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Rinkesh Meena

Department of Fish Nutrition
 and Feed Technology, ICAR-
 Central Institute of Fisheries
 Education, Mumbai,
 Maharashtra, India

Chinmayee Puja Rani Sethi

Department of Fish Nutrition
 and Feed Technology, ICAR-
 Central Institute of Fisheries
 Education, Mumbai,
 Maharashtra, India

Nutritional requirements of Singhi (*Heteropneustes fossilis*)

Rinkesh Meena and Chinmayee Puja Rani Sethi

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Abstract

Heteropneustes fossilis, popularly known as singhi, is a significant tropical freshwater catfish species (Mohamed & Ibrahim, 2001). This obligate air-breather predominantly inhabits shallow aquatic habitats and contributes substantially to India's production of air-breathing fishes. It's highly preferred by consumers due to its distinctive flavour, high protein and iron levels, and minimal fat content. (Pandey *et al.*, 2001). The species is recognized for its ability to efficiently assimilate both plant-derived and animal-based feedstuffs, coupled with remarkable resilience under unfavourable environmental conditions. Its therapeutic properties, strong consumer demand, and compatibility with intensive aquaculture practices have further enhanced its commercial importance (Jawahar *et al.*, 2018). Singhi is well adapted to thrive in neglected or stagnant water bodies, agricultural fields, swamps, and wetlands, exhibiting extraordinary tolerance to elevated ammonia concentrations and prolonged hypoxic conditions (Saha & Ratha, 1998). For sustainable aquaculture, feed formulation, and growth optimization, it is essential to comprehend its nutritional needs. With a focus on protein, fat, carbohydrate, vitamin, and mineral requirements, as well as the implications for feed production, this article summarizes the most recent research on macronutrient and micronutrient requirements.

Keywords: *Heteropneustes fossilis*; protein metabolism; essential fatty acids; vitamin and mineral supplementation

Introduction

The stinging catfish also known as *Heteropneustes fossilis*. It is an omnivorous freshwater species with strong aquaculture potential, as it tolerates high stocking densities and water conditions that are unsuitable for many other fishes (Mohamed & Ibrahim, 2001) [36]. Its flesh is characterized by a favourable nutritional composition, including balanced proteins, lipids, and minerals, which has contributed to widespread consumer acceptance (Pandey *et al.*, 2001; Jawahar *et al.*, 2018) [45, 23]. These attributes have stimulated interest in its farming across the Indian subcontinent, where production volumes continue to rise (Singh *et al.*, 2024) [54]. Despite this progress, the absence of nutritionally balanced feeds remains a major constraint in Singhi aquaculture (Mukul *et al.*, 2023) [37]. Feed costs typically account for more than 70% of variable operational expenses in fish farming, underscoring the importance of precise knowledge of species-specific nutritional requirements (FAO, 2022) [13]. Inadequate dietary composition leads to poor growth and reduced productivity, highlighting the need for high-quality, balanced diets (Lall & Kaushik, 2002) [29]. Among essential nutrients, minerals play a critical role in fish health and growth. Although required in relatively small amounts, they are indispensable for skeletal development, metabolic regulation, and organ function (Lall, 2002; Prabhu *et al.*, 2016) [29, 47]. While fish can absorb certain minerals directly from water, dietary intake remains the primary source (Lall & Kaushik, 2002) [29]. Research on mineral nutrition in fish has advanced slowly, despite its recognized importance in aquaculture sustainability (Prabhu *et al.*, 2016) [47]. Zinc (Zn) is considered one of the most vital trace elements, essential for growth, metabolism, bone formation, gene regulation, and energy production (Lall & Kaushik, 2002) [29]. It is unique in being the only metal present in all six enzyme classes and is the second most abundant transition element in biological systems (Vallee & Falchuk, 1993) [57]. Zinc regulates protein, lipid, and carbohydrate metabolism (Prasad, 2013) [48] and functions as a cofactor in numerous metalloenzymes, including carboxypeptidases, alcohol dehydrogenases, carbonic anhydrases, glutamate dehydrogenases, superoxide dismutase, and nucleic acid polymerases

Corresponding Author:**Rinkesh Meena**

Department of Fish Nutrition
 and Feed Technology, ICAR-
 Central Institute of Fisheries
 Education, Mumbai,
 Maharashtra, India

(Hambidge *et al.*, 2010; Prasad, 2013) ^[18, 48]. Consequently, dietary zinc deficiency disrupts these physiological and biochemical pathways, leading to impaired growth and reduced aquaculture performance (Prabhu *et al.*, 2016) ^[47]. In the context of modern aquaculture, precision nutrition and sustainable feed development are critical. Emerging approaches such as nutrigenomics, microbiome-targeted diets, and alternative feed resources offer promising avenues to enhance nutrient utilization and resilience in singhi culture. This article aims to synthesize current knowledge on the nutritional requirements of *Heteropneustes fossilis*, highlighting its macronutrient and micronutrient demands, feeding strategies, and future prospects for sustainable aquaculture.

Digestive system of the Stinging catfish (Singhi)

The digestive system of *Heteropneustes fossilis* (Asian stinging catfish) demonstrates distinct adaptations that enable its omnivorous feeding habits and survival in freshwater ecosystems. The terminal mouth, armed with villiform teeth, allows the fish to seize and consume a wide range of food items such as insects, detritus, and small aquatic organisms (Kumar & Tembhre, 1996) ^[28]. Beginning with the mouth, which contains sharp teeth for biting and grinding, the digestive tract continues into a short pharynx that connects to a straight, cylindrical oesophagus. This oesophagus leads into a J-shaped stomach lined with glandular mucosa, responsible for secreting digestive juices and enzymes (Ikpegu *et al.*, 2014; Verreth *et al.*, 1992) ^[22, 59]. The J-shaped configuration is thought to prolong the retention of food, thereby enhancing enzymatic digestion. Nutrient absorption primarily occurs in the small intestine, which is equipped with finger-like microvilli that expand the surface area for assimilation (Hamlin *et al.*, 2000) ^[19]. The large intestine functions in reabsorbing water and electrolytes while compacting undigested residues, which are ultimately expelled as waste (Hamlin *et al.*, 2000) ^[19]. Ontogenetic studies reveal that the digestive system of catfish develops progressively from a simple, undifferentiated tube in the larval stage into specialized organs with distinct cellular structures, following a developmental timeline similar to that reported in other teleosts (Hamlin *et al.*, 2000; Ikpegu *et al.*, 2014; Kozarić *et al.*, 2008; Nattabi, 2018; Verreth *et al.*, 1992) ^[19, 22, 27, 59]. Once food enters the stomach, it is further processed in the cardiac and pyloric regions, where gastric glands secrete hydrochloric acid and pepsin to facilitate protein breakdown (Jhingran, 1982) ^[24]. The intestine, moderately long and coiled, is divided into anterior, middle, and posterior sections, lined with columnar epithelium and goblet cells. Microvilli enhance absorption, while the coiling increases digestive efficiency. Accessory organs such as the liver and pancreas secrete bile and enzymes including pepsin and trypsin, which play vital roles in lipid and protein digestion (Al-Hussaini, 1949) ^[5]. In addition, *H. fossilis* possesses a muscular gizzard that grinds and mashes ingested material before it progresses further into the digestive tract, ensuring mechanical breakdown complements chemical digestion.

Diet composition

Aquaculture feeds are formulated to meet the dietary needs of cultured fish species while maintaining an appropriate balance of proteins, carbohydrates, and lipids (Geay & Kestemont, 2015) ^[6]. Achieving this nutrient balance is not

uniform across all species; rather, it varies depending on the specific fish and its developmental stage (The Fish Site, 2007) ^[55]. In intensive aquaculture systems, feeds must be nutritionally complete because fish cannot rely on natural sources for supplementary nutrients. However, the limited availability of published data on the nutritional requirements of *Heteropneustes fossilis* at different life stages poses a significant challenge to designing cost-effective feeds.

Energy

Balancing dietary energy is a key factor in establishing feeding standards for fish. Energy is derived from the metabolism of lipids, carbohydrates, and amino acids (proteins) (Robinson & Li, 2015) ^[50]. In formulated feeds, carbohydrates and lipids serve as the primary energy sources since they are more economical compared to proteins. The level of dietary energy typically regulates feed intake, which in turn influences growth and nutrient utilization. For example, studies have shown that when dietary energy is low, fish tend to consume more feed to meet their energy requirements (Aderolu *et al.*, 2018; De Silva & Anderson, 1995) ^[1, 9]. However, in catfish, this relationship may differ, as feed intake is often determined by the amount the fish can physically consume rather than energy demand alone (Robinson *et al.*, 2006; Robinson & Li, 2015) ^[51, 50]. Conversely, diets with higher energy content may reduce feed intake, which can limit the consumption of essential nutrients and hinder growth. Excessive energy intake has also been linked to increased fat deposition and reduced efficiency of nutrient utilization. Therefore, careful attention must be given to maintaining an optimal dietary energy-to-protein ratio during feed formulation. This ratio not only affects growth performance but also influences digestive enzyme activity and plasma metabolite levels. Moreover, when non-protein energy sources such as lipids and carbohydrates are insufficient, costly proteins are diverted for energy rather than growth, raising feed expenses. Reported energy requirements for catfish are often expressed as the ratio of digestible energy (DE) to crude protein (DE/P), ranging between 7.4 and 12 kcal/g (Robinson & Li, 2015) ^[50], though values of 8.5-9.5 kcal/g are generally considered suitable for commercial feeds (Robinson *et al.*, 2006; Robinson & Li, 2015) ^[51, 50]. Similarly, FAO (2023) ^[13] documented a DE/P range of 8.24-9.19 kcal/g for catfish during the grow-out phase. Experimental findings indicate that fish fed diets with 3.0 kcal/g achieved the best feed conversion ratio (FCR), while those receiving 3.2 kcal/g diets showed the highest protein efficiency ratio (PER). The energy requirements reported by Aderolu *et al.* (2018) ^[1] are lower than those cited by FAO (2023) ^[13], Robinson & Li (2015) ^[50], and Robinson *et al.* (2006) ^[51], a variation likely influenced by factors such as water temperature and production systems.

Protein and Amino Acid Requirements

Proteins are complex nitrogenous compounds formed by amino acid linkages, and they represent the most vital macronutrient in fish diets due to their direct role in growth, tissue repair, reproductive physiology, and feed efficiency (Alberts *et al.*, 2002; Keremah & Beregha, 2014; Fatma & Ahmed, 2020) ^[4, 25, 15]. Since proteins are the most expensive component of fish feed, their use as an energy source is economically unfeasible (Craig & Helfrich, 2017) ^[8]. The dietary protein requirement in catfish varies with life stage,

temperature, feeding level, digestibility, and protein quality (Geay & Kestemont, 2015) [6]. Studies have reported optimal crude protein levels ranging between 28-32% without adverse effects on growth, while others suggest higher requirements of 35-43% depending on species and growth phase (Craig & Helfrich, 2017; Hecht, 2013; Van Weerd, 1995) [8, 21, 58]. For omnivorous and carnivorous catfishes such as *Heteropneustes fossilis*, an inclusion level of about 35-40% dietary protein has been identified as optimal to sustain growth and metabolic activity (NRC, 2011) [38]. Inadequate protein intake leads to stunted growth, poor feed conversion, and weakened immunity, whereas excessive protein increases feed costs and nitrogenous waste, deteriorating water quality (Lall & Kaushik, 2002) [29]. To enhance protein sparing and promote growth, lipids or carbohydrates can be incorporated into diets, but an imbalance in protein-energy ratios negatively affect performance and nutrient utilization (Ahmad, 2008) [2]. Feeding trials confirm that balanced protein levels improve feed conversion efficiency, protein retention, and survival rates in fry and fingerlings, highlighting the necessity of adequate and high-quality protein supply (Khan and Abidi, 2011; Ahmed, 2012) [26, 3].

Amino acid

Fish require a balanced supply of both essential and non-essential amino acids rather than simply a fixed quantity of dietary protein (Miles & Chapman, 2014) [35]. Diets formulated solely on crude protein levels may fail to provide adequate amounts of indispensable amino acids, which are critical for growth and metabolic functions (Nhu *et al.*, 2021) [40]. Deficiencies or imbalances in essential amino acids (EAA) can reduce growth performance and increase the release of nitrogenous waste into the environment (Miles & Chapman, 2014) [35]. Although more than 200 amino acids exist in nature, only ten are considered essential for fish—methionine, arginine, threonine, tryptophan, histidine, isoleucine, lysine, leucine, valine, and phenylalanine—because they cannot be synthesized in sufficient quantities to meet physiological demands and must therefore be supplied through the diet (Craig & Helfrich, 2017; Miles & Chapman, 2006) [34]. Among these, lysine and methionine are often the first limiting amino acids. An ideal protein source should thus provide an optimal balance of amino acids to support maximum growth, feed efficiency, and body composition. In particular, lysine and methionine are indispensable for skeletal development, enzyme production, and immune defense.

Methionine

Most plant-and by-product ingredients commonly used in least-cost fish feed formulations, such as soybean meal, brewer's yeast, hydrolyzed feather meal, groundnut cake, and cottonseed cake, are deficient in methionine (Fagbenro *et al.*, 1999) [11]. Methionine, a sulphur-containing amino acid, plays a central role in protein synthesis (Wang *et al.*, 2016) [61] and serves as a precursor for several key metabolites, including carnitine, succinyl-CoA, cysteine, homocysteine, and creatine (Martínez *et al.*, 2017) [33]. Deficiency of this amino acid has been associated with anorexia (Fagbenro *et al.*, 1999) [11], reduced growth and feed efficiency (Elesho *et al.*, 2021) [10], lower survival rates, and disruption of multiple metabolic and physiological

processes (Wang *et al.*, 2023) [60]. Based on growth response studies, the optimum methionine requirement for catfish fingerlings has been estimated at 31.6 g methionine/kg dietary protein, equivalent to 12.6 g methionine/kg diet (Fagbenro *et al.*, 1999) [11].

Lysine

Lysine is another critical limiting essential amino acid in fish feed ingredients. It plays a fundamental role in protein synthesis (Madrid *et al.*, 2019) [31] and in the production of carnitine, which facilitates the transport of long-chain fatty acids into hepatocytes for energy metabolism (Fagbenro *et al.*, 2010; Yang *et al.*, 2011) [12, 64]. Catfish fingerlings generally show improved performance with higher dietary lysine levels. For instance, fish fed diets containing 21.8-22.0 g/kg lysine (equivalent to 61.7-62.2 g/kg protein) exhibited superior growth compared to those receiving 13.3-13.8 g/kg lysine (Ozório *et al.*, 2001) [44]. In another trial, fingerlings (IBW 15.4±1.6 g) were offered diets with 40% crude protein derived from casein and gelatin, supplemented with graded lysine levels ranging from 40 to 65 g/kg protein. Growth improved up to 55-60 g/kg protein, with the requirement estimated at 57 g/kg dietary protein, corresponding to 22.9 g/kg diet (Fagbenro *et al.*, 2010) [12]. Growth depression beyond this level likely reflected dietary imbalance. Similarly, carcass amino acid analysis in larger catfish (IBW 122-134 g) indicated a lysine requirement of 44.9 g/kg protein. Based on available literature, the recommended lysine range for *H. fossilis* diets is approximately 20-23 g/kg diet.

Lipid and Fatty Acid Requirements

Lipids are a dense energy source and play indispensable roles in maintaining cell membranes, hormone synthesis, and metabolic regulation in fish. In *Heteropneustes fossilis*, dietary lipids are particularly important because they supply essential fatty acids (EFAs) that cannot be synthesized internally and must be obtained from feed. These EFAs are crucial for growth, reproduction, stress tolerance, and immune defense. Feeding experiments with Singhi fingerlings indicate that diets containing 7-11% lipid support maximum growth, efficient feed conversion, and nutrient retention (Anwar & Jafri, 1995) [7]. When lipid levels are too low, fish rely on protein for energy, reducing protein retention efficiency. Conversely, excessive lipid inclusion (>13%) leads to fat accumulation in tissues, reduced feed intake, and deterioration of carcass quality (Anwar & Jafri, 1995) [7]. Thus, maintaining lipid levels within the recommended range is essential for balancing energy metabolism and growth. Essential Fatty Acids (EFAs) Polyunsaturated fatty acids (PUFAs) such as linoleic acid (18:2 n-6) and arachidonic acid (20:4 n-6) are abundant in Singhi muscle and are vital for membrane fluidity, eicosanoid synthesis, and reproductive success (Paul *et al.*, 2016) [46]. Similarly, linolenic acid (18:3 n-3) and long-chain n-3 fatty acids like eicosapentaenoic acid (EPA, 20:5 n-3) and docosahexaenoic acid (DHA, 22:6 n-3) are essential for neural development, larval survival, and stress resistance (Tocher, 2010) [56]. Deficiency in these EFAs can result in poor growth, reproductive failure, fin erosion, and increased vulnerability to stress. Biochemical investigations reveal that lipid content in Singhi varies with age, sex, and season, reflecting its dynamic role in metabolism and reproduction (Rao and Sanjeevaiah, 2020) [49]. Muscle tissue generally

contains moderate lipid levels, while liver and gonads exhibit higher concentrations, indicating their importance in energy storage and reproductive physiology. Lipids also act as carriers for fat-soluble vitamins (A, D, E, and K), further emphasizing their nutritional significance. Sources of lipids fish oil, soybean oil, and linseed oil are commonly used lipid sources in Singhi diets. Fish oil provides long-chain n-3 fatty acids, while soybean and linseed oils supply linoleic and linolenic acids. Combining these oils ensures a balanced fatty acid profile that supports growth and reproductive performance. With sustainability concerns, plant-based oils are increasingly favoured, though their fatty acid composition must be carefully balanced to avoid deficiencies. Optimizing lipid and fatty acid nutrition is vital not only for growth but also for sustainability. Excess lipid inclusion raises feed costs and environmental waste, while inadequate lipid levels compromise fish health. Precision nutrition strategies, including targeted fatty acid supplementation and nutrigenomic approaches, are being explored to improve lipid utilization efficiency in Singhi culture (FAO, 2022) [13]. Sustainable feed formulations that combine plant oils with limited fish oil use can reduce dependence on marine resources while maintaining nutritional adequacy. Lipid and fatty acid nutrition in *Heteropneustes fossilis* is fundamental to growth, reproduction, and resilience. Dietary lipid levels of 7-11% are optimal, with EFAs such as linoleic acid, arachidonic acid, EPA, and DHA playing critical roles in physiological processes. Balanced lipid sources, combining fish oil and plant oils, are recommended to meet nutritional requirements while supporting sustainable aquaculture. Future research should focus on precision lipid nutrition, fatty acid metabolism, and alternative oil sources to enhance productivity and reduce environmental impacts.

Carbohydrates Utilization

Carbohydrates represent the most cost-effective energy source in aquaculture feeds, but their efficiency of use differs among fish species depending on digestive physiology and metabolic pathways. In omnivorous catfishes such as *Heteropneustes fossilis*, carbohydrates can serve as a supplementary energy source, though their utilization is less efficient compared to protein and lipid metabolism (NRC, 2011) [38]. Understanding the tolerance of Singhi to dietary carbohydrates is therefore essential for designing economical feeds that support growth while minimizing nutrient wastage. Feeding trials in catfishes suggest that carbohydrate inclusion of 20-25% in the diet is generally well tolerated, providing energy without impairing protein utilization (Ali & Jauncey, 2004) [6]. In Singhi, moderate carbohydrate levels allow protein to be spared for tissue synthesis rather than oxidized for energy. Diets with very low carbohydrate content force protein catabolism, reducing feed efficiency, while excessive carbohydrate (>30%) often results in poor digestibility, fat deposition, and reduced growth performance (NRC, 2011) [38]. The ability of Singhi to metabolize carbohydrates is linked to its enzymatic activity. Catfishes exhibit moderate levels of amylase and glucokinase, enabling partial digestion and assimilation of starches (Wilson, 1994) [63]. Complex carbohydrates such as gelatinized starch are more efficiently utilized than simple sugars, as they provide sustained energy release and reduce metabolic stress (Ali & Jauncey, 2004)

[6]. However, compared to herbivorous fishes, Singhi shows limited carbohydrate metabolism, consistent with its omnivorous feeding habits. Carbohydrates contribute to energy partitioning by sparing protein and lipid for growth and reproduction. At optimal levels, they reduce reliance on protein oxidation, thereby improving protein retention efficiency (Wilson, 1994) [63]. This is particularly important in Singhi culture, where protein is the most expensive dietary component. By supplying readily available energy, carbohydrates help balance feed costs and enhance growth performance. Common carbohydrate sources in Singhi diets include rice bran, wheat flour, maize starch, and tapioca. These ingredients are inexpensive and widely available, making them suitable for rural aquaculture systems. Processing methods such as gelatinization improve carbohydrate digestibility, while non-starch polysaccharides should be minimized to avoid anti-nutritional effects (Ali & Jauncey, 2004) [6]. Proper balancing of carbohydrate with protein and lipid ensures efficient nutrient utilization and stable growth. Carbohydrates provide an important, though limited, energy source for *Heteropneustes fossilis*. Dietary inclusion levels of 20-25% are optimal, supporting growth and protein sparing without causing metabolic stress. Complex carbohydrates are better utilized than simple sugars, and processing methods such as gelatinization improve digestibility. By optimizing carbohydrate utilization, feed costs can be reduced, protein efficiency improved, and environmental sustainability enhanced in Singhi aquaculture.

Vitamin Requirements

Vitamins must be supplied in the diet of the fish because they are either not synthesized or not synthesized fast enough to cover the fish needs (Geay & Kestemont, 2015) [6]. Vitamins, though required in small amounts, are indispensable for growth, reproduction, and metabolic regulation in fish. Unlike macronutrients, they do not provide energy directly but function as coenzymes and regulators of biochemical pathways. In catfish such as *Heteropneustes fossilis*, supplementation is necessary because natural feed ingredients rarely meet complete requirements; deficiencies can result in growth retardation, deformities, and increased disease susceptibility (NRC, 2011) [38].

Fat-Soluble Vitamins

Fat-soluble vitamins (A, D, E, and K) are stored in body tissues and perform essential physiological roles. Vitamin A supports vision, epithelial integrity, and reproduction, with deficiency causing poor growth, ocular lesions, and reduced fertility (Halver & Hardy, 2003) [17]. Vitamin D regulates calcium and phosphorus metabolism, ensuring skeletal development and mineralization; adequate levels are particularly important in Singhi, which thrives in hypoxic and ammonia-rich environments that stress bone metabolism (Prabhu *et al.*, 2016) [47]. Vitamin E functions as a potent antioxidant, protecting cell membranes from oxidative damage, and supplementation has been shown to improve survival, immunity, and stress resistance in catfishes (Hamre, 2011) [20]. Vitamin K is required for blood clotting and bone health, with deficiency leading to haemorrhages and skeletal deformities (NRC, 2011) [38].

Water-Soluble Vitamins

Water-soluble vitamins must be supplied continuously because they are not stored in significant amounts. Vitamin C (ascorbic acid) is vital for collagen synthesis, wound healing, and stress resistance; deficiency in catfishes causes skeletal deformities, poor healing, and reduced immunity (Lim & Lovell, 1978) ^[30]. The B-complex vitamins (thiamine, riboflavin, niacin, pyridoxine, folic acid, and cobalamin) are central to energy metabolism and enzyme activity. Thiamine deficiency results in anorexia and neurological disorders, riboflavin deficiency causes cataracts and poor growth, while niacin and pyridoxine are essential for amino acid metabolism, and folic acid supports haematopoiesis (Halver & Hardy, 2003) ^[17].

Deficiency and Toxicity

Vitamin imbalances manifest as growth retardation, reduced feed efficiency, and increased disease susceptibility. For instance, inadequate vitamin A or C leads to skeletal deformities, while lack of vitamin E results in oxidative stress and mortality (Hamre, 2011) ^[20]. Excess supplementation can also be harmful; hypervitaminosis A causes bone deformities, and excessive vitamin D leads to abnormal calcification (NRC, 2011) ^[38]. Thus, precise dietary formulation is critical to maintain optimal vitamin levels.

In Singhi culture, vitamins are usually supplied through premixes added to formulated feeds. Although natural

ingredients such as fishmeal and plant meals provide some vitamins, they are often insufficient or unstable during feed processing. Vitamin C, for example, is highly unstable and requires stabilized forms such as L-ascorbyl-2-monophosphate for effective supplementation (Lim & Lovell, 1978) ^[30]. Fat-soluble vitamins are better retained in dietary lipid fractions, whereas water-soluble vitamins must be supplied continuously. Optimizing vitamin nutrition in Singhi has both biological and economic benefits. Adequate supplementation enhances growth, survival, and disease resistance, reducing reliance on antibiotics and chemical treatments. Economically, balanced vitamin inclusion improves feed efficiency and minimizes production losses. Environmentally, healthier fish with optimal vitamin nutrition contribute to sustainable aquaculture by reducing waste and improving resilience under stressful culture conditions (FAO, 2022) ^[13]. Vitamins are indispensable for the nutritional health of *Heteropneustes fossilis*. Fat-soluble vitamins (A, D, E, and K) regulate growth, reproduction, antioxidant defense, and skeletal health, while water-soluble vitamins such as vitamin C and the B-complex are essential for collagen synthesis, energy metabolism, and immunity. Both deficiency and excess impair growth and survival, making precise supplementation essential. Sustainable aquaculture practices for Singhi must therefore incorporate balanced vitamin premixes to ensure productivity, resilience, and environmental sustainability.

Table 1: Vitamin requirements (mg/kg diet) of *Heteropneustes fossilis*.

Name	Quantity (mg/kg diet)
Niacin (vitB3)	25
Pyridoxine (vitB6)	2.4-6
Biotin (vit B7)	0.25
Vitamin C(AA)	60-82

Sources: Data is summarized and adapted from NRC, 2011 ^[38], Nutrient Requirements of Fish and Shrimp. The National Academies Press and Mai, K., Waagbø, R., Zhou, X.Q., Ai, Q.H., Feng, L., 2022b. Chapter3-Vitamins. in: Hardy, R.W., Kaushik, S.J. (Eds.), Fish Nutrition (Fourth Edition). Academic Press, pp.57 179.

Minerals

Mineral requirements of stinging catfish are poorly understood, though both macro- and microminerals are essential for growth, metabolism, and survival. The principal macro minerals include calcium, phosphorus, potassium, magnesium, and sodium, while key trace elements comprise iron, sulphur, chlorine, copper, manganese, iodine, chromium, zinc, fluorine, cobalt, selenium, and molybdenum (FAO, 2023) ^[14]. Among these, phosphorus is particularly important for bone mineralization, growth, and blood pH regulation (Schwarz, 1995; Nwanna *et al.*, 2009) ^[53, 41]. Its requirement depends on diet composition and the form in which it is supplied; for instance, phosphorus in plant ingredients occurs mainly as phytate, which requires phytase enzymes for improved digestibility (Olugbenga *et al.*, 2019; Schwarz, 1995) ^[43, 53]. Growth trials with catfish fingerlings (IBW 10.2 g) indicated an optimal dietary phosphorus range of 6.70-8.20 g/kg, with deficiency leading to poor specific growth rate (SGR) and excess supplementation reducing growth due to environmental pollution (Nwanna *et al.*, 2009) ^[41]. Phosphorus absorption is further influenced by dietary calcium, and both elements together constitute nearly 70% of the mineral content in fish. An optimal Ca:P ratio of 2:1.5 has been suggested for catfish fingerlings (IBW 7.6-7.7 g) to

maximize growth and mineral utilization (Nwanna & Oni, 2018) ^[42]. Zinc is the trace element found in highest concentration in fish tissues (Schwarz, 1995) ^[53]. It supports growth and antioxidant defense, with deficiency resulting in reduced growth rates. Supplementation with nano-zinc oxide at 20 mg/kg diet improved growth performance and antioxidant status in catfish (Mahboub *et al.*, 2020) ^[32]. Potassium also plays a vital role in acid-base balance, nerve function, and enzyme activity. In aquaponics systems, potassium concentrations around 5440 mg/L were recommended to enhance welfare and growth of stinging catfish (IBW 5.44 g), highlighting the need to balance mineral requirements for both fish and plants in integrated culture systems (Wenzel *et al.*, 2021) ^[62].

Conclusion

Heteropneustes fossilis (Singhi) stands out as a nutritionally valuable and highly resilient freshwater catfish with immense promise for aquaculture. Its ability to thrive under challenging environmental conditions, coupled with consumer preference for its protein-rich, low-fat flesh, makes it a species of both economic and nutritional importance. To fully harness its potential, a precise understanding of its dietary requirements including proteins,

essential amino acids, lipids, carbohydrates, vitamins, and minerals is crucial. Balanced feed formulations not only enhance growth, health, and reproductive performance but also reduce production costs and environmental impacts. By integrating sustainable feed resources, optimizing nutrient ratios, and applying modern approaches such as nutrigenomics and precision nutrition, Singhi culture can achieve improved productivity, disease resistance, and long-term sustainability. Ultimately, well-designed diets tailored to its nutritional needs will ensure that Singhi continues to play a vital role in strengthening aquaculture systems and food security.

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