https://doi.org/10.48047/AFJBS.6.12.2024.174-187

AFJBS African Journal of Biological Sciences
Journal homepage: http://www.afjbs.com
Research Paper Open Access

Taurine: A VitalNutrient in the Diet of Freshwater Fish Species

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Article History

Volume 6 Issue 12, 2024
Received: 25 May 2024
Accepted : 25 June 2024
doi:
10.48047/AFJBS.6.12.2024.174-187

ABSTRACT
The incorporation of taurine as a dietary supplement in fish nutrition yields a plethora of advantageous outcomes such as elevated survival rates, enhanced growth, optimized feed utilization, increased retention of proteins and energy, improved intermediary metabolic processes, enhanced antioxidant defence mechanism, reduced stress levels, enhanced disease resistance, superior muscle texture, and elevated reproduction. However, certain fish species have also shown adverse effects from dietary taurine supplementation.Numerous publications on this topic have emerged over the past years, yielding varying results particularly in freshwater fish species. It has been discovered that freshwater fish exhibit a greater capacity for endogenous taurine synthesis compared to marine fishes. However, the inclusion of taurine may be essential when utilizing plant-based ingredients in freshwater fish species. In light of these circumstances, it is paramount that a comprehensive review and critical analysis of the importance of taurine in aquaculture, particularly in nutrition, has to be conducted. Through an examination and discussion of existing studies on taurine in freshwater fish species, as well as taurine's utilization in aquaculture and aquafeeds, this review aims to enhance our understanding of taurine and its significance in the aquaculture field.
Keywords: Dietary, Growth, Taurine, Survival.

INTRODUCTION

Aquaculture is experiencing continuous expansion characterized by a gradual transition from traditional, inexpensive semi-intensive systems to more expensive intensive systems in which processed feed plays a significant role. Aquafeed accounts for a significant portion of operating costs in aquaculture. The cost of ingredients, processing, and transportation can contribute to high feed prices, thus impacting profitability for farmers. The challenge lies in finding cost-effective alternatives without compromising the nutritional requirements of the farmed species. Fishmeal is a widely used ingredient in aquafeed because ofhigh protein content and necessary amino acids. Nevertheless, the sustainability of aquafeed remains an issue because of the escalating demand for fishmeal, which precipitates overfishing and the consequent diminishment of aquatic resources.Finding sustainable alternatives to these ingredients that still provide essential nutrients is a key challenge for the industry. Plant proteins are getting increasing attention due to wider availability and cheaper price. However, poor phosphorus availability, and occurrence of antinutritional factors like trypsin inhibitorsand phytate limit the utilisation of feed that contain plant-based protein (Gatlin et al., 2007).Studies have indicated that substituting out a significant portion of fishmeal with proteins from plant source can be a viable option without compromising the growth and health of fish (Egerton et al., 2020). The optimal replacement level of fishmeal varies depending on the species of fish, their life stage, and the specific composition of the plant sources used.Incorporation of crystalline amino acids (CAAs) has been one of the strategies to fulfil the amino acid balance toovercome the problems faced by the addition of plant proteins in aquafeed formulations (Nunes et al., 2014). Furthermore, adding amino acids or particular combinations of amino acids can improve the nutritional content and palatability of plant-based diets (Chatzifotis et al., 2008).There is also growing interest in incorporating non-protein amino acids, such as taurine, into feed formulations due to their various beneficial roles.

Taurine has critical roles in many functions, such as antioxidant defence, and bile acid conjugation in fish (Huxtable, 1992; Han et al., 2014; Salze and Davis, 2015). Many fish species appear to be negatively impacted by taurine deficiencies in terms of development and feed utilisation (Salze and Davis 2015). It has been demonstrated that taurine has stress-reducing properties by regulating the stress hormones and neurotransmitters in the body (Mezzomo et al., 2019). Including taurine in aquafeed can help alleviate the negative effects of stress, promoting better performance and overall well-being. Supplementation of taurine in plant ingredient-based diets for fish is crucial to ensure optimal growth, health, and overall well-being of the fish. Taurine plays a critical and indispensable role in freshwater fishes. The advantageous impacts of taurine on mammals have been well investigated for numerous years (Huxtable 1992; Stapleton et al., 1997; Lourenco & Camilo 2002; Kuzmina et al., 2010). Marine fish like the European glass eel (*Anguilla anguilla*), European sea bass fry (*Dicentrarchuslabrax*), and gilthead sea bream fry (*Sparus aurata*) showed increased activity when fed with diets containing taurine compared to those without or with low taurine levels (Sola & Tosi 1993; Martinez et al., 2004; Chatzifotis et al., 2008). Similar effects of dietary taurine have been observed in certain freshwater fish such as pangasius (Peter et al., 2022) as well. In rainbow trout (Yamashita et al., 2006) and channel catfish (*Ictalurus punctatus*) (Rolen & Caprio, 2008), taurine were found to stimulate their gustatory systems more effectively.Earlier, scientists believed that freshwater fish species could synthesize taurine endogenously, obviating the need for dietary taurine. However, recent findings indicate that supplementation of taurine is necessary when plant proteins are utilized in their diet.There has been growing interest in the importance of taurine for fish, particularly in various freshwater fish species, prompting current investigations.

TAURINE BIOSYNTHESIS

Taurine is a sulphur containing amino acid. The main pathway for the synthesis of taurine is cysteinesulfinate-dependent pathway. Taurine is synthesized from methionine and cysteine in the liver of fish. The main pathway of taurine biosynthesis includes several steps of the oxidation process (Wang et al., 2016). Cysteine gets converted by cysteine dioxygenase (CDO) into cysteine sulfinic acid, which is then processed by cysteine sulfonate decarboxylase (CSD) into hypotaurine. Hypotaurine dehydrogenase then produces taurine (Hays et al., 2020). The rate-limiting step in taurine production is the CSD enzyme, while CDO regulates the cysteine concentration. CDO and CSD are the pivotal enzymes in biosynthesis process of taurine in the liver (Wang et al., 2016). Furthermore, a membrane transporter of taurine has a significant role for transport and recycling of taurine. The CSD activity is significantly higher in hepatocytes than in muscle, kidney, or enterocytes in mammals, thus this scenario is tissue-specific (Stipanuk et al., 2015). The CSD and CDO enzyme activities are influenced by the feed formulation, hormone levels, ontogenetic phases, and osmotic circumstances. Low or absence of CSD activity in liver could be a lack or low capacity of taurine synthesis in the juvenile stage of fish (Martins etal., 2018). Early research on fish found that the families Labridae, Scombridae, Soleidae, as well as the family Rajidae did not exhibit CSD activity (Bergeret and Chatagner, 1956) or cysteic acid decarboxylase (CAD) activity in Gadidae (Blaschko, 1942). Compared to herbivorous fish, carnivorous fish have a reduced ability for taurine biosynthesis.

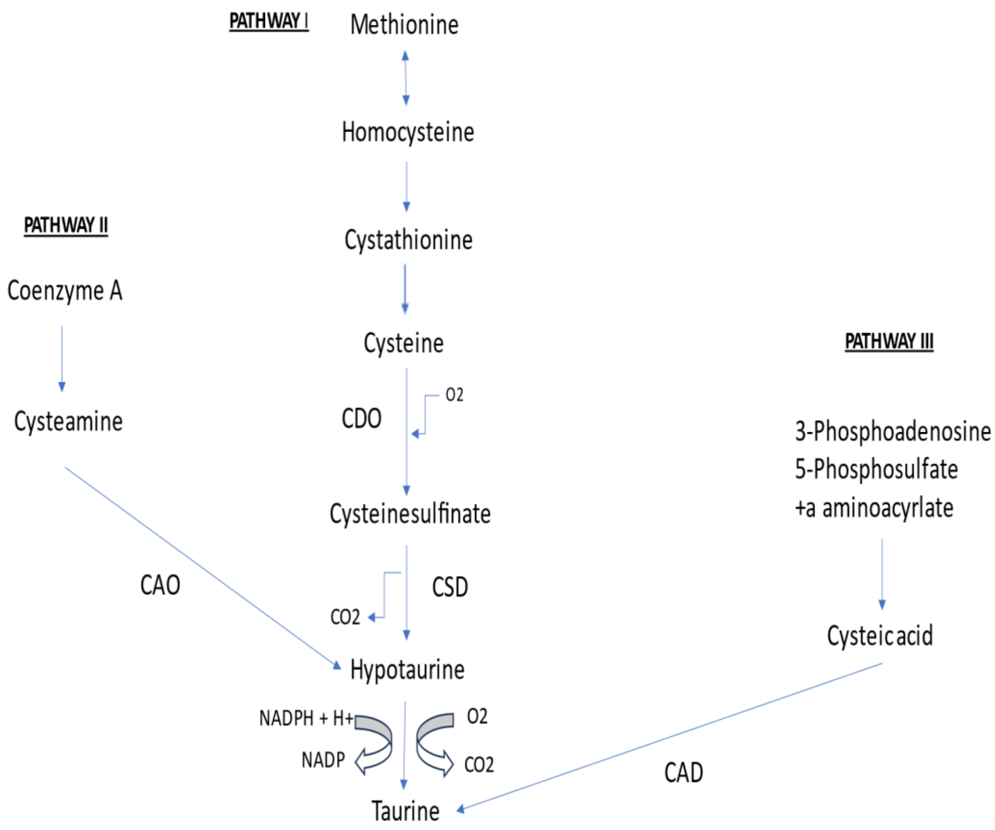

Figure 1: Biosynthesis pathway of taurine

REQUIREMENT OF TAURINE IN FRESH WATER FISH SPECIES

Recent studies indicated that freshwater fish may need exogenous taurine for adequate growth, feed consumption, digestion and assimilation, and other physiological activities(Abdel-Tawwab & Monier, 2018; Adeshina & Abdel-Tawwab, 2020; Li et al., 2016, Gonçalves et al., 2011, Gaylord et al.,2006). Taurine requirement depends on the size of fish, fish species, life stage, feed contents and culture environment. According to Gaylord et al., (2006, 2007), fish fed fishmeal-based diets (high in methionine and taurine) presentedno results with dietary taurine, but rainbow troutfed diets which are low in methionine and taurine needed 0.5% of taurine supplementation for better growth. A study conducted by Al Feky et al. (2016) in larval tilapia grown with soybean-based diets indicated that 9.7 g/ kg dietary taurine was needed for the optimum growth and the study shows that Nile tilapia lack the ability to biosynthesize taurine from methionine via CSD pathway at the larval stage. African catfish fed high plant-based dietsfound that taurine plays a crucial role as a limiting factor affecting growth, immunity, and antioxidant responses in the fish and the study suggests that taurine should be included in the African catfish diets at an optimal level of 20 g/kg diet to maximize the physiological outcomes (Adeshina & Abdel-Tawwab, 2020). For aquaculture and for future research, it is crucial to have current knowledge regarding the ideal dietary taurine levels.

Table I: Dietary Taurine requirement of fresh water fish species

Fish	**Life stage**	**Protein source**	**Tau requirement**	**Effects**	**Reference**
Black carp	Juvenile	SBM, CSM, SFM	0.1%	Growth, enzyme activity, antioxidant status	Zhang et al., (2018)
Channel catfish	Juvenile	SBM, CSM	0.2%	Growth, feed efficiency	Peterson and Li (2018)
Common carp	Larvae	SBM, CF, FM	1.5%	Growth, enzyme activity, antioxidant capacity (AOC), tolerance	Abdel-Tawwab and Monier (2018)
Grass carp	Juvenile	SBM, RSM, CSM	0.15%	Hypoxia-tolerance	Yang et al., (2013)
Hybrid snakehead	Juvenile	FM, SBM	1.5%	Survival, resist ammonia stress	Tan et al., (2018)
Largemouth bass	Juvenile	SBM, FM	NR	Growth, body composition	Frederick et al., (2016)
Nile tilapia	Juvenile	SBM, SPC	0.4%	Growth, metabolic response	Michelato et al., (2018)
	Juvenile	Casein, gelatin	1%	Growth, metabolism of amino acids/ lipids/energy	Shen et al., (2018)
	Larvae	SBM, FM	1%	Growth, feed efficiency	Al-Feky et al., (2016)
Rice field eel	Juvenile	FM, SBM, CGM	0.15%	Growth, lipase activity, total AOC, catalase, lysozyme, T-SOD	Hu et al., (2018)

Yellow catfish	Juvenile	SPC, SBM, CGM, WGM	1.09%	Growth, immunity, hyperammonemia	Li et al., (2016)
Zebrafish	Adult	PP, FM	NR	Growth, reproductive performance (not affected)	Guimaraes et al., (2018)
Beluga	Juvenile	FM, SBM,	1.23%	Growth, antioxidant activty	Slami et al.,(2021)
Snakehead fish	Juvenile	FM, SBM, PM	0.5%	Growth performance and feed utilization	Hongmanee et al.,(2022)
Sterlet	Juvenile	FM, SBM, WGM	3%	Growth performance, hepatic, digestive, and antioxidant enzyme	Bavi et al.,(2022)
Pangasius	Juvenile	Casein, Gelatin	1.5%	Growth, feed utilization and antioxidant enzyme	Peter et al.,(2022)

Abbreviations: SBM, Soyabean meal; CSM, Cotton seed meal; SFM, Steam fishmeal; CF, Corn flour; RSM, Rapeseed meal; SPC, Soy protein concentrate; CGM, Corn gluten meal; WGM, Wheat gluten meal; PP, Plant protein; PM, Poultry meal; NR, Not required.

Functions of taurine

Taurine is characterized by its distinctive attributes including low molecular mass, nitrogen composition, hydrophilic nature, and potential role as a stimulant for fish nutrition which is highly valued in aquaculture. Given that amino acids, in their general, function as effective attractants for promoting feeding in aquatic species, which increases growth in fish populations. (Carr, 1982). Taurine has now been reported to be an attractive feed stimulant by attracting olfactory system of rainbow trout (Hara et al., 1984). Growth depression is a highly noticeable and commonly observed symptom associated with taurine deficiency. Taurine deficiency often leads to lower feed and protein efficiencies, as documented in various studies (Aksnes et al., 2006b; Chatzifotis et al., 2008; Enterria et al., 2011). Insufficient levels of taurine can result in stunted growth and increased mortality rates. The fish fed with lessfishmeal feed showed lower growth rate because of the limited mineral availability. Taurine acts as an organic acid, which enhances the accessibility of minerals. Studies suggests that adding taurine to the diet can enhance the growth of fish fed with less fish meal diets (Hien et al., 2015; Wu et al., 2015; Koven et al., 2016) or diets consisting entirely of plant materials (Takagi et al. 2008). Taurine is involved in the conjugation of bile acids in the liver. Taurine conjugates with bile acids to form bile salts, which are then released into the intestines to aid in fat digestion and absorption. This process is crucial for maintaining healthy digestion and nutrient absorption (Bellentani et al., 1987). Taurine is implicated in

reducing haemolysis by affecting osmoregulation and stabilizing bio membranes in fish (Takagi et al., 2006a). Given its involvement in various biological functions, deficiencies or insufficient dietary levels of taurine have been associated with a spectrum of physiological issues and histological alterations.

Figure 2: Functions of taurine

Role of taurine on growth, digestion and nutrient utilization

Growth is a very important parameter for successful aquaculture. The effect of taurine on growth has been studied in several fish species such as carps (*Mylopharyngodonpiceus* and *CtenopharyngodonIdella)*, catfishes (*Clarias gariepinus* and *Pelteobagrusfulvidraco*), Nile tilapia (*Oreochromis niloticus*), and rainbow trout (*Oncorhynchus mykiss*). The requirement of taurine for growth has been establish within 0.1 to 1.5% of their diet (Zhang et al., 2018, Yan et al., 2019,Adeshina, I., & Abdel-Tawwab, M. 2020, Li et al., 2016, Biasato et al.,2022, Michelato et al., 2018). Decreased feed and protein efficiencies are typically seen due to taurine deficiency (Aksnes et al., 2006b; Chatzifotis et al., 2008; Enterria et al. 2011; Kim et al., 2007, 2005a; Matsunari et al., 2008b). In a study carried out by Widiastuti (2015), it was found that including taurine in the diet of gourami and tilapia juveniles resulted in significant enhancements in their overall growth parameters such as body weight, length, and width when compared to a group that was not given taurine. Another study by Abdel-Tawwab and Monier,(2018)in common carp fry noted that taurine inclusion improved the growth performance, nutrient utilisation and health of carp fry with an optimal level of 15 g/kg diet. The effects of adding taurine to the diet of *Acipenser ruthenus*, or sterlet, were investigated in a study by Bavi et al., (2022). The results revealed that higher levels of taurine supplementation had advantageous outcomes on the growth, nutrient utilisation, digestion antioxidant activity of sterlet. Additionally, a dosage of 30 g/kg of taurine in the diet led to enhanced growth performance. In a study carried out by Hien et al.,(2015) in juvenile snakehead, research has shown that soyabean meal can substitute 30% of fish meal without taurine addition and 40% of fish meal with taurine supplementation. In addition, Takagi et al., (2005) reported that growth of juvenile yellowtail fed with soyabean meal-based diets (58% soybean protein) was better by 3% taurine supplementation. Fish given soybean meal devoid of taurine addition resulted in poor growth performance, low feed conversion ratio, higher mortality and anaemia, and also greater incidence of green liver. According to the study, green liver syndrome might occur in fish that are fed soybean meal, possibly due to hindered bile pigments drainage from liver into bile, and haemolytic biliverdin overproduction associated with the deficiency of taurine in the diet. In another study conducted by Nguyen and team in 2015 in fingerling yellowtail with fermented soybean meal (fermented with Bacillus sp and Lactobacillus sp) with taurine. The study suggests that although taurine addition to soybean meal diet enhanced the absorption and digestion of lipids, it failed to improve the growth performance as compared with the fish meal fed fishes. For rainbow trout grown with vegetable protein (soy protein concentrate and rapeseed meal), 2.5 and 10 g/kg taurine supplementation levels seem to be efficient for growth, nutrient utilisation, body composition, and histomorphological features (Biasato et al. 2022).

Role of taurine on immune status and antioxidant activity

Antioxidants possess the scavenging capacity for free radicals that are formed within cells, thus preventing or reducing the damage caused by oxidation. Taurine has a significant role in antioxidant activity and anti-inflammation, primarily through its influence on liver and intestine-related genes and enzymes in fish (Coutinho et al., 2017). Taurine modulates the defence system against oxidation in various ways, such as inhibiting the activity of the enzymes that produce reactive oxygen species like Xanthine Oxidase and NADP oxidase, as well as maintaining the electron-transport chain's integrity in mitochondria (Surai et al., 2021). The NF-κB pathway greatly affects the regulation of immunological and inflammatory responses. At the location of inflammation, hydrogen peroxide undergoes conversion into hypochlorous acid (Agca et al., 2014). Taurine, however, transforms hypochlorous acid into taurine chloramine, which is less harmful. The plant-based protein in the feed may have a harmful influence on the antioxidant status of fish. When giving feed with plant-based protein, antioxidant capacity of fish seems to be decreased (Gan et al., 2017). Incorporation of taurine in a low-fish-meal diet increased the immune function and enhanced anti-stress ability in black carp, grass carp (Yan et al., 2019) and rice field eel (Hu et al., 2018). In rice field eels when fed with diets containing less fish meal, the actions of catalase, superoxide dismutase, and total anti-oxidative capacity dramatically improved with higher taurine levels in the diet (Hu et al., 2018). During an eight-week feeding experiment, black carp were fed a low-fish-meal diet containing 0, 0.05%, 0.1%, 0.2%, and 0.4% dietary taurine. As the amount of taurine progressed, the serum levels of superoxide dismutase and glutathione peroxidase likewise increased (Zhang et al., 2018). Similar findings were also reported in common carp (Abdel-Tawwab & Monier, 2018) when fed with 15 g/kgtaurine.

Role of taurine in lipid and glucose metabolism

Taurine is one of the important components in the process of breaking down fats through the action of bile acids. The liver produces bile acids, which are obtained from cholesterol, are accountable for the breakdown of lipids in the intestine, furthermore, the absorption of fat-soluble vitamins and the enhancement of dietary fats. Previous studies in mammals have shown that taurine stimulates the expression of cholesterol 7α-hydroxylase, an enzyme that is crucial for bile acid synthesis (Xu et al., 2020). The farnesoid X receptor activation may be involved in this process. Taurine also influences cholesterol metabolism by affecting the LDL receptor and lipoprotein modulation(Ebihara et al., 2006). Recent research suggests that the mitogen-activated protein kinase signalling pathways at the cellular level may greatly impact taurine's effects on bile acid and cholesterol metabolism (Xu et al., 2020). Soybean meal being the main ingredient for the replacement of fishmeal causes abnormalities in lipid metabolism as it lacks taurine. As stated by Li et al. (2016), juvenile yellow catfish fed all-plant protein diets experienced a significant decrease in triglycerides and cholesterol levels as dietary taurine levels increased up to 2.55%. The whole-body lipid content in black carp was considerably reduced when given 0.1% taurine in a low fishmeal diet (Zhang et al., 2018). Furthermore, lipase activity in black carp was significantly increased with taurine supplementation in diet with less fish meal (Zhang et al.,2018). Therefore, taurine plays significant roles in lipid metabolism in fish, such as bile acid synthesis, lipid emulsification, lipid digestion and absorption.

Taurine enhances the uptake of glucose and amino acids by cells in association with insulin or insulin-like compounds (Baliou et al., 2021). An increase in taurine levels may facilitate glycolysis and gluconeogenesis to meet the increased demands of fish body growth. Taurine influences glucose metabolism through two mechanisms: by impacting insulin secretion from β-cells and by interfering with the insulin signalling pathway and post-receptor events (De la Puerta et al., 2010). It works together with insulin or insulin-like molecules to enhance cellular absorption of amino acids and glucose. Taurine can bind specifically to insulin and exhibit insulin-like properties, thereby enhancing insulin signalling, controlling glycolysis, and activating glucose transporters. Taurine may promote glycogen production in the liver rather than in the muscle (Gomez et al., 2018). Its effects on increasing insulin secretion, enhancing insulin receptor sensitivity, disrupting the insulin signalling cascade, and activating hepatic glycogen deposition through glycogen synthase kinase (GSK) are primarily responsible for this. Dietary taurine supplementation increased the activity of intestinal amylase in common carp (Abdel-Tawwab and Monier, 2018) and black carp (Zhang et al., 2018).

Role of taurine in gut microbiota

Taurine has been demonstrated to have an impact on the intestinal environment (Qian et al., 2023). In recent years, there has been growing interest in the connection between taurine and gut microbes. Adding taurine to the diet of healthy mice has been found to change the intestinal microenvironment and impact its metabolism, leading to an increase in the production of short-chain fatty acids (Yu et al., 2016).A recent study described how adding taurine to the diet can shape the gut microbiota, promoting the growth of bacteria that utilize taurine and restructuring the microbiota's functionality (Stacy et al., 2021). These bacteria can metabolize taurine into ammonia, acetate, and sulfide, with sulfide specifically hindering the aerobic respiration of harmful bacteria. This process enhances the gut's ability to resist colonization by pathogens (Stacy et al., 2021). In a study conducted by Shi et al., (2022) in *Monopterus albus* demonstrated that supplementation of 5g/kg taurine can regulate the homeostasis of intestinal microbiota. In another study by Peng et al., 2019 in rice field eel indicated that a diet high in oxidized fish oil could disrupt the stability of the microbial community and lead to microbial dysfunctions. However, supplementing with taurine helped maintain intestinal microbiota balance and restored its proper function.

Role of taurine in reproduction

Only limited study has been carried out to evaluate the impacts of taurine supplementation in broodstock diet on the reproductive results of fish especially in freshwater fish species. The research conducted by Al Fekyet al., (2016) aimed to assess the impact of addition of taurine on the reproduction of tilapia broodstock that were fed diets primarily consisting of soybean meal. The findings from the quadratic regression analyses indicated that the peak spawning performance was observed at a dietary taurine level of 8 g/kg. Broodstock fed with 10 g/kg taurine produced eggs with significantly higher hatchability, quicker hatching and yolk-sac absorption times, and greater larval weight compared to other taurine levels. Moreover, the highest levels of egg protein, total amino acids, and taurine were detected at the 10 g/kg taurine level. These outcomes suggest that an ingestion of 8 g/kg taurine is essential for the optimal reproductive outcomes of tilapia broodstock. To date, no research has been undertaken to investigate the impact of taurine on the successful reproduction of freshwater fish species.

Conclusion

The taurine needs of different freshwater fish species vary between 0.1% and 3% of their diet, and this can be influenced by factors such as the levels of dietary methionine, the life stage and fish species, the criteria employed to determine the taurine requirement, and the composition of the base diet. Both insufficient and excessive amounts of taurine can impede fish growth, and the response of fishes to an increase in dietary taurine levels is not consistent. The incorporation of taurine may enhance the digestive enzyme, increase the digestibility of nutrients, improve the health and structure of the intestines, and maintain a balanced composition of microbiota. Collectively, these effects contribute to enhanced utilization of feed. However, there is a lack of research on taurine synthesis in freshwater fish species compared to marine fish species. Previous studies suggested that freshwater fish are capable ofendogenous taurine synthesis, but the supplementation of taurine is necessary when their diet includes plant proteins.

ACKNOWLEDGEMENT

The first author is thankful to Kerala State Council for Science, Technology and Environment, Sastra Bhavan, Pattom, Trivandram, Kerala, India for the KSCSTE Research Fellowship. The authors are also thankful to Department of Aquaculture and Centre of Excellence for Indigenous Fish Production and Aquatic Animal Health Management (CIFPAAH), Kerala University of Fisheries and Ocean Studies.

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