, while potentially reducing the environmental footprint of feed production. This dual role, whether as an additive to enhance existing diets or as a full or partial replacement for conventional mineral ingredients, positions microalgae as a flexible and sustainable feed component.

However, practical challenges remain in scaling up microalgae production for widespread use. High production costs, nutrient variability and regulatory hurdles present significant barriers that must be addressed to make microalgae a viable large-scale feed ingredient. Additionally, the potential for contamination with heavy metals or harmful algal toxins requires stringent quality control, as contamination could pose health risks to both swine and consumers. Consistent monitoring and adherence to regulatory standards are essential to ensure the safety of microalgae in animal nutrition.

Future research should focus on advancing cultivation and pre-treatment technologies to enhance nutrient bioavailability, reduce costs and maintain consistent quality. Long-term feeding trials are necessary to fully understand the impacts of microalgae on swine health, performance and economic feasibility in diverse production settings. As technologies evolve and economies of scale improve, microalgae have the potential to support sustainable swine production, aligning with broader goals for environmental sustainability and food security.

Author contributions

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The author(s) declare that no Generative AI was used in the creation of this manuscript.

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