FORMULATING SUSTAINABLE FEEDS: UNDERSTANDING NUTRIENT AND ENERGY REQUIREMENTS IN FINFISH AQUACULTURE

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ABSTRACT

Fish foods are known for their long standing health benefits to humans.Feed qualityenhancement provides an opportunity to improve sustainable aquaculture productions contributing to matchable fish demandsand consequent consumer gain.Preparation of balanced, cost effective feed based on the nutrition and health needs of fish is thus an essential precondition. Forcost-compliant production, diets must be formulated based on accurate apportionment of essential nutrients and energy gains according tofundamental needs of the species. Present study describes dietary requirements of finfish in terms of proteins, amino acids, lipids, constituent fatty acids, carbohydrates, and energy. The work also evaluates importance of feed processing in improvingdietary parameters for sustainable quality aquaculture productions.

KEYWORDS: *Aquafeeds, Protein, Finfish, Nutrition Quality, Sustainability.*

INTRODUCTION

Fish and fish foods are known for promoting human health. Dietary supplementation of fish proteins canprevent malnutrition, fish oils are good source of essential fatty acids with antioxidant, anti-inflammatory effects (Chen et al., 2022).Feed is the foremost important input for fish welfare in sustainable intensive aquaculture productions. It is a source of nutrients and energy, fundamental for growth, reproduction, and fish health (NRC, 1993). Quality feed is important for scaling up fisheries outturn by fulfilling the balanced nutritional requirements of fish (Puri et al., 2022). Sustainable, quality feeds can confer health benefits to aquaculture and consequently to humans (consumers). In terms of quantity as well as quality, dietary requirements of fish vary as per life stage of the species, feeding habits and environmental fluctuations of temperature, salinity and natural food availability in the culture environment (Giri, 2017). Formulating balanced, least expense feed based on the nutrition and health needs of fish is thus an essential prerequisite (Ahmed and Ahmad, 2020). For cost-effective, economical production, diets must be formulated in agreement with the elementary nutritional needs of the specific species, containing accurate apportionment of protein, lipid, carbohydrate as well as energy gains. Present study describes dietary requirements of finfish in terms of proteins, amino acids, lipids, constituent fatty acids, carbohydrates, and energy gained from feed.

1. Protein and Amino Acid Requirement

Protein comprise most treasuredconstituent in fish feed compositions in terms of quality it offers andin directing the feed cost (Fatma and Ahmed, 2020). Protein requirements of fish is for growth accretion and survival. Proteins comprise 50% of dietary constituents in fish feeds (Benitez,1989).Dietary needs of protein for fish is nearly 2 to 4-fold higher than other vertebrates (Wilson, 2003). Carnivorous species havegreater protein requirements (40-50% crude protein), than omnivore and herbivore (25-35%) fishes (Jauralde et al., 2021; NRC,1993; Gatlin, 2010). For maximal growth, dietary crude protein requirement of cultured fish varies between 300-550 g kg^{-1} of diet (Tacon and Cowey, 1985; Wilson, 1989). In a meta-analysis approach, Teles et al. (2020)enlist requirement of 624g protein for fish to achieve 1kg weight gain,accomplishing protein retention efficiency(PER) of 32%. Dietary protein necessities are relatable to trophic level, salinity, rearing temperature, stock size, frequency of feeding, non-protein source of dietary energy, diet quality of protein (Fatma and Ahmed, 2020; Teles et al., 2020). Proteins comprise mix of amino acids (AAs) as building blocks. According to Nunes et al. (2014), nutritional and economic gains from a protein are dynamics of protein digestibility and AA composition. Moreover, Peres and Oliva-Teles (2008), suggest AA profile of whole body of fish to be largely interrelated to their essential amino acid (EAA) needs.EAA include arginine (arg), methionine (met), leucine (leu), lysine (lys), histidine (his), isoleucine (ile), threonine (thr), phenylalanine (phe), tryptophan (tryp) and valine (val). EAAs are nutritionally essential and obtainedfrom extraneous dietary source. Table 1 lists indispensable EAA requirements of juvenile stages of *Labeo rohita, Ictalurus punctatus, Catla catla, C. carpio, Oncorhynchus niloticus, Anguilla japonica, O. tshawytscha, Salmo salar and O. mykiss* (FAO, 2013; Kaushik, 1995; NRC, 1993). In an “ideal protein”, ratio between EAA to non-EAA (NEAA) remains constant despite variations in each AA requirement across life stages of fish (Bicudo and Cyrino, 2014; Ogino, 1980). NEAA in fish nutrition includes alanine (ala), proline (pro), asparagine (asn), cystine (cys), aspartate (asp), glycine (gly), serine (ser), glutamine (gln), tyrosine (tyr) and glutamate (Li et al., 2011). NEAAs such as cys can be synthesized from met; tyrosine (tyr) synthesis occurs from phe. Thus, appropriate EAAs can supplement NEAA requirement (Wilson, 2003; Nunes et al., 2014). High amounts of NEAA present in animal origin proteins can reduce energy cost and EAA requirements for their de novo synthesis in animals, causing improved feed efficiencies (Li and Wu 2018, 2020).Dietary protein is a source of both EAA and NEAA Together EAA and NEAA comprise proteinogenic amino acids (PAAs). Since NEAA biosynthesis is energy driven, dietary proteins that suffice the requirements of fish for both EAA and NEAA will contribute to most efficient fish growth (NRC,1993; Li and Wu, 2020). Amino acids have fundamental role in fish functions involving protein synthesis, growth, metabolic processes, synthesis of neurotransmitters (val, leu, ile, phe, tyr, tryp, gln); ammonia detoxification (ornithine orn; gln, arg), lipid oxidation (arg), inhibition of protein degradation (val, leu, ile); immunostimulation, antioxidant (met, cys) and osmolytic properties (sarcosine, sar; taurine, tau) (Andersen et al., 2016; Ahmed and Khan, 2006; Waarde, 1988). High quality fishmeal (FM) has balanced amount of all EAAs predominantly lys (Miles and Chapman,2006); n3 omega polyunsaturated FAs chiefly, DHA as well as EPA; essential minerals andvitamins; with 85% of aquaculture species relying on fish meal (FM), from feed (Jeyasanta and Patterson, 2020). Fishmeal replacement owing to its scarcity and incremental feed cost (Naylor et al.,2009) has shifted focus to marine, plant-based sources of equivalent protein provisions. Although, many plant based feedstuffs and harshly processed ingredients of animal origin (used in preparation of artificial diets for fish) are deficient in met and lys enlisted to be initial-limiting AA (Gatlin et al., 2007; NRC, 2011).

Table1 Indispensable amino acid, EAA requirements of fishes (as g 100g^{-1} diet = % of diet,dryweight basis).

Amino Acids	*L. rohita*	*C. catla*	*C. carpio*	*I. punctatus*	*S. salar*	*A. japonica*	*O. niloticus*	*O. mykiss*	*O. tshawytscha*
Arginine	2.30	1.9	1.6	1.0	2.0	1.7	1.18	2.0	2.4
Histidine	0.90	1.0	0.8	0.4	0.7	0.8	0.48	0.7	0.7
Isoleucine	1.20	0.9	0.9	0.6	0.8	1.5	0.87	0.8	0.9
Lysine	1.50	2.5	2.2	1.2	1.8	2.0	1.43	1.8	2.0
Leucine	2.27	1.5	1.3	0.8	1.4	2.0	0.95	1.4	1.6
Methionine	1.42	1.4	1.2	0.6	1.0	1.2	0.75	1.0	1.6
Phenylalanine	1.48	1.5	2.5	1.2	1.2	2.2	1.05	1.2	2.1
Threonine	1.71	2.0	1.5	0.5	0.8	1.5	1.05	0.8	0.9
Tryptophan	0.45	0.4	0.3	0.12	0.2	0.4	0.28	0.2	0.2
Valine	1.50	1.4	1.4	0.71	1.3	1.5	0.78	1.3	1.3

2. Lipid and fatty acid requirement

Lipids help accomplish essential fatty acid (EFA) and energy needsof fish to perform physiological functions.Lipidshave significant role in determiningfish health, reproductive success, immune state and survival (Arts and Kohler, 2009). Fatty acids (FAs) are components of lipids as organic acids with a carbon chain containing terminal carboxyl group. According to the presence, inclusion of total double bonds, FAs are classified assaturated, monounsaturated (SFAs, MUFAs) and polyunsaturated (PUFAs) (Chen and Liu, 2020); depending on chain length of C1-C6 carbons as short chain (SC), C7-12 medium chain (MC), more than C14 as long or highly chained (LC or HC) FAs (Schönfeld and Wojtczak, 2016; NRC,1989).Among types of PUFA, n3,n6,n9 are found in all animals, including fish. Fishes have regulated ability to synthesize *de novo* only n9 PUFAs Thusboth n3, n6 PUFA are essential FAs (EFAs) and need to be obtained from diet sources to fish. EFA needs of fish vary across species. Marine fish require n3LC-PUFAdocosahexaenoic acid (DHA, 22:6) and eicosapentaenoic acid (EPA, 20:5); rainbow trout requires n3FAs such as alpha-linolenic acid (ALA, 18:3 n3) and n3HC-PUFA; carp nutrition needs are for both n3, n6 FAs and tilapia requires n6 linoleic acid (LA,18:2 n6) (Takeuchi et al., 1991; Hasan, 2001; Opstvedt, 1985). Incorporation of lipids in dietary formulations can expand sparing effect on dietary protein (Hasan, 2001; Watanabe, 1982).

Plant-derived oils used in aquafeeds (such as sunflower, linseed, soybean) are rich sources of n6-series of SC-PUFA, and MC-PUFAs (LA C18:2, n6). n3 LC-PUFAs (= heavy chain PUFA, HC-PUFA) of larger interest DHA 22:6 and EPA 20:5 are opulently found in marine origin oils (such as fish oils, algal oils) and animal fats (Gonzalez-Silvera et al., 2016). n3PUFA, EPA and DHA are important for growth, cardiovascular health, anti-inflammatory response, neural and brain development. PUFAs have biological role in plasma membranes composition and fluidity, gene transcription regulation, cell signal modulation (Czumaj and Sledzinski, 2020; Arts and Kohler, 2009). Table 2 lists EFA deficiency symptoms reported in fishes. All fishes require EFA at 1-2% of diet, as per dry weight (Hasan, 2001). Recommended intake of EPA and DHA for humans lies between 200-500 mg per day (Strobel,2012) with need of dietary n3:n6 ratio above or at least equal to 1:1 (Simopoulos,1991). Dietary percentage of lipids required by fish is dependent on lipid type as well as digestible energy to protein ratio, DE:P in diet (NRC,1993).

Table 2 EFA deficiency symptoms reported in fishes.Source: Tacon (1992); Takeuchi et al. (1990, 1991)

Fish	Deficiency symptom
C. carpio	High mortality, fatty liver
Ctenopharyngodon idella	Lordosis, decreased growth and feed efficiency,shock syndrome
O. mykiss	shock syndrome, liver degeneration, high mortality
O. niloticus	Swollen pale liver
Lates calcarifer	Effects growth, feed efficiency, fin reddening
Scophthalmus maximus	High mortality, decreased growth, gill epithelium degeneration

3. Carbohydrate Requirements

Fish do not have any preciserequirement for dietary carbohydrates(NRC, 2011). Yet,being least expense source of energy, digestible forms of carbohydrates are frequently appended in commercial diets to essentially counter retaindietary lipids and proteins (=sparing effect) (Gatlin, 2010). Soluble forms of carbohydrates, specifically starch also help in pellet binding and stability improving dietary properties (Hardy and Barrows, 2002; Kamalam et al., 2017). Proficiency to utilize dietary carbohydrate depends on composition of feed, processing technique and fish physiology,varying substantiallyamong finfish species.Commercial feeds for carnivorous species allow 20% carbohydrate inclusion, lesser compared to herbivore and omnivore requirements 25-45%. This is due to limited capability of carnivorous fishes to efficiently utilize dietary carbohydrates as energy source.

4. Energy Requirements

Energy itself is a non-nutrient and is obtained from metabolization of dietary nutrient sources of fats, proteins and carbohydrates (NRC,1993). Gross energy (GE) value of feed, is the heat generated on complete ignition of feed compounds. GE is a measure of absolute energy offered from organic dietary constituents to the organism. Estimation ofGE helpevaluate other feed energyvalues,namely metabolizable (ME) and digestible energy (DE) (Weiss and Tebbe, 2018). Total intake energy (IE) from diet of fish is relatable to GE content of feeds. In a compounded diet GE is contribution of its constituents each with their mean energy contribution; protein comprising 23.6 kJg^{-1} diet, lipids 39.5,and carbohydrates 17.2 $kJ\ g^{-1}$ (NRC, 2011). It is measured by burning compounded feed under controlled oxygen pressure in a thick metal walled container known as 'bomb' through which the technique finds name as bomb calorimetry (NRC, 2011). It is important to evaluate energy estimates of diet available for utilization by fish.Formulation of feed based on knowledge of energy utilizations of fish at various stages of life history would be cost effective approach preventing over addition of nutrients (NRC,1993). GE of feed ingredients is fundamental to precise feed formulation for fish performance and sustainable environment effects (Sayed et al., 2018). Retention of energy by fish for growth and other physiological functions (ME) is partly dependable on available energy from feed (GE), along with type, life history stage and culture conditions of fish. Feed formulations ideal for one species may not be optimal for other species and is also a function of culture conditions for fish development (Sales, 2009). Optimization of digestible protein (DP) and DE content (DE = GE of feed subtracting GE lost to faeces) of fish diet is the foremost consideration in feedformulation (Zuidhof, 2019; White, 2013; Happel,2020). For cultured fish species, these ratios range between 81 -117 mg DPkcal^{-1}DE (NRC, 2011). DE requirements for fry to fingerling stage of fishes such as carp, rohu, mrigal, silver and grass carp scopes between 3500 to 4500 Kcalkg^{-1} of diet at level of 37%- 47% protein, 30% carbohydrate, and 7% lipid in diet (FAO, 2017; Giri, 2017). Energy values are important considerations in choice of dietary ingredients for optimizingcost effective feed formulations.

5. Processing of fish feeds: Extrusion and Pelletization

Processing of feeds can improve organoleptic properties, improve digestibility, reduce negative impacts of non-nutrients, pathogensthus yielding sustainable, good quality aquaculture diets. Extrusion is a sought after technique for aquafeed processing with merits of feed nutritional quality improvement. During extrusion process feed is mixed, sheared and heated under high temperature, high pressure with extrudate leaving the die of proper dimension. Extruder parameters temperature, shear, screw type, pressure, size of die; and diet composition have great influence of physical and nutritional quality of extruded feed (Sorensen et al., 2005). Extruded diets provide enhanced feed digestibility owing to diminution of anti-nutritional factors (tannins, phytates, phenols) and pathogenic interferences from diet. Hot-extrusion is performed at temperatures above 100°C forming floating diets for surface feeders such as, *O. niloticus*; cold extrusion identifies at ambient temperatures producing sinking pellets for bottom dwelling finfish including *Clarius gariepinus* (Choton et al., 2020). Were et al. (2021), demonstrated benefits of hot extrusion processing of feeds in reducing microbial interferences in insect and larval meal replacement of FM diet for Nile tilapia and African catfish.Extrusion cooking affects nutritional quality of diet at various degrees. In its beneficial aspect, in addition to destruction of antinutrient factors, extrusion diets contain gelatinized starch, improved soluble dietary fiber; increasing its digestibility to fish and feed physical properties in water (Welker et al., 2018; Glencross et al., 2011). On the contrary, depending on extrusion conditions heat susceptible vitamins can be lost, with protein-sugar reactions at high extrusion temperatures deteriorating feed nutrient profiles (Singh et al., 2007). Even coated forms of ascorbate are largely lost at high rates to extrusion. Most susceptible vitamins to extrusion are thiamine (due to high shear rates of extrusion), vit. A, C and folate. Yang et al. (2020), evaluated impact of extrusion temperatures and encapsulation procedure on vitamin stability to conclude high stability of micro-encapsulated vitamin compared to un-encapsulated forms in feed. Storage loss of vit A is reported due to oxidative influences (Harper,1988). Since many parameters need to be optimized for extrusion processing of feeds, the technique require precise controlled operating conditions to restore maximal nutrient benefits from feeds. Extruded feed are more resilient to dissociation in water and produces low density floatable diets (Khater et al., 2014), that allow aqua culturist to account amount of feed consumption by fish. Extrusion can produce durable and stable aquafeeds abating problems of aquatic pollution in farming environment (Liu et al., 2021).

Pelleting aggregates ingredients into large homogenized particles under effect of heat, pressure and moisture (Lovell,1980). Riaz et al. (2009) evaluated vitamin stability due to extrusion, and pelleting procedures at three months storage, reporting extrusion loss of thiamine (88%) compared to pelleting loss ranging between 60-96%. Pelleted diets in comparison to extruded diets are dense with low floatability.Pelletization process require steam water addition to diet mixture and have high moisture content that must be reduced for their use as fish diets.Pelleted diets are less costly than extruded feeds thus provides cost effective feeds.

CONCLUSIONS

Fed aquaculture has contributed to significant growth in fisheries productions besides fulfilling basic nutritional requirements forhumans. Nutrition and feeding are primary themes in sustainable aquaculture paradigm.Adequatelyformulated nutrient rich feeds can safeguard significant amount of the total production costs of fed-aquaculture. Since,feeds have essential role in aquafarming development appropriate knowledge followed by astute evaluation of nutritional quality of feed and feedstuffs is important for sustaining aquaculture welfare and health.

REFERENCES

1. Ahmed I and Ahmad I (2020). Effect of dietary protein levels on growth performance, hematological profile and biochemical composition of fingerlings rainbow trout, *Oncorhynchus mykiss* reared in Indian Himalayan region.*Aquaculture Reports***16:** 100268.

2. Ahmed I and Khan MA (2006). Dietary branched-chain amino acid valine, isoleucine and leucine requirements of fingerling Indian major carp, *Cirrhinus mrigala* (Hamilton). *British Journal of Nutrition***96:** 450-460.

3. Andersen SM, Waagbø R, Espe M (2016). Functional amino acids in fish health and welfare. *Frontiers in Bioscience* (Elite Ed) **8**(1): 143-169.

4. Arts MT and Kohler CC (2009). Health and condition in fish: the influence of lipids on membrane competency and immune response. In: Kainz M, Brett M, Arts M (eds) Lipids in Aquatic Ecosystems. Springer, New York, NY.

5. Benitez LV (1989). Amino acid and fatty acid profiles in aquaculture nutrition studies, In: De Silva SS (ed.) Fish Nutrition Research in Asia. Proceedings of the Third Asian Fish Nutrition Network Meeting. Asian Fish. Soc. Spec. Puhl. 4, 166 p. Asian Fisheries Society, Manila, Philippines pp 23-35.

6. Bicudo AJA and Cyrino JEP (2014). Evaluation of methods to estimate the essential amino acids requirements of fish from the muscle amino acid profile. *Latin American Journal of Aquatic Research* **42**(1): 271-275.

7. Chen J and Liu H (2020). Nutritional indices for assessing fatty acids: A mini-review. *International Journal of Molecular Sciences* Int. J. Mol. Sci., 21, 5695.

8. Chen J, Jayachandran M, Bai W, Xu B (2022). A critical review on the health benefits of fish consumption and its bioactive constituents. *Food Chemistry***369:** 130874.

9. Choton S, Gupta N, Bandral JD, Anjum N, Choudary A (2020). Extrusion technology and its application in food processing: A review. *The Pharma Innovation Journal***9**(2): 162-168.

10. Czumaj A and Sledzinski T (2020). Biological role of unsaturated fatty acid desaturases in health and disease. *Nutrients***12:** 356.

11. FAO (2013). Rohu nutritional requirement, aquaculture feed and fertilizer information system, food and agriculture organization of united nations, Rome, Italy.

12. FAO (2017). Aquaculture feed and fertilizer resources information system. FAO, Rome.

13. Fatma S and Ahmed I (2020). Effect of water temperature on protein requirement of *Heteropneustes fossilis* (Bloch) fry as determined by nutrient deposition, hemato-biochemical parameters and stress resistance response. *Fisheries and Aquatic Sciences* **23:**1.

14. Gatlin DM (2010). Principles of fish nutrition. Southern Regional Aquaculture Center SRAC Publication No. 5003.

15. Gatlin DM, Barrows FT, Brown P, Dabrowski K, Gaylord TG, Hardy RW, Herman E, Hu G, Krogdahl Å, Nelson R, Overturf K, Rust M, Sealey W, Skonberg D, Souza EJ, Stone D, Wilson R, Wurtele E (2007). Expanding the utilization of sustainable plant products in aquafeeds: a review. *Aquaculture Research***38:** 551-579.

16. Giri SS (2017). Farm-Made Feeds for Sustainable Aquaculture Development: A South Asian Perspective In: Giri SS (ed.) Farm-made Aquafeeds: Opportunities, Challenges and Policy Intervention. SAARC Agriculture Centre, Dhaka, Bangladesh pp 1-22.

17. Glencross B, Hawkins W, Evans D, Rutherford N, McCafferty P, Dods K, Hauler R (2011). A comparison of the effect of diet extrusion or screw-press pelleting on the digestibility of grain protein products when fed to rainbow trout (*Oncorhynchus mykiss*). *Aquaculture***312:** 154-161.

18. Gonzalez-Silvera D, Martinez-Rubio L, Mateo MEA, Rabadan-Ros R, Jimenez JAL, Lopez FJM (2016). Assessing feeding history and health status through analysis of fatty acids and fat content in golden mullet *Liza aurata*. *ICES Journal of Marine Science***73**(10): 2632-2643.

19. Happel A, Sealey WM, Myricka CA, Powell MS (2020). Effects of varying dietary levels of digestible protein and digestible energy on growth performance in juvenile Yellowstone cutthroat trout (*Oncorhynchus clarkia bouvieri*).*Aquaculture Reports***17:** 100336.

20. Hardy RW, Barrows FT (2002). Diet formulation and manufacture. In: Halver JE, Hardy RW (ed.) Fish Nutrition. Third Edition Academic Press, London, pp. 505-600.

21. Harper JM (1988). Effects of extrusion processing on nutrients. In: Karmas E and Harris R S (ed.) Nutritional evaluation of food processing. 3rd ed. Van Nostrand Reinhold Company, New York, US pp. 365-391.

22. Hasan MR (2001). Nutrition and feeding for sustainable aquaculture development in the third millennium. In: Subasinghe RP, Bueno P, Phillips MJ, Hough C, McGladdery SE, Arthur JR (eds.) Aquaculture in the third millennium. Technical proceedings of the

conference on aquaculture in the third millennium, Bangkok, Thailand and FAO, Rome pp 193-219.

23. Jauralde I, Velazco-Vargas J, Tomás-Vidal A, Cerdá MJ, Martínez-Llorens S (2021). Protein and energy requirements for maintenance and growth in juvenile meagre *Argyrosomus regius* (Asso, 1801) (Sciaenidae). *Animals (Basel)***11**(1): 77.

24. Jeyasanta KI and Patterson J (2020). Study on the effect of freshness of raw materials on the final quality of fish meals. *Indian Journal of Geo Marine Sciences* **49**(1): 124-134.

25. Kamalam BS, Medale F, Panserat S (2017). Utilisation of dietary carbohydrates in farmed fishes: New insights on influencing factors, biological limitations and future strategies. *Aquaculture*, **467:** 3-27.

26. Kaushik SJ (1995). Nutrient requirements, supply and utilization in the context of carp culture. *Aquaculture* **129:** 225-241.

27. Khater EG, Bahnasawy AH, Ali SA (2014). Physical and mechanical properties of fish feed pellets. *Journal of Food Process Technology***5:** 378.

28. Li P and Wu G (2018). Roles of dietary glycine, proline and hydroxyproline in collagen synthesis and animal growth. *Amino Acids* **50:** 29-38.

29. Li P and Wu G (2020). Composition of amino acids and related nitrogenous nutrients in feedstuffs for animal diets. *Amino Acids***52:** 523-542.

30. Li X, Rezaei R, Li P, Wu G (2011). Composition of amino acids in feed ingredients for animal diets.*Amino Acids***40:** 1159 -1168.

31. Liu K, Frost J, Welker TL, Barrows FT (2021). Comparison of new and conventional processing methods for their effects on physical properties of fish feed. *Animal Feed Science and Technology***273:** 114818.

32. Lovell RT (1980). Practical Fish Diets. ADCP/REP/80/11 - Fish Feed Technology Lectures presented at the FAO/UNDP Training Course in Fish Feed Technology Seattle, Washington, U.S.A

33. Miles RD and Chapman FA (2006). The benefits of fish meal in aquaculture diets. FA122 Fisheries and Aquatic Sciences Department, UF/IFAS Extension, Florida.

34. Naylor RL, Hardy RW, Bureau DP, Chiu A, Elliott M, Farrell AP, Forster I, Gatlin DM, Goldburg RJ, Hua K, Nichols PD (2009). Feeding aquaculture in an era of finite resources. *Proceedings of the National Academy of Sciences USA***106** (36): 15103-15110.

35. NRC (1989). Fat-soluble vitamins. National Research Council -Committee on diet and health: Implications for reducing chronic disease risk / Committee on diet and health, food and nutrition board, commission on life sciences, National Academies Press, Washington DC, US. https://www.ncbi.nlm.nih.gov/books/NBK218749/

36. NRC (1993). Nutrient requirements of fish. National Research Council -Subcommittee on Fish Nutrition. http://www.nap.edu/catalog/2115.html

37. NRC National Research Council (2011). Nutrient requirement of fish and shrimp.

38. Nunes AJP, Sá MVC, Browdy CL, Vazquez-Anon M (2014). Practical supplementation of shrimp and fish feeds with crystalline amino acids.*Aquaculture***431:** 20–27.

39. Ogino C (1980). Requirement of carp and rainbow trout for essential amino acids. *Bulletin of the Japanese Society of Scientific Fisheries***42:** 71-75.

40. Opstvedt J (1985). Fish lipids in animal nutrition. IFOMA technical bulletin.

41. Peres H and Oliva-Teles A (2008). Lysine requirement and efficiency of lysine utilization in turbot (*Scophthalmus maximus*) juveniles. *Aquaculture* **275:** 283-290.

42. Puri P, Sharma JG, Singh R (2022). Biotherapeutic microbial supplementation for ameliorating fish health: developing trends in probiotics, prebiotics, and synbiotics use in finfish aquaculture. *Animal Health Research Reviews* **23** (2):113-135.

43. Riaz MN, Asif M , Ali R (2009). Stability of vitamins during extrusion. *Critical Reviews in Food Science and Nutrition*, **49:** 361-368.

44. Sales J (2009). Prediction of digestible energy content across feed ingredients and fish species by linear regression. *Fish Physiology and Biochemistry* **35:** 551-565.

45. Sayed SF, Khan IA, Ameen Basheer RA (2018). Gross energy densities of the locally-available, unconventional feed ingredients for poultry feeds.

46. Schönfeld P and Wojtczak L (2016). Short- and medium-chain fatty acids in energy metabolism: the cellular perspective.*Journal of Lipid Research***57:** 943-954.

47. Simopoulos AP (1991). Omega-3 fatty acids in health and disease and in growth and development, a review. *The American Journal of Clinical Nutrition***54:** 438-463.

48. Singh S, Gamlath S, Wakeling L (2007). Nutritional aspects of food extrusion: a review. *International Journal of Food Science and Technology***42:** 916-929.

49. Sorensen M, Storebakken T, Shearer KD (2005). Digestibility, growth and nutrient retention in rainbow trout (*Oncorhynchus mykiss*) fed diets extruded at two different temperatures. *Aquaculture Nutrition***11:** 251-256.

50. Strobel C, Jahreis G, Kuhnt K (2012). Survey of n-3 and n-6 polyunsaturated fatty acids in fish and fish products. *Lipids in Health and Disease***11:** 144.

51. Tacon AGJ (1992). Nutritional fish pathology. Morphological signs of nutrient deficiency and toxicity in farmed fish. Fish Technical Paper. No. 330 FAO, Rome.

52. Tacon AGJ and Cowey CB (1985). Protein and amino acid requirements. In: Tytler P and Calow P (ed.) Fish Energetics: New Perspectives. The Johns Hopkins University Press, Baltimore, Maryland, pp. 155-183.

53. Takeuchi T (1990). Requirement of juvenile red seabream *Pagrus major* for eicosapentaenoic and docosahexaenoic acids. *Nippon Suisan Gakkaishi* **56:** 1263-1269.

54. Takeuchi T, Watanabe K, Yong W-Y, Watanabe T (1991). Essential fatty acids of grass carp *Ctenopharyngodon idella*. *Nippon Suisan Gakkaishi***57**(3): 467-473.

55. Teles AO, Couto A, Enes P, Peres H (2020). Dietary protein requirements of fish - a meta-analysis. *Aquaculture* **12**(3): 1445-1477.

56. Waarde AV (1988). Biochemistry of non-protein nitrogenous compounds in fish including the use of amino acids for anaerobic energy production. *Comparative Biochemistry and Physiology Part B: Comparative Biochemistry***91**(2): 207-228.

57. Watanabe T (1982). Lipid nutrition in fish. *Comparative Biochemistry* and *Physiology* **73B**(1): 3-15.

58. Weiss WP and Tebbe AW (2019). Estimating digestible energy values of feeds and diets and integrating those values into net energy systems. *Translational Animal Science***3:** 953-961.

59. Welker TL, Overturf K, Snyder S , Liu K, Abernathy J, Frost J, Barrows FT, (2018). Effects of feed processing method (extrusion and expansion-compression pelleting) on water quality and growth of rainbow trout in a commercial setting. *Journal of Applied Aquaculture***30:** 97-124.

60. Were GJ, Irungu FG, Ngoda PN, Affognon H, Ekesi S, Nakimbugwe D, Fiaboe KKM, Mutungi CM (2021). Nutritional and microbial quality of extruded fish feeds containing black soldier fly (*Hermetia illucens* L.) larvae meal as a replacement for fish meal for Nile Tilapia (*Oreochromis niloticus*) and African sharp tooth catfish (*Clarius gariepinus*). *Journal of Applied Aquaculture.*

61. White P (2013). Environmental consequences of poor feed quality and feed management. In: Hasan MR and New MB (eds.) On-farm feeding and feed management in aquaculture. FAO Fisheries and aquaculture technical paper no. 583. Rome, pp. 553-564.

62. Wilson RP (1989). Amino acids and proteins. In: Halver JE (ed.) Fish nutrition. Second Edition Academic Press, San Diego, pp111-151.

63. Wilson RP (2003). Amino acid requirements of finfish and crustaceans. In: D'Mello JPF (ed.) Amino acids in animal nutrition. Second Edition CABI Publishing, Wallingford, UK.

64. Yang P, Wang H, Zhu M, Ma Y (2020). Evaluation of extrusion temperatures, pelleting parameters, and vitamin forms on vitamin stability in feed. *Animals* **10:** 894.

65. Zuidhof MJ (2019). A review of dietary metabolizable and net energy: uncoupling heat production and retained energy. *Journal of Applied Poultry Research***28:** 231-241.