International Journal of Advanced Biochemistry Research 2024; SP-8(4): 30-35

International Journal of Advanced Biochemistry Research

**ISSN Print:** 2617-4693
**ISSN Online:** 2617-4707
IJABR 2024; SP-8(4): 30-35
www.biochemjournal.com
Received: 25-01-2024
Accepted: 28-02-2024

**Jham Lal**
ICAR-Central Inland Fisheries
Research Institute, Barrackpore,
Kolkata, West Bengal, India

**Anand Vaishnav**
College of Fisheries, Central
Agricultural University,
Lembucherra, Tripura, India

**Sanjay Chandravanshi**
TNJFU-Fisheries College and
Research Institute, Thoothukudi,
Tamil Nadu, India

**Narsingh Kashyap**
TNJFU-Fisheries College and
Research Institute, Thoothukudi,
Tamil Nadu, India

**Rahul Jaiswar**
TNJFU-Fisheries College and
Research Institute, Thoothukudi,
Tamil Nadu, India

**Atul Kumar**
ICAR-Central Inland Fisheries
Research Institute, Barrackpore,
Kolkata, West Bengal, India

**Durgesh Kumar Verma**
ICAR-Central Inland Fisheries
Research Institute, Barrackpore,
Kolkata, West Bengal, India

**Rajesh Jayaswal**
ICAR-Central Inland Fisheries
Research Institute, Barrackpore,
Kolkata, West Bengal, India

**Aritriya Jana**
ICAR-Central Inland Fisheries
Research Institute, Barrackpore,
Kolkata, West Bengal, India

**NK Acharjya**
ICAR-Central Inland Fisheries
Research Institute, Barrackpore,
Kolkata, West Bengal, India

**Corresponding Author:**
**Jham Lal**
ICAR-Central Inland Fisheries
Research Institute, Barrackpore,
Kolkata, West Bengal, India

# Unraveling the secrets of fish biochemistry: A comprehensive review of recent advances

**Jham Lal, Anand Vaishnav, Sanjay Chandravanshi, Narsingh Kashyap, Rahul Jaiswar, Atul Kumar, Durgesh Kumar Verma, Rajesh Jayaswal, Aritriya Jana and NK Acharjya**

**DOI:** https://doi.org/10.33545/26174693.2024.v8.i4Sa.899

## Abstract

Fish biochemistry is a multifaceted field that plays a crucial role in understanding the physiological mechanisms governing aquatic life. The biochemical composition of fish is a fascinating topic that sheds light on the nutritional value and functional aspects of fish. This comprehensive review delves into recent advances in fish biochemistry, shedding light on the intricate molecular processes underlying various physiological functions. These include metabolism, protein synthesis, enzymology, lipid metabolism, and the role of bioactive compounds. Energy generation, growth, and general health are all greatly impacted by these complex metabolic processes. Recent breakthroughs in omics technologies, including genomics, transcriptomics, proteomics, and metabolomics, have revolutionized our understanding of fish biochemistry, enabling researchers to unravel complex metabolic pathways and regulatory networks. Moreover, this review explores the implications of fish biochemistry in aquaculture, environmental monitoring, and human health, emphasizing the importance of sustainable practices and conservation efforts. By synthesizing recent findings and highlighting emerging trends, this review provides valuable insights into the dynamic and evolving landscape of fish biochemistry, paving the way for future research endeavors and innovations in aquatic science.

**Keywords:** Fish, biochemistry, metabolism, antioxidant, adaptations

## 1. Introduction

Fish biochemistry is a multidisciplinary field that explores the intricate biochemical processes within fish organisms. It encompasses various aspects, including genetics, physiology and ecology. The primary focus is on understanding how fish interact with their environment at a molecular level. Fish play essential roles in ecosystems, and their beauty and diversity captive both scientists and enthusiasts. Understanding fish biochemistry helps improve fishing practices, sustainable management, and conservation efforts.

Bioactive substances, found in abundance in fish and fish products, have beneficial effects on human health that go beyond those of a simple dietary supplement. There are a number of well-known bioactive chemicals found in fish, and two of them are omega-3 fatty acids, EPA and DHA. Many studies have linked these fatty acids to positive health outcomes, such as improved cardiovascular function, enhanced cognitive function, and reduced inflammation. In addition to its high nutritional content and possible health advantages, fish is a good source of bioactive substances such as peptides, antioxidants, and trace elements (Paulo, 2023) [27].

The world's demand for seafood is met in large part by the fishing industry. Studying the biochemical processes in aquatic creatures, especially fish, is the focus of fisheries biochemistry, an interdisciplinary field that integrates biological and chemical principles. To optimize fish health, improve the quality of fish products, guarantee the purity of seafood for human consumption, and for sustainable fishery management, it is vital to recognize fishery biochemistry. Evaluating the effects of fishing on the environment is another important function of fishery biochemistry. Over time, chemical toxins like pesticides, heavy metals, and organic contaminants can build up in fish tissues, endangering human health. Paulo (2023) [27] states that in order to monitor environmental contamination and adopt rules to decrease the presence of these pollutants in seafood, it is helpful to study how these chemicals bioaccumulate and biotransform in fish.

## 2. Structural Components of Fish Biochemistry

The biochemical composition of fish is a fascinating topic that sheds light on the nutritional value and functional aspects of fish.

1. **Water:** Fish tissue primarily consists of water, which makes up around 66% to 81% of its mass. This high water content contributes to the overall texture and juiciness of fish flesh.
2. **Protein:** Fish is an excellent source of protein, accounting for approximately 16% to 21% of its composition. Proteins play a crucial role in growth, repair, and various physiological functions in the human body.
3. **Lipids (Fat or Oil):** Fish contains essential fatty acids, including omega-3s, which are beneficial for cardiovascular health. The lipid content in fish ranges from 0.1% to 25%. These fats contribute to flavor, texture, and energy storage.
4. **Ash (Minerals)**: Ash refers to the mineral content in fish, including essential elements like calcium, phosphorus, and iron. It constitutes about 0.4% to 1% of fish tissue.
5. **Vitamins and Minerals:** Fish also contains vitamins (such as vitamins A, D, and B12) and minerals (like selenium and zinc), which play vital roles in overall health and well-being (Ochiai and Ozawa, 2020; Venugopal and Shahidi, 1996) [24, 36].

## 3. Metabolic Pathways in Fish

Energy generation, growth, and general health are all greatly impacted by these complex metabolic processes. Even though it only accounts for around 8% of the cell's ATP synthesis, the glycolysis pathway might be a nontrivial source of ATP for an egg with big glucose reserves. Some cell types, like cancer cells, and their ability to divide and contract are supported only by the glycolytic pathway. For nonnucleated erythrocytes, glycolysis is likely the sole means of obtaining energy. Boulekbache (1981) [5} also noted that the mature oocyte continues to employ glycolysis all the way up to fertilization.

1. **Fuel Metabolism:** Fish utilize various metabolic substrates to generate energy. These include carbohydrates, lipids (fats), and proteins. Swimming fish, especially those with high aerobic demands, exhibit specific adjustments in their energy supply pathways. Understanding these pathways helps us appreciate how fish efficiently convert nutrients into usable energy (Weber and Haman, 1996) [38].
2. **Mineral Metabolism:** Aquatic animals, including fish, absorb and retain essential minerals from their diets and water. Quantitative dietary requirements have been established for macroelements (calcium, phosphorus, and magnesium) and trace minerals (zinc, iron, copper, manganese, iodine, and selenium) in selected fish species. Mineral deficiency signs in fish include reduced bone mineralization, anorexia, lens cataracts (zinc), skeletal deformities (phosphorus, magnesium, zinc), and other specific symptoms. Maintaining a delicate balance between mineral deficiency and toxicity is vital for fish homeostasis (Lall and Kaushik, 2021) [16].
3. **Metabolomics in Fish Nutrition:** Biomarkers and the metabolic processes of fish can be better understood by metabolomics, a non-targeted study of metabolites. We can improve sustainable aquaculture operations and guarantee the safety and quality of fish-based food products by studying fish metabolomes. At the level of genes, transcripts, proteins, and metabolites, omics technology allows for a new comprehensive view of a biological system. The field of nutrigenomics, which studies the connection between specific foods and their effects on gene expression, has grown in prominence in recent years. One notable discovery is the effect of plant-based diets on the regulation of genes involved in protein, lipid, and carbohydrate metabolism in fish (Panserat *et al*. 2009; Geay *et al*. 2011) [26, 11].

## 4. Hormonal Regulation and Signaling

These intricate biochemical processes play a crucial role in energy production, growth, and overall health.

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3. **Hormonal regulation of digestion:** The feedstuffs' energy and nutrients are released through a series of steps. Substances such as monosaccharides, fatty acids, monoglycerides, and amino acids and peptides are hydrolyzed from complex polymers like proteins, starches, and lipids. These smaller molecules are then absorbed by the epithelial cells through their apical membrane and transferred into the systemic circulation through their basolateral membrane. Expenditures on the digestive system and its upkeep are substantial. According to Alsop and Wood (1997) [2} and Owen (2001) [25], the gastric intestines (GIT) use up to 70% more energy and oxygen during food processing, and the GIT is responsible for 20-25% of all protein synthesis in animals. Add in the related organs, like the pancreas and liver, and the prices go up (Gill *et al*., 1989) [12]. Due to the significant expenditures, efficient regulation of the GIT is important. The various regulatory chemicals that work in inter-organ system signaling networks, both locally and within the GIT, are responsible for this.
4. **Metabolomics in Fish Nutrition Research:** Biomarkers and the metabolic processes of fish can be better understood by metabolomics, a non-targeted

study of metabolites. We can improve sustainable aquaculture operations and guarantee the safety and quality of fish-based food products by studying fish metabolomes. Transporters in the enterocytes' apical membrane are responsible for nutrient absorption, whereas those in the basolateral membrane are responsible for nutrient transfer to the systemic circulation. Nutrient transporter activities and densities in the gastrointestinal tract of fish are influenced by changes in the content of their diet, just like in other vertebrates (Buddington *et al*., 1987; Collie and Ferraris, 1995) [7, 9]. Although there is limited information available for fish, it is known that solute transporters can be influenced by various signals within the gastrointestinal tract (e.g., enteroglucagon and somatotropin; Bird *et al*., 1994; Stumpel *et al*., 1998) [4, 35], as well as by hormones that travel between different organ systems (e.g., estrogen, testosterone, growth hormone; Reshkin *et al*., 1989) [29]. It has been suggested that pre-existing transporters have been inserted into the apical membrane, as the transporter responses can be detected within 30 minutes of exposure. Alterations in the number of enterocytes containing transporters and the density of transporters per cell produce alternative reactions, which are slower and take days to weeks to manifest (Buddington and Krogdahl, 2004) [8].

## 5. Lipid Metabolism and Membrane Dynamics

These processes are essential for maintaining cellular function, energy production, and overall health. Lipid dynamics in mammals have been extensively studied. Dietary lipids, mostly triacylglycerols (TG), are broken down in the gut lumen by pancreatic lipases into 2-monoacylglycerols (2-MG) and free fatty acids (FFA) after being emulsified into particles with bile components that are 1000 nm in diameter (Masoro, 1968) [18]. Micelles made composed of bile salts, cholesterol, and phospholipids absorb the FFA and 2-MG, creating mixed micelles about 10 nanometers in diameter. The jejunal mucosal cells are penetrated by FFA and 2-MG as they diffuse from the coupled micelles. When FFA longer than ten carbon atoms are activated on the smooth endoplasmic reticulum in mucosal cells, they generate fatty acyl-CoA derivatives, which are re-esterified to 2-MG in order to reconstitute TG. Chiylomicra, which include triacylglycerols and are massive lipoprotein complexes with a molecular weight of up to 3 x 10 t°, accumulate in the lymphatic system before entering the blood circulatory system through the thoracic duct. Lipides and other short-chain fatty acids are able to pass through the intestinal mucosa and out of the body through the hepatic portal vein because they are soluble in plasma to a sufficient degree. These short-chain fatty acids can join the endogenous lipid transport system in the liver and combine into other types of lipoproteins, like very low density lipoprotein (VLDL) (Allen, 1976) [1]. Cholesterol iipid hydrolysis by lipoprotein lipase leads to lipid deposition into storage areas like adipose tissue. Hydrolytic products, including FFA and 2-MG, are absorbed and resynthesized into TG, the end product of storage. Through the activity of lipoprotein lipase, lipids are transported to other peripheral tissues, like muscle, on VLDL. The transport and deposition processes of lipids seem to be very different in fish compared to homeothermic animals (Sheridan, 1988) [34].

1. **Membrane Contact Sites (MCSs):** MCSs are regions where the membranes of two organelles closely interact. They play critical roles in inter-organelle communication, lipid trafficking, intracellular signaling, and organelle biogenesis. Initially identified as "fraction X" in the early 1990s, MCSs facilitate local lipid synthesis and inter-organelle lipid transfer, contributing to cellular lipid homeostasis. These sites are crucial for maintaining lipid balance and membrane organization (Xu and Huang, 2020) [40].
2. **Lipid Synthesis and Breakdown at MCSs:** MCSs are hotspots for lipid metabolism. They participate in both lipid synthesis and breakdown. Local lipid synthesis occurs at MCSs, allowing for the production of specific lipids needed for membrane integrity and function. Lipid breakdown processes, such as lipolysis, also take place at these sites, ensuring efficient energy utilization (Fernández-Murray and McMaster, 2016) [10].
3. **Proteins Involved in Lipid Metabolism:** Specific proteins operate at MCSs to regulate lipid metabolism. These include enzymes responsible for lipid synthesis, remodeling, and degradation. Understanding the roles of these proteins sheds light on how MCSs contribute to lipid homeostasis and overall cellular health (Grabner *et al*., 2021) [13].
4. **Beyond Lipid Homeostasis:** MCSs serve purposes beyond maintaining lipid balance. They impact cellular physiology and systemic lipid metabolism. Research explores the physiological relevance of MCSs, emphasizing their role in lipid-related diseases and metabolic disorders (Natesan and Kim, 2021) [22].

## 6. Carbohydrate Utilization and Energy Production

The proper functioning, development, and general well-being of cells depend on these activities. Despite the anticipated wide species variation, the chemical may serve primarily as an oxidative substrate to certain fish cells and tissues; nonetheless, it may have a secondary function to lipids and proteins (Hemre *et al*., 2002) [14]. Fishes, with the exception of a few rare species like tunas and eels, have rates of glucose oxidation and turnover that are an order of magnitude lower than those of mammals of similar size. Decreased attention on glucose as a metabolic focal point may regulate the remaining variation, but lowered body temperature and slower metabolic rate may explain part of it. The use of glucose increases nearly thirtyfold during peak activity, demonstrating the undeniable central role of glycogen and glucose in the metabolism of muscle exercise (West *et al*. 1993) [39]. Nevertheless, it is important to consider this remarkable figure in relation to the total amount of glucose utilized by muscle tissues during activity. Even with the rise, the percentage of oxidative metabolism fueling glucose utilization remained below 10%. The low rates of hepatic gluconeogenesis, inactivation of the Cori cycle, and absence of an alanine-glucose cycle equivalent all lend credence to this view. Glycogen and glucose metabolism in muscles can also be seen as an airway within the muscle that is nearly closed (Milligan 1996) [19]. In addition, during the prewinter season, carp and certain of their relatives have abnormally high liver glycogen levels, which play a crucial role in their methods for surviving hypoxia and the cold. However, according to Hemre *et al*. (2002) [14], this level of extremes is not typical of fish metabolism.

1. **Carbohydrates as Fuel:** Carbohydrates serve as the primary substrate for energy production in fish. During high-intensity exercise, contracting skeletal muscles rely on carbohydrates for quick energy. The preference for glucose (a type of carbohydrate) as an energy source is crucial for sustaining physical activity (Mul *et al.*, 2015) [21].
2. **Role of Glucose**: Many cells, including red blood cells, prefer glucose over other compounds like fatty acids for energy production. Glucose is readily available and efficiently metabolized to produce ATP (adenosine triphosphate), the cell's energy currency (Newsholme and Dimitriadis, 2001) [23].
3. **Exercise and Glucose Uptake:** Exercise enhances glucose uptake in skeletal muscle. Distinct signaling pathways mediate the effects of exercise and insulin on glucose uptake. Exercise can increase glucose uptake even in the presence of insulin resistance, benefiting individuals with type 2 diabetes (Hulett *et al.*, 2022) [15].

## 7. Antioxidant Defense Systems

Antioxidant Defense Systems play a crucial role in maintaining cellular health by counteracting the effects of reactive oxygen species (ROS).

1. **ROS Generation and Its Impact:** Reactive oxygen species (ROS) are natural by-products of normal cell activity. They participate in cellular signaling but can also be harmful when their levels increase. Oxidative stress, resulting from an imbalance between ROS production and antioxidant defense, is associated with various human diseases, including cancer, cardiovascular issues, neurodegenerative disorders, inflammation, and aging. Tumor cells often exhibit elevated ROS levels, which can have both positive and negative effects on cancer development. ROS can promote molecular genetic alterations necessary for tumor growth and progression, but they can also induce tumor cell death (Schieber and Chandel, 2014) [33].
2. **Sources of ROS Generation: ROS can be generated through various processes**

- **Oxidative phosphorylation (OXPHOS)**: Occurs during cellular respiration.
- **Transition metal ions**: Involved in redox reactions.
- **Oxidase activity**: Enzymes like NADPH oxidases.
- **Protein folding**, **thymidine**, and **polyamine catabolism (Deshpande and Mohiuddin, 2020).

3. **Antioxidant Defense Systems:** These systems regulate ROS levels and protect cells from oxidative damage.

### Enzymatic Antioxidants

- Catalase (CAT): Breaks down hydrogen peroxide.
- Superoxide dismutases: Convert superoxide radicals to hydrogen peroxide.
- Peroxiredoxins: Scavenge peroxides.
- Glutathione S-transferases (GST): Detoxify xenobiotics.
- Epoxide hydrolase 2 (EPHX2): Involved in detoxification.
- Nonenzymatic Low-Molecular Weight Antioxidants:
- These include molecules like glutathione, ascorbic acid (vitamin C), and tocopherols (vitamin E).

## 8. Adaptations to Environmental Stressors

Adaptations to environmental stressors are essential for the survival and well-being of living organisms.

1. **Physiological Adaptations:** When faced with environmental stressors, organisms mobilize physiological adaptations to maintain homeostasis. These adaptations allow for normal biological functions even in challenging conditions. Acclimation refers to the process of responding to a single stressor, often in an experimental or laboratory context. During acclimation, organisms adjust their physiological processes to cope with the stressor (Leonard, 2015) [17].
2. **Types of Adaptations**

   **Genetic (Darwinian) Adaptations:** These adaptations result from **natural selection** and are biologically heritable. Over generations, genetic changes occur in response to environmental pressures. Examples include the development of thicker fur in cold climates or resistance to specific toxins.

   Functional (Physiological) Adaptations: These adaptations are acquired during an individual's lifetime and are not genetically heritable. They allow organisms to cope with immediate stressors. For instance, sweating to regulate body temperature or adjusting metabolic pathways in response to nutrient availability (Leonard, 2015) [17].
3. **Environmental Stress as a Force Shaping Evolution:** Environmental stress plays a crucial role in shaping adaptation and evolution. Researchers have made significant progress in understanding how stress influences evolutionary processes over the last decade (Bijlsma and Loeschcke, 2005) [3].
4. **Cellular and Molecular Mechanisms:** Organisms adapt to stress through defined regulatory mechanisms: Changes in gene expression: Triggered by stress, these changes lead to altered protein production.

   Morphological adaptations: Alterations in body structures or functions.

   Physiological adjustments: Responses such as increased heart rate or altered metabolism. Understanding these mechanisms is vital for survival in challenging environments (Rossnerova *et al.*, 2020) [31].

## 9. Nutrient Transport and Homeostasis

1. **Achieving Global Perfect Homeostasis:** In nutrient homeostasis, achieving balance is crucial. Negative feedback regulation of plasma membrane transporters is essential. Researchers study how simple uptake systems can achieve global perfect homeostasis (Savir *et al.*, 2017) [32].
2. **Nutrition & Transport in Animals**

   **Gas Exchange and Transport**: The respiratory system is an intricate network that allows animals to take in oxygen and exhale carbon dioxide. Blood carries oxygen by binding to hemoglobin. One of oxygen's most important functions is in cellular energy production. Oxidation and other energy-generating processes rely on a steady flow of oxygen into the cells. Mammals take in oxygen from the air we breathe in through their lungs, and then it travels through our circulatory system to our tissues, where it is mostly used by our mitochondria. This simplified view masks a lot of unanswered concerns about the physical mechanics of transport at various points along the pathway. How important are diffusion and chemical kinetics in the transfer of oxygen in blood, and is pure convection the primary mechanism? In what ways do the transport barriers offered by different types of cell membranes (e.g., red blood cells, endothelial cells, and parenchymal cells) influence the pathway (Popel, 1989) [28].

**Circulatory Systems:** The circulatory systems of animals can be classified as open, closed, single, or double. The heart, blood arteries, and circulatory system are all part of a closed system in mammals. No matter where it begins in development or how it is structured, any network of fluids that shortens the functional diffusion distance that gases, nutrients, and metabolic waste products must travel is considered a circulatory system (Brusca and Brusca, 2003) [6]. The cardiovascular system is extremely diverse. The process in diploblasts entails pumping saltwater into an exposed internal cavity. In contrast, triploblasts' circulatory fluid is an intracellular, non-cellular, aqueous medium that is either disseminated across the animal's cavities or through interconnected systems of veins, sinuses, and organs that pump blood around the body. Muscle action or ciliary function can transport circulatory fluids. The use of one-way valvesand/or synchronized peristaltic waves of contraction allows for directional flow. Two systems of internal circulation—the coelomic and the blood vascular—are present. In addition to their blood vessels, the majority of triploblastic animals also have a coelomic circulatory system (Monahan-Earley *et al*., 2013) [20].

**Mammalian Cardiac Cycle:** The heart contracts and relaxes rhythmically, pumping blood through the circulatory system. Phases include diastole (relaxation) and systole (contraction).

## 10. Conclusions

New insights into fish biochemistry have expanded our knowledge of the complex physiological processes at work in aquatic creatures and revealed a plethora of previously unknown secrets. We have learned a great deal about the molecular basis of fish biology from studying metabolism, protein synthesis, enzymology, lipid metabolism, and the complex interactions of bioactive chemicals. This area has advanced greatly thanks to the incorporation of state-of-the-art omics technologies, which have provided researchers with unprecedented clarity in their attempts to understand intricate metabolic pathways and regulatory networks. Biomarkers, physiological adaptations, and environmental responses can be better understood with the use of genomic, transcriptomic, proteomic, and metabolomic tools that have uncovered the genetic, transcriptomic, proteomic, and metabolomic landscapes of fish species. In addition to its obvious scientific applications, fish biochemistry has far-reaching consequences for aquaculture, environmental monitoring, and human health. An in-depth familiarity of fish metabolism and dietary needs is essential for sustainable aquaculture techniques, and biomarkers and molecular indicators of ecosystem health are useful for environmental monitoring. Fish also contains bioactive chemicals that could be used in the pharmaceutical and nutraceutical industries to create new drugs and functional foods.

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