# The Function and Requirement of Methionine in Aquatic Animals


## Abstract

Finding a viable replacement for fishmeal in aquatic animal feeds has become urgently necessary due to fluctuating supply and pricing of fishmeal.

The aquafeed industry has made significant progress towards sustainability by using alternative ingredients more extensively.

Despite its achievements, the sector continues to face difficulties in maximising the growth and health of aquacultured animals fed terrestrial proteins because raw feedstuffs often lack some essential amino acids (EAAs) such as Methionine (Met).

The functions and applications of Met supplementation in aquafeeds are highlighted in this article. As a proteinogenic amino acid, Met offers a timely and vital solution for the major bottleneck of animal production because it enables low-fishmeal, fishmeal-free or low-protein feed formulation without adversely impacting feed intake, growth and health of animals while reducing production costs and environmental pollution.


Tran Thi Thanh Hien[1]
To Pham Thi Ha Van[2]

[1] College of Aquaculture and Fisheries, Can Tho University, Can Tho, Vietnam
[2] The Center for Aquaculture Technologies, Souris, Prince Edward Island, Canada

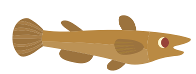
## Introduction

For decades, fish nutritionists have been focused on developing feed formulations that can promote the growth and health of farmed aquatic animals while controlling costs.

Much of this endeavor has largely been directed towards reducing dependency on marine ingredient sources. Fishmeal has historically been the favoured protein source due to its high protein content and well-balanced amino acid profile. However, due to the environmental and economic concerns associated with fishmeal production, it is necessary to use more alternative protein ingredients from terrestrial plants (e.g., soybean meal, canola meal, wheat gluten meal, etc) and rendered animal by-products (e.g., feather meal, poultry-by product meal, blood meal, etc).

Levels of crude protein/essential amino acids (EAAs) and digestibility are what ultimately determine a protein ingredient's nutritional value. However, the crude protein level is often lower in most alternative ingredients than in fishmeal, and even when the crude protein levels are comparable, plant-based protein sources commonly lack one or two EAAs such as lysine and methionine (Met).

There are two methods for increasing Met content in diets.1) increasing dietary inclusion levels of high-Met feedstuffs such as corn gluten meal (aka ingredient -based formulation), or 2) supplementing the diets wit synthetic methionine sources (aka nutrient-based formulation). The former approach may result in excessive level of dietary crude protein, which raises costs, amino acid imbalances and high nitrogen load-related water population. Whereas the latter approach is becoming more popular and widely practised because dietary Met requirements can be met by supplementing only a small amount of Met through using the least -cost principle. The principle enables feed formulators to produce functional and environmentally oriented aquafeeds.

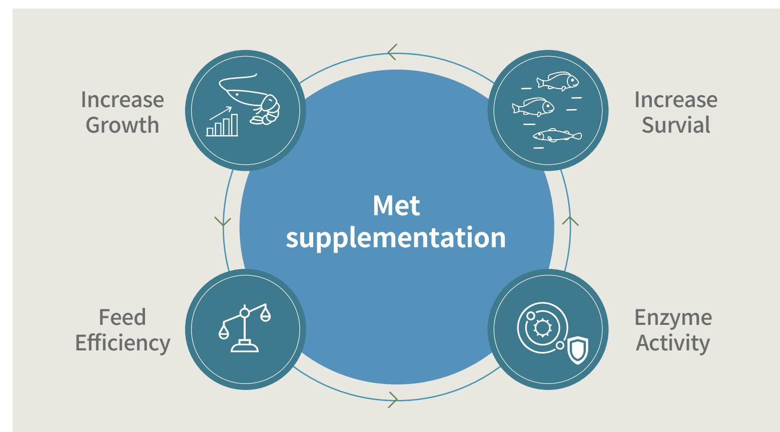


## Methionine and Function in Aquatic Animals

Methionine (Met) is a non-polar, sulfur-containing AA ($CH_3$-S-$CH_2$-$CH_2$-CH($NH_2$) -COOH) that was first isolated from casein in 1922 by Mueller (Vickery and Schmidt, 1931).

In 1928, Barger and Coyne defined its chemical formula as ι -methylthiol-α-aminobutyric acid in (Vickery and Schmidt, 1931). Despite its late discovery, Met has received a lot of interest because it serves as the initiating AA for nearly all eukaryotic protein synthesis (Brosnan et al., 2007; Sperandio et al., 2007), including fish, and the higher Met intake, the higher hepatic S-adenosyl-methionine (SAM) concentration (Espe et al., 2008). SAM donates a methyl group that is important for synthesis of essential biomolecules such as amino acids, phosphatidylcholine, polyamines, carnitine, epinephrine, melatonin and inorganic sulfates.

As intermediate products, homocysteine and cysteine are synthesized from Met via trans-sulfuration pathway. Cysteine can either be incorporated into glutathione or metabolised to taurine. Methionine itself, taurine, and glutathione are all recognised to have antioxidant and immune-enhancing properties in fish (Espe and Holen, 2013; Kuang et al., 2012; Lin et al., 2018).



# The Function and Requirement of Methionine in Aquatic Animals

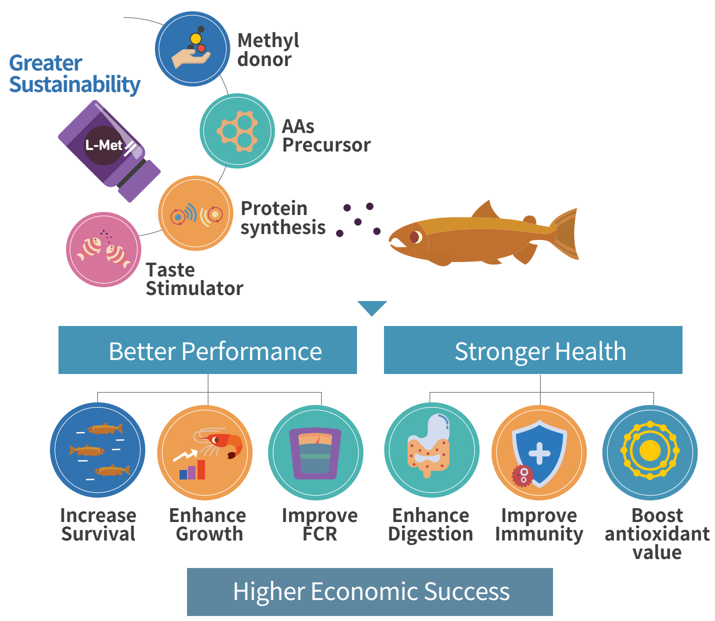
Dietary Met supplementation have been shown to improve growth and feed conversion ratio (FCR) in variety of aquatic species including snakehead, grouper, largemouth bass and cobia (Hien et al., 2018; Luo et al., 2005; Wang et al., 2021; Zhou et al., 2006). In shrimp, growing evidence suggests that Met-supplemented diets increase survival, growth, feed efficiency and enzyme activity in Pacific white shrimp (Façanha et al., 2016; Guo et al., 2020), black tiger shrimp (Richard et al., 2010) and kuruma shrimp (Michael et al., 2006). Met's role in crustacean is highlighted further by the de novo biosynthesis of phosphatidylcholine via SAM-dependent methylation of phosphatidylethanolamine. Phosphatidylcholine, a component of cell membranes, is an essential compound that supports molting process, growth, lipid digestibility, stress resistance and mortality reduction in shrimp (Coutteau et al., 2000; Zhang et al., 2019), crab (Wang et al., 2016), lobster (D'Abramo et al., 1981) along with fish (Geurden et al., 2008; Kasper and Brown, 2003). In mammalian cells, polyamines (spermidine, spermine, and putrescine) with well-defined functions are produced by catalysing the amino-propyl groups of dc-SAM (Pegg, 2016). Although there is not a lot of research on polyamines' effects on fish, studies on seabass and killifish have shown that they play a role in inducing intestinal maturation, regulating digestive enzymes and mediating ion osmoregulation (Guan et al., 2016; Péres et al., 1997; Tovar-Ramırez et al., 2004).

Similarly, the methyl group of SAM is used in the biosynthesis of other important compounds such as carnitine (fatty acid oxidation), epinephrine (neurotra-nsmitter and hormone) and melatonin (circadian rhythm regulator), all of which have well-documented functions in fish (Fang and Niu, 2022; Manki-ewicz et al., 2021; Sánchez-Vázquez et al., 2019). Together, Met occupies a central position in cellular metabolism, ensuring efficient conversion of variety of vital nutrients and bioactive substances. As expected, Met deficiency have been linked to depressed muscle protein turnover (Belghit et al., 2014), poor growth (Alam et al., 2000), low survival (Goff and Gatlin, 2004), cataracts (Poston, 1986) and intestinal health issues (Gao et al., 2019) in a wide range of aquatic species.

## Methionine Sources and Supplemental Met in Aquafeeds

Although fishmeal is a good protein ingredient with high digestible Met source, reducing reliance on this high-priced and non-renewable marine ingredient in feeds is critical to ensuring the aquaculture industry's sustainable and scalable growth. Several Met products, including L-methionine (L-Met), DL-methionine (DL-Met), DL-2-hydroxy-4-(methylthio) butanoic acid (DL-HMTBA) or DL-methionyl-DL-methionine (DL-Met-Met) have been used in aquafeeds. L-Met (99% purity) is a biologically active form of Met that is produced through fermentation process (Willke, 2014). Because carbon sources from fruits and vegetables are used as substrates in the fermen-tation process, it is an environmentally friendly method of producing Met (Gomes and Kumar, 2005). DL-Met (99% purity) is a pure powder product

Figure 1. The benefits of Methionine supplemented feed




with a 50:50 mixture of D- and L-isomers (Shen et al., 2015).
Liquid or calcium salt DL-HMTBA has 88% or 84% active substances, respectively (Boebel and Baker, 1982; Opapeju et al., 2012). Dipeptide DL-Met-Met (97% purity) is a new source of Met that have been recently introduced in aquafeed (Santos et al., 2018). Once absorbed, the active form L-Met can be directly used for metabolic processes, whereas D-Met or DL-MHA must be converted into L-Met, which requires several enzymes: D-amino acid oxidase (D-AAOX) is needed for D-Met, while D-2 hydroxy acid dehydrogenase (D-HADH) and L-2 hydroxy acid oxidase (L-HAOX) are needed for D-and L-MHA, respectively. That could explain the differences in bio-efficacy between Met products. In rainbow trout and sunshine bass, L-Met produced fastest growth, followed by DL-Met and DL-MHA (Keembiyehetty and Gatlin, 1997; Poston, 1986).

In terrestrial meal-based or low protein formulation, fortifying proteins with only a small amount of synthetic Met provides a unique opportunity to reduce feed costs without compromising animal growth and health. Webster et al. (1995) showed that a 35% protein diet formulated with soybean meal and 0.9% L-Met supplementation could completely replace fishmeal without adversely affecting weight gain, FCR or body composition of blue catfish (~8.9 g). Similarly, stinging catfish fry fed fishmeal-free enriched with 1.5% L-Met displayed normal growth, feed utilization, blood parameters and gut morphology (Billah et al., 2022). Successfully total or partial replacement of fishmeal with terrestrial-based diets augmented with Met have been also well reported in other species such as tilapia (El-Saidy and Gaber, 2003), flounder (Alam et al., 2011) and shrimp (Xie et al., 2018). According to "barrel theory", the nutrient that is most limiting determines the maximal yield that can be achieved. Animals require amino acids, which are protein building blocks, rather than protein itself. Lay and colleagues (Nguyen et al., 2020) demonstrated that by introducing a well-balanced blend of EAAs (methionine, lysine, tryptophan, histidine and valine) into the diet of Nile tilapia (~12.7 g), dietary protein levels could be reduced from 32.0 to 27.2% without compromising growth, survival, or FCR.

# The Function and Requirement of Methionine in Aquatic Animals

## Methionine Requirements in Aquatic Animals

Fish and crustaceans are unable to synthesize Met de nova and must depend solely on dietary Met intake. Estimating quantitative nutrient requirement involves fitting responses (e.g., growth parameters, feed utilization, nutrient retention, digestive or antioxidant indices) to graded levels of dietary nutrient of interest using linear or non-linear regression statical models. The dietary requirement of Met has been quantified for numerous fish species, ranging from 0.5-1.7% based on optimal growth and FCR: sea bream 1.71% (Zhou et al., 2011), Japanese flounder 1.49% (Alam et al., 2000), yellow croaker 1.44% (Mai et al., 2006), grouper 1.31% (Luo et al., 2005), cobia 1.19% (Zhou et al., 2006), snakehead 1.19% (Hien et al., 2018), striped catfish 1.01% (Hien et al., 2014), red drum 0.94% (Moon and Gatlin, 1991), gibel carp 0.71% (Ren et al., 2017) and tilapia 0.49% (Nguyen and Davis, 2009). The variation for Met requirement among studies could be attributed to discrepancy in fish species, life stage, Met source and the presence of cystine, a nonessential sulfur-containing amino. In these cited studies, dietary cystine ranged from 0.06-0.67%, while cystine could spare 40-60% Met in meeting the requirement for total sulfur amino acids (Goff and Gatlin, 2004; Harding et al., 1977; Moon and Gatlin, 1991). In grass carp fry (~0.36 g), dietary L-Met supplementation at higher inclusion levels (0.71-1.20%) improved intestinal digestion (e.g., increased trypsin activity and up-regulated mRNA levels of amylase, chymotrypsin, and alkaline phosphatase) and oxidant status (e.g., increased glutathione and catalase activities) (Liang et al., 2022).
The additional benefits of adequate Met supplementation on immune responses and survival were more pronounced when fish were challenged with pathogens. For example, Kuang et al. (2012) found that Jian carp (~8.2 g) fed diets containing 0.58-0.88% DL-MHA significantly increased immune response-related parameters (e.g., lysozyme, immunoglobin, acid phosphatase and leukocyte phagocytic activity). Importantly, fish fed MHA had ~10% better survival compared to fish fed non-supplemented feeds after 17 days of A. hydrophila challenge. Similarly, gras carp (~ 259.7 g) fed diets supplemented with 0.64% of either DL-MHA or DL-Met had about 30% reduction in gill-rot morbidity compared to control fish (Wu et al., 2018).
Assessing the effects of Met in shrimp is somewhat difficult because of their eating habits. The slow feeding rate and bottom-feeding nature of shrimp are conductive to nutrients leaching and only a portion of dietary Met being consumed. Attempts to increase stability of crystalline Met in diets, such as the use of coated Met or novel Met-Met, have been promising (Chi et al., 2011; Niu et al., 2018).

The dietary Met requirement have been established at 1.3% for kuruma shrimp (Teshima et al., 2002), 0.96% for Atlantic ditch shrimp (Palma et al., 2015) and 0.89% for black tiger shrimp (Millamena et al., 1996) based on whole-body Met and weight gain. In Pacific white shrimp, Façanha et al. (2016) found that the best growth and FCR performance were obtained in diets containing 0.72-0.81% Met for stocking density up to 75 shrimp/m2 with access to natural food sources. Wang and co-author (2019) proposed a slightly higher Met requirement (0.87% of diet) for white shrimp reared in flow through water without natural food enrichment. With growing interest in intensive and super intensive farming in low salinity water using recirculating system, higher dietary Met would be expected, necessitating further research in the future.

# The Function and Requirement of Methionine in Aquatic Animals

Table 1. Methionine requirement in aquatic species

| Species | IBW | Diet CP (%) | Estimated Met requirement (% diet) | Response variable | Model | Met source | Reference |
|---|---|---|---|---|---|---|---|
| Black seabream (*Sparus macrocephalus*) | 14.2 | 38 | 1.71-1.72 | SGR, PPV | Broken-line regression | L-Met | Zhou et al., 2011 |
| Japanese flounder (*Paralichthys olivaceus*) | 2.8 | 50 | 1.44-1.49 | FE, WG | Broken-line regression | L-Met | Alam et al., 2000 |
| Yellow croaker (*Pseudosciaena crocea*) | 1.2 | 43 | 1.39-1.44 | SGR, FE | Second-order polynomial regression | L-Met | Mai et al., 2006 |
| Grouper (*Epinephelus coioides*) | 13.2 | 48 | 1.31 | WG | Broken-line regression | L-Met | Lou et al., 2005 |
| Cobia (*Tachycentron canadum*) | 11.6 | 44 | 1.19 | SGR | Second-order polynomial regression | L-Met | Zhou et al., 2006 |
| Snakehead (*Channa striata*) | 2.4 | 42 | 1.19 | DWG | Broken-line regression | L-Met | Hien et al., 2018 |
| Striped catfish (*Pangasianodin hypophthalmus*) | 3.3 | 38 | 1.01 | SGR | Broken-line regression | L-Met | Hien et al., 2014 |
| Red drum (*Sciaenops acellatus*) | 22.6 | 35 | 0.94 | WG, FE | Broken-line analysis | L-Met | Moon and Gatlin, 1991 |
| Givel carp (*Carassius auratus gibelio*) | 6.7 | 36 | 0.71 | SGR, FCR | Broken-line regression | L-Met | Ren et al., 2017 |
| Nile tilapia (*Oreochromis niloticus*) | 5.6 | 28 | 0.49 | WG | Broken-line regression | L-Met | Nguyen and Davis, 2009 |
| Kuruma shrimp (*Marsupenaeus japonicus*) | 0.79 | 50 | 1.30 | WBM | ANOVA | | Teshima et al., 2002 |
| Atlantic ditch shrimp (*Palaemonetes varians*) | 0.017 | 45 | 0.96 | WG | Broken-line regression | DL-Met | Palma et al., 2015 |
| Black tiger shrimp (*Litopenaeus vannamei*) | 0.021 | 37 | 0.89 | WG | Broken-line regression | | Millamena et al.,1996 |
| Pacific white shrimp (*Litopenaeus vannamei*) | 1.97<br>0.98 | 36<br>39 | 0.72-0.81<br>0.87 | WGR, FCR<br>WG | ANOVA<br>Broken-line regression | DL-Met<br>Met-Met | Façanha et al., 2016<br>Wang et al., 2019 |

- IBW : initial body weight
- CP : crude proteun
- SGR : specific growth rate
- WG : weigh gain
- DWG : daily weight gain
- WGR : weekly growth rate
- PPV :protein productive value
- FE : feed efficiency
- FCR : feed conversion ratio
- WBM : whole body Met

## Conclusion

Methionine is a nutritionally EAA that donates a methyl group for numerous cellular metabolism activities, ensuring normal growth and physiological functions, but it is frequently lacking in terrestrial-protein ingredients. Dietary Met requirements ranged from 0.5-1.7% for optimal growth and health in fish and shrimp, which could be supplemented with L-Met, DL-Met, DL-MHA, or DL-Met-Met. L-Met is a biologically active form of Met that animals are likely to prefer. It can be concluded that Met is a keystone proteinogenic amino acid that can alleviate a major bottleneck in sustainable aquaculture production by enabling the rapid, cost-effective, and resourceful production of animal proteins.

## References


- Alam, M.S., Teshima, S.I., Ishikawa, M., Koshio, S., 2000. Methionie requirement of juvenile Japanese flounder Paralichthys olivaceus. J. World Aquac. Soc. 31, 618–626.
- Alam, M.S., Watanabe, W.O., Myers, A.R., Rezek, T.C., Carroll, P.M., Longfellow, S., 2011. Effects of replacement of menhaden fish meal protein by solvent-extracted soybean meal protein supplemented with or without L-Methionine and L-Lysine in the diet of juvenile southern flounder. N. Am. J. Aquac. 73, 350–359.
- Belghit, I., Skiba-Cassy, S., Geurden, I., Dias, K., Surget, A., Kaushik, S., Panserat, S., Seiliez, I., 2014. Dietary methionine availability affects the main factors involved in muscle protein turnover in rainbow trout (Oncorhynchus mykiss). Br. J. Nutr. 112, 493–503.
- Billah, S.M., Sumi, K.R., Howlader, S., Sarkar, S., Ferdous, Z., Islam, S.M.M., Shahjahan, M., 2022. Effects of supplemental L‐methionine for total replacement of fish meal by soybean meal on growth, feed utilisation and health status of stinging catfish, Heteropneustes fossilis fry. Aquac. Fish Fish. 2, 355–363.
- Boebel, K.P., Baker, D.H., 1982. Efficacy of the calcium salt and free acid forms of methionine hydroxy analog for chicks. Poult. Sci. 61, 1167–1175.
- Brosnan, J.T., Brosnan, M.E., Bertolo, R.F., Brunton, J.A., 2007. Methionine: a metabolically unique amino acid. Livest. Sci. 112, 2–7.
- Chi, S.Y., Tan, B.P., Lin, H.Z., Mai, K.S., Ai, Q.H., Wang, X.J., Zhang, W.B., Xu, W., Liufu, Z.G., 2011. Effects of supplementation of crystalline or coated methionine on growth performance and feed utilization of the pacific white shrimp, Litopenaeus vannamei. Aquac. Nutr. 17, e1–e9.
- Coutteau, P., Kontara, E.K.M., Sorgeloos, P., 2000. Comparison of phosphatidylcholine purified from soybean and marine fish roe in the diet of postlarval Penaeus vannamei boone. Aquaculture 181, 331–345.
- D'Abramo, L.R., Bordner, C.E., Conklin, D.E., Baum, N.A., 1981. Essentiality of dietary phosphatidylcholine for the survival of juvenile lobsters. J. Nutr. 111, 425–431.
- El-Saidy, D.M.S.D., Gaber, M.M.A., 2003. Replacement of fish meal with a mixture of different plant protein sources in juvenile Nile tilapia, Oreochromis niloticus (L.) diets. Aquac. Res. 34, 1119–1127.
- Espe, M., Hevrøy, E.M., Liaset, B., Lemme, A., El-Mowafi, A., 2008. Methionin intake affect hepatic sulphur metabolism in Atlantic salmon, Salmo salar. Aquaculture 274, 132–141.
- Espe, M., Holen, E., 2013. Taurine attenuates apoptosis in primary liver cells solated from Atlantic salmon (Salmo salar). Br. J. Nutr. 110, 20–28.
- Façanha, F.N., Oliveira-neto, A.R., Figueiredo-silva, C., Nunes, A.J.P., 2016. Effect of shrimp stocking density and graded levels of dietary methionine over the growth performance of Litopenaeus vannamei reared in a green-water system. Aquaculture 463, 16–21.
- Fang, H.H., Niu, J., 2022. Dietary supplementation of L-carnitine relieved detrimental impacts of a high-fat diet in juvenile Trachinotus ovatus. Aquac. Reports 24, 101139.
- Gao, Z., Wang, X., Tan, C., Zhou, H., Mai, K., He, G., 2019. Effect of dietary methionine levels on growth performance, amino acid metabolism and intestinal homeostasis in turbot (Scophthalmus maximus L.). Aquaculture 498, 335–342.
- Geurden, I., Kaushik, S., Corraze, G., 2008. Dietary phosphatidylcholine affects postprandial plasma levels and digestibility of lipid in common carp (Cyprinus carpio). Br. J. Nutr. 100, 512–517.
- Goff, J.B., Gatlin, D.M., 2004. Evaluation of different sulfur amino acid compounds in the diet of red drum, Sciaenops ocellatus, and sparing value of cystine for methionine. Aquaculture 241, 465–477.
Gomes, J., Kumar, D., 2005. Production of L-methionine by submerged fermentation: A review. Enzyme Microb. Technol. 37, 3–18.
- Guan, Y., Zhang, G. xia, Zhang, S., Domangue, B., Galvez, F., 2016. The potential role of polyamines in gill epithelial remodeling during extreme hypoosmotic challenges in the Gulf killifish, Fundulus grandis. Comp. Biochem. Physiol. Part - B Biochem. Mol. Biol. 194, 39–50.
- Guo, J., Zhou, W., Liu, S., Zhang, W., Mai, K., 2020. Efficacy of crystalline methionine and microencapsulation methionine in diets for Pacific white shrimp Litopenaeus vannamei. Aquac. Res. 51, 4206–4214.
- Harding, D.E., Allen, O.W., Wilson, R.P., 1977. Sulfur amino acid requirement of channel catfish: L-methionine and L-cystine. J. Nutr. 107, 2031–2035.
- Hien, T.T.T., Duyen, N.T.C., Tu, T.L.C., Khanh, N. Van, Phu, T.M., 2018. Dietary methionine and lysine requirement of snakehead (Channa striata) fingerlings. Int. J. Sci. Res. Publ. 8, 795–805.
- Hien, T.T.T., Thuy, T.T.T., Trung, N.H.D., Tu, T.L.C., 2014. Dietary Methionine Requirement of Stripped Catfish (Pangasianodon hypophthalmus) fingerlings. Can Tho Univ. J. Sci. 302–309.
- Kasper, C.S., Brown, P.B., 2003. Growth Improved in Juvenile Nile Tilapia Fed Phosphatidylcholine. N. Am. J. Aquac. 65, 39–43.
- Keembiyehetty, C.N., Gatlin, D.M., 1997. Performance of Sunshine Bass Fed Soybean-Meal-Based Diets Supplemented with Different Methionine Compounds. Progress. Fish-Culturist 59, 25–30.
- Kuang, S.Y., Xiao, W.W., Feng, L., Liu, Y., Jiang, J., Jiang, W.D., Hu, K., Li, S.H., Tang, L., Zhou, X.., 2012. Effects of graded levels of dietary methionine hydroxy analogue on immune response and antioxidant status of immune organs in juvenile Jian carp (Cyprinus carpio var. Jian). Fish Shellfish Immunol. 32, 629–636.
- Liang, H., Ji, K., Ge, X., Zhu, J., Ren, M., Mi, H., 2022. Methionine played a positive role in improving the intestinal digestion capacity, anti-inflammatory reaction and oxidation resistance of grass carp, Ctenopharyngodon idella, fry. Fish Shellfish Immunol. 128, 389–397.
- Lin, Y., Miao, L., Pan, W., Huang, X., Dengu, J.M., Zhang, W., Ge, X., Liu, B., Ren, M., Zhou, Q., Xie, J., Pan, L., Xi, B., 2018. Effect of nitrite exposure on the antioxidant enzymes and glutathione system in the liver of bighead carp, Aristichthys nobilis. Fish Shellfish Immunol. 76, 126–132.
- Luo, Z., Liu, Y., Mai, K., Tian, L., Yang, H., 2005. Dietary l-methionine requirement of juvenile grouper Epinephelus coioides at a constant dietary cystine level. Aquaculture 249, 409–418.
- Mai, K., Wan, J., Ai, Q., Xu, W., Liufu, Z., Zhang, L., Zhang, C., Li, H., 2006. Dietary methionine requirement of large yellow croaker, Pseudosciaena crocea R. Aquaculture 253, 564–572.

## References

·Mankiewicz, J.L., Deck, C.A., Taylor, J.D., Douros, J.D., Borski, R.J., 2021. Epinephrine and glucose regulation of leptin synthesis and secretion in a teleost fish, the tilapia (Oreochromis mossambicus). Gen. Comp. Endocrinol. 302, 113669.

·Michael, F.R., Koshio, S., Teshima, S. ichi, Ishikawa, M., Uyan, O., 2006. Effect of choline and methionine as methyl group donors on juvenile kuruma shrimp, Marsupenaeus japonicus Bate. Aquaculture 258, 521–528.

·Millamena, O.., Bautista-Teruel, M.., Kanazawa, A., 1996. Methionine requirement of juvenile tiger shrimp Penaeus monodon Fabricius. Aquaculture 143, 403–410.

·Moon, H.Y., Gatlin, D.M., 1991. Total sulfur amino acid requirement of juvenile red drum, Sciaenops ocellatus. Aquaculture 95, 97–106.

·Nguyen, L., Dinh, H., Davis, D.A., 2020. Efficacy of reduced protein diets and the effects of indispensable amino acid supplements for Nile tilapia Oreochromis niloticus. Anim. Feed Sci. Technol. 268, 114593.

·Nguyen, T.N., Davis, D.A., 2009. Methionine requirement in practical diets of Juvenile Nile Tilapia, oreochromis niloticus. J. World Aquac. Soc. 40, 410–416.

·Niu, J., Lemme, A., He, J.Y., Li, H.Y., Xie, S.W., Liu, Y.J., Yang, H.J., Figueiredo-Silva, C., Tian, L.X., 2018. Assessing the bioavailability of the Novel Met-Met product (AQUAVI® Met-Met) compared to DL-methionine (DL-Met) in white shrimp (Litopenaeus vannamei). Aquaculture 484, 322–332.

·Opapeju, F.O., Htoo, J.K., Dapoza, C., Nyachoti, C.M., 2012. Bioavailability of methionine hydroxy analog-calcium salt relative to dl-methionine to support nitrogen retention and growth in starter pigs. Animal 6, 1750–1756.

·Palma, J., Andrade, J.P., Lemme, A., Bureau, D.P., 2015. Quantitative dietary requirement of juvenile Atlantic ditch shrimp Palaemonetes varians for lysine, methionine and arginine. Aquac. Res. 46, 1822–1830.

·Pegg, A.E., 2016. Functions of polyamines in mammals. J. Biol. Chem. 291, 14904–14912.

·Péres, A., Cahu, C.L., Infante, J.L.Z., 1997. Dietary spermine supplementation induces intestinal maturation in sea bass (Dicentrarchus labrax) larvae. Fish Physiol. Biochem. 16, 479–485.

·Poston, H.A., 1986. Response of rainbow trout to source and dietary methionine. Comp. Biochem. Physiol. 83, 739–744.

·Ren, M., Liang, H., He, J., Masagounder, K., Yue, Y., Yang, H., Ge, X., Xie, J., Xi, B., 2017. Effects of DL-methionine supplementation on the success of fish meal replacement by plant proteins in practical diets for juvenile gibel carp (Carassius auratus gibelio). Aquac. Nutr. 23, 934–941.

·Richard, L., Blanc, P.P., Rigolet, V., Kaushik, S.J., Geurden, I., 2010. Maintenance and growth requirements for nitrogen, lysine and methionine and their utilisation efficiencies in juvenile black tiger shrimp, Penaeus monodon, using a factorial approach. Br. J. Nutr. 103, 984–995.

·Sánchez-Vázquez, F.J., López-Olmeda, J.F., Vera, L.M., Migaud, H., López-Patiño, M.A., Míguez, J.M., 2019. Environmental cycles, melatonin, and circadian control of stress response in fish. Front. Endocrinol. (Lausanne). 10, 279.

·Santos, L.S., Htoo, J.K., Fracaroli, C., Silva, W.C., Gobi, J.P., Veira, A.M., Barbosa, N.A.A., Hauschild, L., 2018. Bioavailability of di-peptide DL-methionyl-DL-methionine in comparison to DL-methionine in weaned and growing pigs. Anim. Feed Sci. Technol. 241, 94–101.

·Shen, Y.B., Ferket, P., Park, I., Malheiros, R.D., Kim, S.W., 2015. Effects of feed grade L-methionine on intestinal redox status, intestinal development, and growth performance of young chickens compared with conventional DL-methionine. J. Anim. Sci. 93, 2977–2986.

·Sperandio, B., Gautier, C., McGovern, S., Ehrlich, D.S., Renault, P., Martin-Verstraete, I., Guédon, E., 2007. Control of methionine synthesis and uptake by MetR and homocysteine in Streptococcus mutans. J. Bacteriol. 189, 7032–7044.

·Teshima, S., Alam, M.., Koshio, S., Ishikawa, M., Kanazawa, A., 2002. Assessment of requirement values for essential amino acids in the prawn, Marsupenaeus japonicus (Bate). Aquac. Res. 33, 297–304.

·Tovar-Ramırez, D., Infante, J., Cahu, C., Vázquez-Juárez, R., 2004. Influence of dietary live yeast on European sea bass (Dicentrarchus labrax) larval development. Aquaculture 234, 415–427.

·Vickery, H.B., Schmidt, C.L.A., 1931. The history of the discovery of the amino acids. Chem. Rev. 9, 169–318.

·Wang, J.T., Han, T., Li, X.Y., Hu, S.X., Jiang, Y.D., Wang, C.L., 2016. Effects of dietary phosphatidylcholine (PC) levels on the growth, molt performance and fatty acid composition of juvenile swimming crab, Portunus trituberculatus. Anim. Feed Sci.Technol. 216, 225–233.

·Wang, L., Ye, L., Hua, Y., Zhang, G., Li, Y., Zhang, J., He, J., Liu, M., Shao, Q., 2019. Effects of dietary dl-methionyl-dl-methionine (Met-Met) on growth performance, body composition and haematological parameters of white shrimp (Litopenaeus vannamei) fed with plant protein–based diets. Aquac. Res. 50, 1718–1730.

·Wang, W., Yang, P., He, C., Chi, S., Li, S., Mai, K., 2021. Effects of dietary methionine on growth performance and metabolism through modulating nutrient-related pathways in largemouth bass (Micropterus salmoides ). Aquac. Reports 20, 100642.

·Webster, C.D., Goodgame‐Tiu, L.S., Tidwell, J.H., 1995. Total replacement of fish meal by soy bean meal, with various percentages of supplemental L‐methionine, in diets for blue catfish, Ictalurus furcatus (Lesueur). Aquac. Res. 26, 299–306.

·Willke, T., 2014. Methionine production a critical review. Appl. Microbiol. Biotechnol. 98, 9893–9914.

·Wu, P., Pan, F.Y., Feng, L., Jiang, W.D., Jiang, J., Kuang, S.Y., Tang, L., Tang, W.N., Zhang, Y.A., Zhou, X.Q., Liu, Y., 2018. Methionine hydroxy analogue supplementation modulates gill immunological and barrier health status of grass carp(Ctenopharyngodon idella). Fish Shellfish Immunol. 74, 637–648.

·Xie, J.J., Lemme, A., He, J.Y., Yin, P., Figueiredo-Silva, C., Liu, Y.J., Xie, S.W., Niu, J., Tian, L.X., 2018. Fishmeal levels can be successfully reduced in white shrimp (Litopenaeus vannamei) if supplemented with DL-Methionine (DL-Met) or DL-Methionyl-DL-Methionine (Met-Met). Aquac. Nutr. 24, 1144–1152.

·Zhang, W., Wang, F., Tan, B., Dong, X., Zhang, H., Chi, S., Liu, H., Zhang, S., Yang, Q., 2019. Effect of the dietary phosphatidylcholine at different growth stages of Pacific white shrimps, Litopenaeus vannamei. Aquac. Nutr. 25, 555–566.

·Zhou, F., Xiao, J.X., Hua, Y., Ngandzali, B.O., Shao, Q.J., 2011. Dietary L-methionine requirement of juvenile black sea bream (Sparus macrocephalus) at a constant dietary cystine level. Aquac. Nutr. 17, 469–481.

·Zhou, Q., Wu, Z., Tan, B., Chi, S., Yang, Q., 2006. Optimal dietary methionine requirement for Juvenile Cobia (Rachycentron canadum). Aquaculture 258, 551–557.