AE2026 - Aquaculture in Global Change

aquaculture europe

VOL. 51 (1) MARCH 2026

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FEEDING FOR RESILIENCE:

How Proven Mineral Nutrition Can Proactively Support Aquatic Health

DR. CLAUDIA FIGUEIREDO SILVA
Global Technical Services Aquaculture, Zinpro Corporation
LinkedIn Profile

Introduction

The aquaculture industry is entering a new phase, one that is shaped by climate variability, rising sea temperatures, and increasing biological stressors. A 0.85 °C increase in the mean surface temperature of global waters since the early 1800s is expected to rise at least another 3.5 °C by the end of the century (Scafetta, 2021). Projections also point toward an escalation in the frequency and intensity of heatwaves across Europe and Asia. The Mediterranean Sea is particularly susceptible to warming due to its semi-enclosed structure and limited exchange with oceanic waters. Over the past 50 years, while a 0.11 °C per-decade rise in water temperature has been observed for the world's oceans, the Mediterranean has observed an upswing of 0.61 °C each decade (Belkin et al., 2009; Oliver et al., 2018). These environmental shifts are occurring rapidly and at an accelerating pace. Aquatic species are being pushed beyond their thermal comfort zones, leading to reduced feed intake, impaired growth, and increased disease susceptibility. This cascade of stressors contributes to significant economic losses for aquaculture producers.

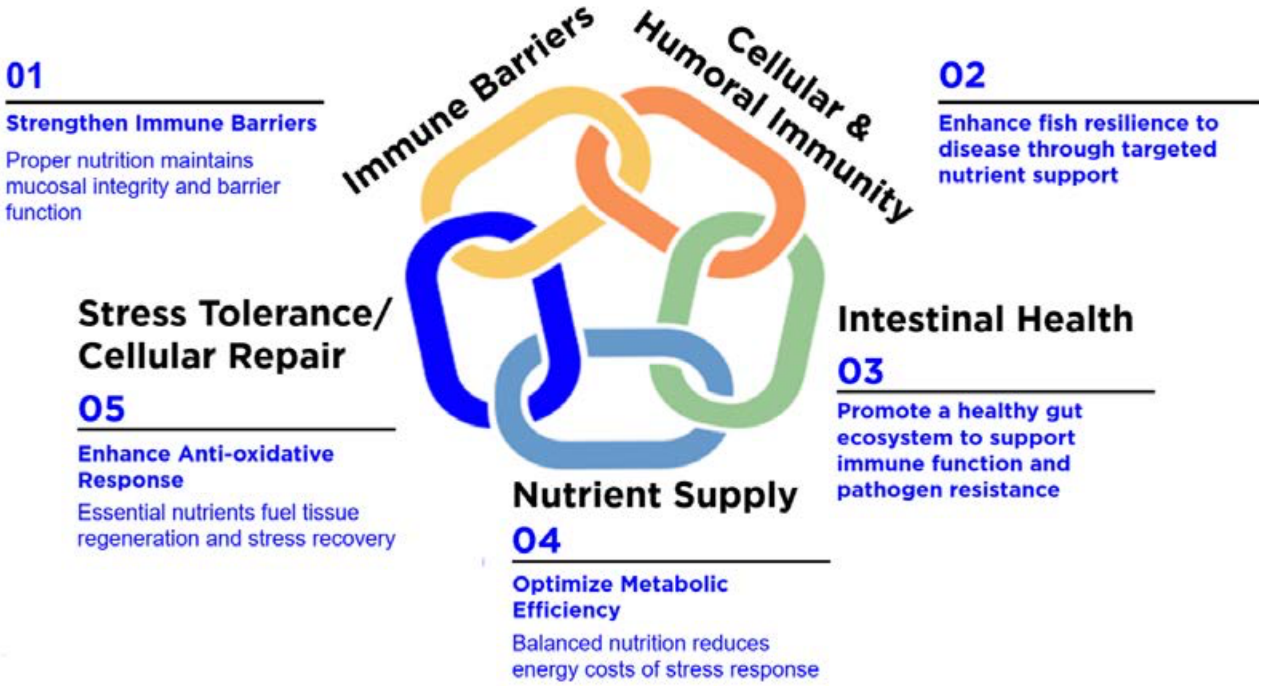

Figure 1: Influence of Nutrition on Disease Resilience

Disease	Pathogen	Species Affected	Temperature Impact
Salmon louse infestation	*Lepeophtheirus salmonis*	Atlantic salmon	Increased infestation and resistance to treat-ments at higher temperatures
Vibriosis	*Vibrio spp.*	Abalone, shrimp, oysters	Increased virulence and mortality with elevated temperatures
Gill disease	Multiple pathogens	Atlantic salmon	Higher prevalence and severity in late summer/ autumn
Sparicotylosis	*Sparicotyle chrysophrii*	Gilthead Seabream	Lethargy due to the hypoxia, necrosis of gill filaments, changes gill microbiome, and causes severe anemia

Table 1. Examples of Climate-adapted Disease Outbreaks in Aquatic Species

Economic Impact of Thermal Stress and Disease

Farmed fish are often reared outside their natural habitat, where they are vulnerable to temperature extremes. Species such as gilthead seabream naturally inhabit deeper waters than those in which they are typically cultured. Exposure to heat stress disrupts their metabolism, growth, and immune function. Elevated water temperatures also increase oxidative stress and inflammation in both Atlantic salmon and seabream. Oxygen demand and susceptibility to hypoxia rise in warmer water, where climate change alters microbial ecosystems, promoting pathogen proliferation and weakening fish microbiomes.

The proliferation of *Vibrio* spp., *Aeromonas* spp., and *Flavobacterium* spp. heightens the risk of vibriosis, hemorrhagic septicemia, and columnaris disease. Parasitic infections such as *Enteromyxum leei, Sparicotyle chrysophrii*, and *Argulus* spp. are likewise exacerbated by higher temperatures. These parasites can cause anemia, cachexia, and mortality rates approaching 100% in susceptible stocks. Despite improvements in disease surveillance and management, economic losses from disease outbreaks in aquaculture are estimated to exceed 9.5 billion USD per year (Shinn et al., 2015). These findings are summarized in Table 1 and reinforce the urgency of promoting strategies to address climate-adapted disease.

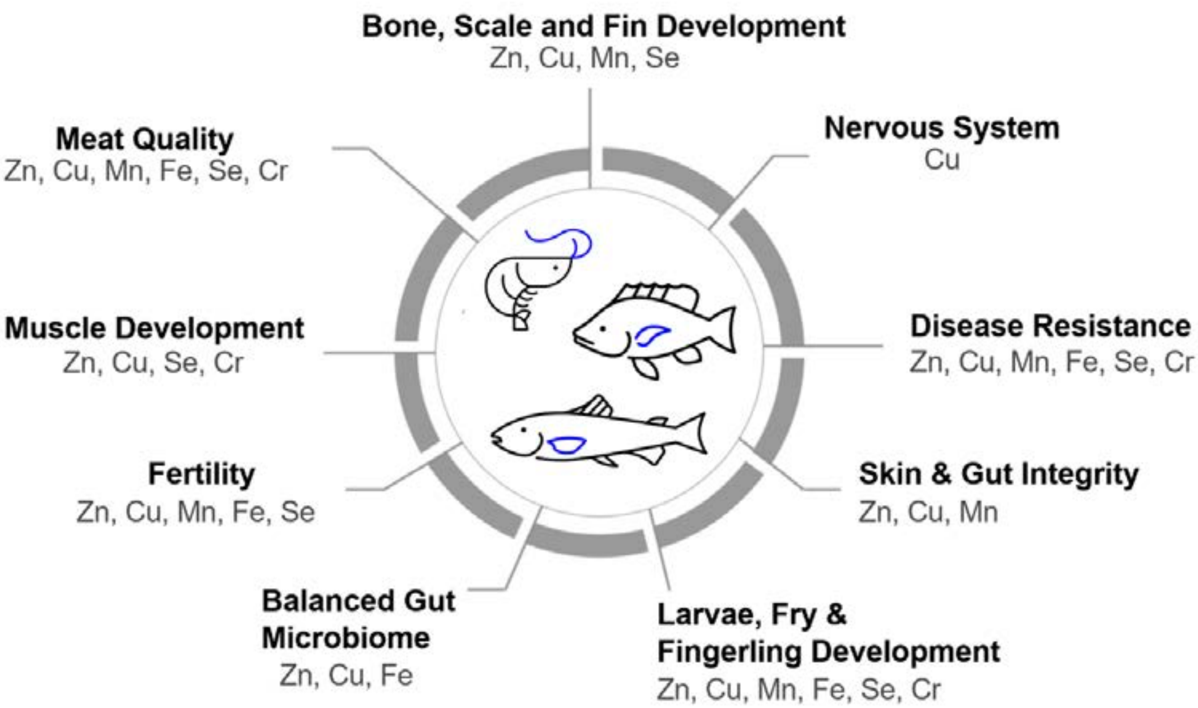

Figure 2: Essentiality of Trace Minerals in Aquaculture

Nutrition as a Strategic Solution: The Power of Trace Minerals

While environmental management and therapeutics play a role, nutrition remains a powerful and underutilized tool for building resilience in fish. Nutritional interventions are especially critical before and during periods of thermal stress, when metabolism is altered and immune defenses are compromised. A targeted nutritional approach can also help counteract microbiome disruption caused by warming waters. Dietary strategies designed to support fish during these conditions can (Figure 1):

- Strengthen the immune barriers of the skin, gills, and intestine
- Support immune system function
- Enhance anti-oxidative responses and cellular repair mechanisms
- Reduce the energetic cost of the stress response
- Promote a gut microbiome that resists parasites and infections

Trace minerals are essential for hundreds of biological functions throughout the aquatic life cycle (Figure 2). Minerals such as zinc (Zn), selenium (Se), iron (Fe), and chromium (Cr) play important roles in maintaining physiological stability under stressors associated with climate change, especially rising water temperatures. Optimizing mineral nutrition represents an important opportunity to improve fish resilience during thermal stress. The effectiveness of trace minerals depends strongly on their source, as chemical forms vary widely in bioavailability and physiological impact. Inorganic mineral sources (e.g., sulfates, oxides, hydroxychlorides) are often poorly absorbed and highly reactive in the gut, where they readily bind or compete with other dietary components and are frequently excreted before they can be utilized. Research using Zinpro® Performance Minerals® (ZPM) has demonstrated the distinct physiological contributions that Zn, Se, Fe, and Cr each provide to metabolic, immune, and antioxidative defenses (Figure 3), making them a promising nutritional package for addressing climaterelated challenges in aquaculture.

Zinc (Zn): *Skin Integrity & Wound Healing*

Zinc is a first line of defense mineral, essential for maintaining epithelial integrity, particularly in the skin, the fish's largest organ and a primary barrier against pathogen entry. In a 60-day feeding trial with post-smolt Atlantic salmon challenged by sea lice, fish supplemented with Zinpro® Availa® Zn showed significantly improved skin outcomes: 88% had no lesions compared with 78% in the control group. This underscores zinc's role in wound healing and barrier protection.

Zinc also supports immune cell development in key organs such as the head kidney and spleen. By stabilizing thymic hormones and promoting the proliferation of immune cells, zinc strengthens both innate and adaptive immune responses.

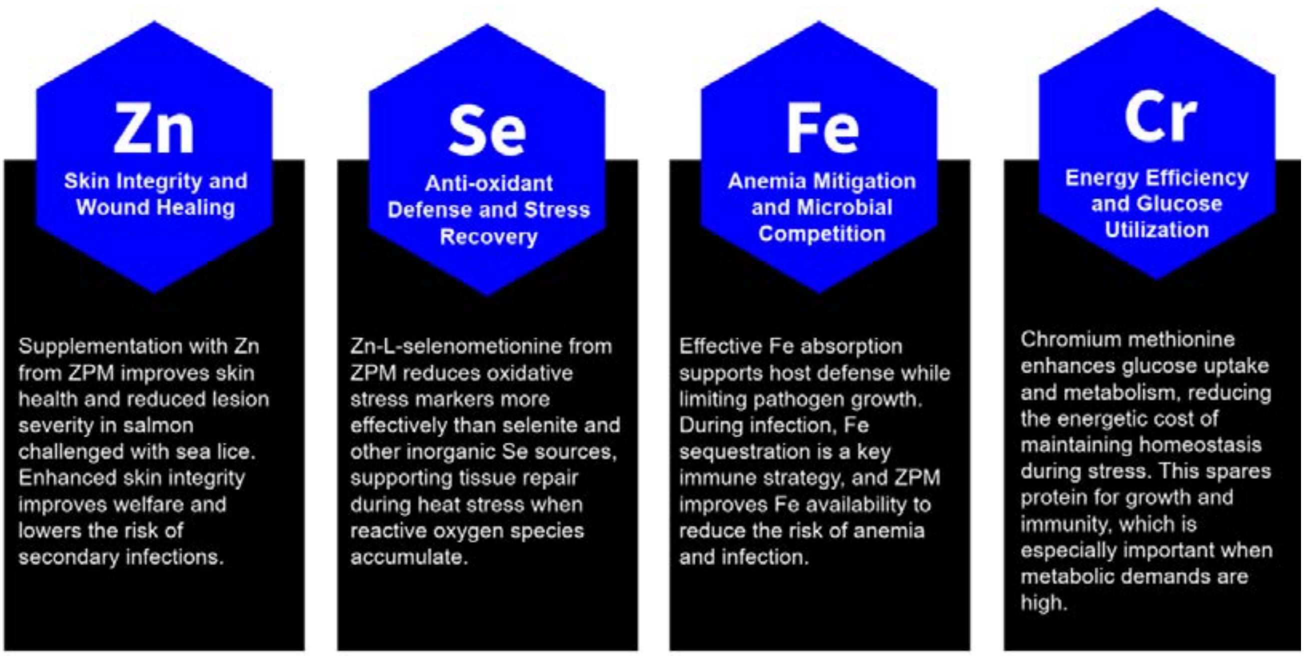

Fig. 3 A Four-mineral Approach to Optimizing Fish Health: Functional Roles Under Thermal and Disease Stress

Selenium (Se): *Antioxidant Defense & Stress Recovery*

Selenium plays a pivotal role in oxidative stress management through its involvement in glutathione-dependent antioxidant pathways. Zinpro® Availa® Se consistently outperforms inorganic selenite in reducing oxidative stress markers. In gilthead seabream exposed to acute stress, Availa Se increased total glutathione (TGSH) and reduced oxidative stress indices more effectively than inorganic sources. These effects contribute to faster tissue repair and improved physiological resilience during thermal challenges.

Iron (Fe): *Anemia Mitigation & Microbial Competition*

Iron is essential not only for hemoglobin synthesis and oxygen transport but also for modulating microbial dynamics in the gut. Efficient absorption of Fe from Zinpro Performance Minerals helps maintain host defense by ensuring adequate iron availability while limiting the iron accessible to pathogens. In Nile tilapia, replacing inorganic Fe sources with Zinpro Availa® minerals led to a 75–96% reduction in harmful *Streptococcus* species and a 124–126% increase in beneficial *Bacillus* populations. Gut morphology also improved, with longer villi and increased goblet cell density, enhancing mucosal immunity and nutrient absorption.

Chromium (Cr): *Energy Efficiency & Glucose Utilization*

Chromium methionine (CrMet) enhances glucose uptake and metabolic efficiency, helping fish redirect energy toward growth and immune function during periods of thermal stress. By lowering the energetic cost of maintaining homeostasis under stress, Zinpro Availa® Cr (also known as Zinpro® MICROPLEX®) supports improved feed conversion and overall performance. This makes chromium methionine a valuable component in nutritional strategies aimed at supporting fish during climate-related metabolic challenges.

Conclusion: Feeding for the Future

Climate-driven stressors are reshaping aquaculture, challenging the metabolic stability, immune function, and overall performance of farmed fish. Building resilience must therefore begin from within. This review demonstrates that targeted mineral nutrition, particularly bioavailable forms of Zn, Se, Fe, and Cr, provides a proactive and proven foundation for strengthening skin integrity, antioxidant defenses, microbial balance, and energy efficiency during thermal stress. Research using Zinpro Performance Minerals highlights how each mineral contributes uniquely to supporting aquatic health under climaterelated pressures. By integrating advanced mineral nutrition strategies, producers can enhance fish welfare, reduce losses, and move toward a more resilient and sustainable aquaculture future.

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