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Review Article

Biochemical Study Of Lipid, Protein And Carbohydrate In Liver Of Teleost : A Review

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ABSTRACT

The liver being the central metabolic organ in teleost fish, regulates lipid, protein and carbohydrate metabolism for energy supply by maintaining homeostasis. It produces glucose from protein and lipid stores during long-term fasting and protects organelles, cells and tissues from damage caused by excess lipid accumulation. The metabolic processes in liver tissue involve multiple enzymatic reactions that are regulated by hormones especially insulin. Insulin plays a key role in regulating lipid metabolism by controlling lipid synthesis, storage and mobilization. These processes are essential for the proper growth, development and metabolic balance in fish. Therefore, the biochemical study of lipids, proteins and carbohydrates in liver provides valuable information about the physiological condition and health status of teleost fishes

INTRODUCTION

Lipids are a major energy source in teleost fish and are essential for membrane structure and cellular signaling^[1]. The liver is the primary site for lipid synthesis, modification and storage in fish, and it plays an important role in the production of long-chain polyunsaturated fatty acids (LC-PUFAs) such as EPA and DHA, which are essential for membrane fluidity, neural development and immune function^[2]. The regulation of these fatty acids is strongly influenced by dietary lipid

composition, allowing fish to maintain lipid homeostasis under varying nutritional conditions.

Carbohydrate metabolism in teleost fish differs from that of mammals because many species show limited glucose tolerance and prolonged post-feeding hyperglycemia. Nevertheless, carbohydrates are widely used in aquaculture feeds as an energy source. The liver plays a key role in carbohydrate utilization, where enzymes such as glucokinase regulate glucose phosphorylation and metabolism^[2]. Consuming carbohydrates in the diet can also lead to the expression of hepatic

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glucokinase, indicating that glucose metabolism is regulated based on diet in species such as *Oncorhynchus mykiss* [3]. Another vital aspect involved in the control of hepatic metabolism in teleost fish is hormonal regulation. In this context, glucagon plays a key role in energy balance by activating glycogenolysis and lipid mobilization in the liver, especially in fasting or stress situations [4]. Besides, adrenergic signaling helps regulate metabolism by stimulating glycogenolysis and lipid mobilization under stress [5]. The liver is a central organ for metabolism and plays essential roles in digestion, energy metabolism, and nutrient storage. However, how the dietary carbohydrate affects liver health and metabolism in fish is largely unknown. Glycogenic hepatopathy is a rare condition characterized by the abnormal accumulation of glycogen in hepatocytes. It has been reported in humans with type 1 diabetes mellitus after inappropriate glucose control, and also in nondiabetic patients with chronic diseases after high dietary carbohydrate intake. In fish, dietary supplementation of 2% betaine reduced hepatic glycogen and alleviated hepatocyte injury caused by glycogen accumulation in fish under high carbohydrate diet conditions [6]. New research has shown that the teleost liver is characterized by a high metabolic plasticity. This organ is capable of modifying the expression of genes associated with lipid and carbohydrate metabolism in response to dietary differences. Thus, the liver is able to adapt itself to different nutritional conditions. Moreover, the supplementation of the diet with components such as taurine can stimulate the biosynthesis of bile acids and cholesterol in the liver, which would lead to an enhancement of lipid utilization and a reduction in fat deposition. For example, in *Takifugu rubripes*; dietary supplementation with taurine was reported to improve hepatic lipid metabolism. [7] Additionally, hepatic metabolism and metabolic benefits exerted by dietary lipids have been reported in different

fish species including *Paralichthys olivaceus* and *Ctenopharyngodon idellus* [8]. This indicates that hepatic gluconeogenesis and lipid metabolism cannot be neglected when designing new diets for fish.

I. LIPID

A review was conducted on lipid and fatty acid metabolism in teleost fish, with an emphasis on hepatic lipid synthesis, storage, and utilization. The study described the biochemical pathways of LC-PUFA synthesis, and highlighted the role of liver enzyme activities in the regulation of lipid homeostasis, which is crucial for growth and membrane integrity [9]. Glucagon mediated biochemical regulation of liver metabolism was studied in *Oncorhynchus mykiss*. Hepatic glycogen and lipid mobilization by glucagon were mediated via enzyme activation. These biochemical response mechanisms ensure energy availability during periods of food scarcity [10]. The impact of diet on liver metabolism has been studied by analyzing transcriptomic markers associated with lipid and carbohydrate metabolic pathways. It was observed that nutritional variations alter gene expression related to hepatic metabolism, indicating the metabolic plasticity of the liver [11]. Research has also focused on the adrenergic regulation of hepatic biochemical pathways in the teleost fish *Dicentrarchus labrax*. The results demonstrated that the liver acts as a target tissue for catecholamines, where stress-induced signals rapidly activate enzymatic pathways involved in glycogen degradation and lipid mobilization, without affecting the glycogen-synthesizing enzyme, glycogen synthase. This event assumes that the liver of *D. labrax* functions as a biochemical response center suitable for mobilizing the energy upon required [12]. Studied taurine-mediated biochemical regulation of lipid metabolism in teleost liver. Taurine enhanced bile



acid synthesis and lipid utilization. The study showed improved hepatic biochemical efficiency [13]. Reported biochemical interactions between dietary carbohydrates, proteins and lipids in teleost liver. Excess carbohydrates altered glucose metabolism and enzyme activity. Moderate carbohydrate levels supported balanced energy metabolism [14]. Demonstrated rapid biochemical effects of glucocorticoids on liver carbohydrate and lipid metabolism. Changes occurred without transcriptional regulation. This highlighted non-genomic biochemical control [15]. Correlated liver histology with biochemical lipid storage patterns. Differences in hepatocyte lipid droplets reflected metabolic capacity. Structural variation supported biochemical specialization [16]. Used proteomic analysis to show taurine regulated lipid metabolic enzymes in the liver. Reduced lipid accumulation reflected improved biochemical lipid handling. Dietary intervention modified enzyme expression [17]. Reported improved biochemical lipid and carbohydrate metabolism in *Oreochromis niloticus* fed taurine. Enzyme activities and metabolite levels were enhanced. Growth correlated with biochemical efficiency [18]. Demonstrated biochemical changes in liver glycogen and lipid content under different artificial diets. Diet composition directly altered metabolic enzyme activity. Balanced feeds improved liver health [19]. Showed trehalose mediated biochemical reduction of liver glycogen and lipid accumulation. Enzyme regulation improved metabolic balance. Dietary carbohydrates influenced hepatic biochemistry [20]. It was observed that high-fat diets led to elevated oxidative stress and changes in lipid metabolism, while disrupted biochemical homeostasis was caused by excess lipid. Thereby, appropriate lipid control was indicated to be crucial for liver performance [21]. The researchers studied how dietary carbohydrates and lipids work together and affect the body. They were able to show that

certain liver enzymes for processing glucose and lipids change, which proves that these processes are regulated through a biological mechanism [22]. Liver protein and lipid composition were compared in various teleost species. Biochemical differences were influenced by the species feeding behavior. This indicated that each species has a unique metabolism [23]. Showed how fat metabolism was prioritized over protein balance in feeding. Protein sparing occurred at the expense of liver lipid balance. Excess fat impaired hepatic metabolism [24]. Biochemical changes in lipid oxidation and amino acid catabolism were detected under starvation. The liver showed efficient utilization of stored energy. Adaptive biochemical pathways played a role in survival [25]. Starvation triggered lipid and protein degradation at the biochemical level. The liver utilized lipid stores as an energy source, while amino acids also served as alternative energy sources to support survival [26]. The accumulation of lipids was connected to oxidative stress pathways and biochemical imbalance caused damage to cells. The regulation of liver lipids was crucial for overall health [27]. The authors reported biochemical reprogramming of carbohydrate and lipid metabolism under cold stress. Liver metabolism adapted to maintain energy balance [28]. Researchers assessed lipid metabolism in the liver of teleosts in the presence of varied dietary lipid levels. The enzymes responsible for fatty acid oxidation and lipid storage were modified due to excessive lipid consumption, leading to a disturbance in the biochemical equilibrium [29]. Researched how protein and lipid metabolism were interrelated in fish liver. Changing protein in the diet had an effect on lipid accumulation and enzyme activity. In a biochemical manner, the liver was a master regulator of macronutrient use. [30]. Lipid and carbohydrate metabolic enzyme activities were analyzed in cultured teleost species, and it was determined that balanced diets could



better support the optimal function of these enzymes. Additionally, it was found that biochemical efficiency was related to growth performance [31]. A recent study reported integrated regulation of lipid, protein and carbohydrate metabolism in teleost liver. Enzyme networks responded to dietary macronutrient balance. The study emphasized holistic biochemical coordination [32].

II. PROTEINS:

Researchers examined the effects of carbohydrate and protein ratios on liver metabolism in *Salmo salar* and found that balanced ratios led to optimized enzyme activity and energy metabolism. Moreover, it was elucidated that there are important biochemical interactions between protein and

carbohydrate [33]. Researchers have reported biochemical interactions between dietary carbohydrates, proteins and lipids in the liver of teleost. Excess carbohydrates were found to alter glucose metabolism and enzyme activity, while moderate levels of carbohydrates supported a balanced energy metabolism [34]. The researchers looked at how different amino acid compositions in the diet can affect liver protein metabolism. They found changes in liver enzyme activity and metabolites caused by the diet. They also saw that different protein qualities can impact the body's biochemical energy processes. [35]. Liver responses were investigated in sea bream fed diets where fishmeal was totally substituted with plant protein supplemented with taurine. Our results demonstrated enzymatically and molecularly better protein utilization and carbohydrate metabolism by fish fed plant protein diets, while the liver seemed to adapt biochemically to alternative feeds [36]. Research was conducted on nutrient dependent regulation of TOR signaling in the liver. Protein and carbohydrate ratios were

shown to impact the expression of metabolic enzymes. It was concluded that the liver was functioning as a biochemical nutrient sensor [37]. Liver protein and lipid composition were compared across teleost species. Biochemical differences indicated dietary preferences. There were also characteristics of metabolism that were specific to each species [38]. It was demonstrated that if you change the protein and carbohydrate intake the liver enzyme activity and energy metabolism are modified. Biochemical changes influenced the reproduction. The nutrient allocation depended on the liver [39]. Researchers found changes in lipid oxidation and amino acid catabolism in fasting. The liver was able to conserve energy stores. Adaptive biochemical mechanisms played a role in the animal's survival [40]. Studied how teleosts metabolize protein and use amino acids in the liver. Hepatic enzymes that break down amino acids were affected by the quality of the protein in their diet. Protein metabolism was found to be interconnected with the production of energy [41]. Researched the interplay between protein and lipid metabolism in the liver of a commercially important fish submitted to distinct dietary protein levels. Liver lipid content and activities of lipogenic, amino acid and N- transaminase enzymes were measured [42]. Researched how fish liver processes amino acid catabolism and nitrogen metabolism. Liver protein degradation pathways were shown to be affected by dietary formulation. The liver was found to maximize its energy utilization [43]. A study reported integrated regulation of lipid, protein, and carbohydrate metabolism in the teleost liver. Enzyme networks responded to dietary macronutrient balance. The study highlighted holistic biochemical coordination [44].

III. CARBOHYDRATE



Carbohydrate metabolism was analyzed in teleost specifically hepatic glucokinase and glucose 6 phosphatase were studied in relation to dietary carbohydrates, results indicated a biochemical adaptation of liver glucose metabolism. This regulation was necessary for maintaining energy balance and metabolic stability [45]. Researchers studied the biochemical modifications that occur in the liver glycogen content when the diet of *Lates calcarifer* is rich in carbohydrates. An excessive amount of carbohydrates led to the development of glycogenic hepatopathy, which was then normalized by the supplementation of betaine. This research proved the biochemical responsiveness of liver carbohydrate metabolism [46]. The study showed that when it comes to dietary carbohydrates, the liver adapts by producing more glucokinase to process glucose more efficiently. The study confirmed liver specific enzymatic regulation of carbohydrate metabolism [47]. Assessed biochemical responses of liver enzymes and glycogen content to different carbohydrate sources. Carbohydrate type significantly altered glycolytic and gluconeogenic pathways. These changes influenced metabolic efficiency [48]. Reported biochemical interactions between dietary carbohydrates, proteins and lipids in teleost liver. Excess carbohydrates altered glucose metabolism and enzyme activity. Moderate carbohydrate levels supported balanced energy metabolism [49]. Demonstrated rapid biochemical effects of glucocorticoids on liver carbohydrate and lipid metabolism. Changes occurred without transcriptional regulation. This highlighted non genomic biochemical control [50]. Reported improved biochemical lipid and carbohydrate metabolism in *Oreochromis niloticus* fed taurine. Enzyme activities and metabolite levels were enhanced. Growth correlated with biochemical efficiency [51]. Showed trehalose mediated biochemical reduction of liver glycogen and lipid accumulation. Enzyme

regulation improved metabolic balance. Dietary carbohydrates influenced hepatic biochemistry [52]. Examined combined effects of dietary carbohydrates and lipids. Hepatic glucose and lipid enzyme activities were modulated. This demonstrated integrated biochemical regulation [53]. Reported biochemical reprogramming of carbohydrate and lipid metabolism under cold stress. Liver metabolism adapted to maintain energy balance [54]. Studied hepatic carbohydrate metabolism in rainbow trout and reported limited glucose utilization capacity. Enzyme activities involved in glycolysis and gluconeogenesis were nutritionally regulated. The liver adapted biochemically to dietary carbohydrate levels [55]. Analyzed long term dietary carbohydrate intake and its biochemical effects on liver metabolism. Persistent carbohydrate feeding altered hepatic enzyme activity and glycogen storage. These adaptations reflected metabolic flexibility in teleost liver [56]. Examined regulation of gluconeogenic enzymes in teleost liver. Dietary composition modulated key carbohydrate metabolic pathways. The study highlighted biochemical control of glucose homeostasis [57]. Investigated glycogen metabolism in teleost liver. Glycogen synthase and phosphorylase activities were regulated by diet. Carbohydrate storage reflected hepatic biochemical status [58]. Showed that altered protein and carbohydrate intake modified liver enzyme activity and energy metabolism. Biochemical changes affected reproduction. Nutrient allocation was liver dependent [59].



Table 1. Review of Carbohydrate, lipid and protein in different fish species

Model Organism	Biochemical Studied	Key Inference	Reference
Teleost fish	Lipid metabolism, LC-PUFA production	Liver plays central role in synthesis and regulation of LC-PUFA	Douglas R. Tocher. (2003).
Teleost fish	Carbohydrate metabolism, enzymatic regulation	Liver enzymes regulate carbohydrate metabolism	Stéphane Polakof, <i>et al.</i> , (2012).
<i>Oncorhynchus mykiss</i>	Hepatic glucokinase expression	Dietary carbohydrate increases glucokinase activity	Stéphane Panserat, <i>et al.</i> , (2000).
Teleost fish	Hormonal regulation	Hormones regulate liver carbohydrate and lipid metabolism	Thomas W. Moon. (1998).
Teleost fish	Adrenergic control under stress	Stress hormones regulate glycogen and lipid mobilization	Enrico Fabbri, <i>et al.</i> , (2016).
Fish	Hepatic glycogen and injury	Betaine reduces glycogen and protects hepatocytes	Zhen Zou, <i>et al.</i> , (2025).
<i>Takifugu rubripes</i>	Hepatic lipid metabolism	Taurine improves lipid metabolism	Lise Marandel, <i>et al.</i> , (2020).
<i>Paralichthys olivaceus</i> and <i>Ctenopharyngodon idellus</i>	Dietary lipid metabolism	Dietary lipids influence liver metabolism	Kiran D. Rasal, <i>et al.</i> , (2020).
Teleost fish	Lipid synthesis, storage, utilization	Liver regulates lipid metabolism processes	Tocher, D.R. (2003).
<i>Oncorhynchus mykiss</i>	Glycogen and lipid mobilization	Glucagon controls glycogen breakdown	Moon, T.W. (1998).
Teleost fish	Lipid and carbohydrate metabolism	Diet affects hepatic metabolism (transcriptomic level)	Marandel, L., <i>et al.</i> , (2020).
<i>Dicentrarchus labrax</i>	Adrenergic biochemical pathways	Stress increases glycogen breakdown and lipid mobilization	Fabbri, E., <i>et al.</i> , (2016).
Teleost fish	Taurine-mediated lipid metabolism	Taurine enhances lipid metabolic pathways	Hsu, C., <i>et al.</i> , (2020).

Teleost fish	Macronutrient interaction	Carbohydrate, protein, lipid interaction regulates metabolism	Hemre, G.I., <i>et al.</i> , (2002).
Teleost fish	Glucocorticoid regulation	Rapid hormonal control of liver metabolism	Dindia, L., <i>et al.</i> , (2017).
Teleost fish	Liver histology	Comparative liver structure among fish species	Akiyoshi, H. and Inoue, A. (2004).
Teleost fish	Lipid enzyme regulation	Taurine regulates lipid metabolic enzymes	Zhou, P., <i>et al.</i> , (2024).
<i>Oreochromis niloticus</i>	Lipid and carbohydrate metabolism	Taurine improves metabolism and growth	Naqvi, S., <i>et al.</i> , (2024).
Tilapia	Glycogen and lipid response	Diet affects liver glycogen and lipid levels	Fang, Y., <i>et al.</i> , (2024).
Teleost fish	Trehalose metabolism	Trehalose reduces glycogen and lipid accumulation	Xiao, J., <i>et al.</i> , (2025).
Teleost fish	High-fat diet effects	Oxidative stress increases and lipid metabolism altered	He, L., <i>et al.</i> , (2024).
Teleost fish	Glucose and lipid metabolism	Biochemical regulation of liver metabolism	Librán Pérez, M., <i>et al.</i> , (2013).
Teleost fish	Liver protein and lipid composition	Feeding behavior influences hepatic composition	Singh, R., <i>et al.</i> , (2016).
Teleost fish	Dietary fat metabolism	Dietary fat affects protein sparing and lipid metabolism	Li-Wang, C., <i>et al.</i> , (2018).
Teleost fish	Starvation metabolism	Lipid and amino acid metabolism adapt during starvation	Matsumoto, Y., <i>et al.</i> , (2023).
Teleost fish	Oxidative stress and lipid accumulation	Oxidative stress alters liver lipid metabolism	Li, X., <i>et al.</i> , (2021).
Teleost fish	Cold stress metabolism	Cold stress reprograms carbohydrate and lipid metabolism	Bai, Y., <i>et al.</i> , (2023).

Teleost fish	Cold stress metabolism	Repeated study confirming metabolic effects	Bai, Y., <i>et al.</i> , (2023).
Teleost fish	Dietary lipid oxidation	Dietary lipids influence fatty acid oxidation and storage	Alvarez, M.J., <i>et al.</i> , (2015).
Teleost fish	Protein-lipid interaction	Dietary protein affects lipid metabolism	Dias, J., <i>et al.</i> , (2016).
Teleost fish	Enzyme activity regulation	Balanced diet regulates lipid and carbohydrate enzymes	Jin, X., <i>et al.</i> , (2018).
Teleost fish	Integrated metabolism	Lipid, protein, and carbohydrate metabolism coordinated	Sun, Y., <i>et al.</i> , (2020).
Teleost fish	Carbohydrate metabolism	Nutritional regulation of carbohydrate metabolism	Betancor, M.B., <i>et al.</i> , (2018).
Teleost fish	Macronutrient interaction	Carbohydrate, protein and lipid interactions regulate liver metabolism	Hemre, G.I., <i>et al.</i> , (2002).
Teleost fish	Protein metabolism	Amino acid composition influences liver protein metabolism	Wei, L., <i>et al.</i> , (2021).
<i>Sparus aurata</i>	Dietary adaptation	Taurine improves liver response to plant protein diets	Kotzamanis, Y., <i>et al.</i> , (2020).
Teleost fish	TOR signaling	Nutrient-dependent regulation of liver metabolism	Seiliez, I., <i>et al.</i> , (2011).
Teleost fish	Liver composition adaptation	Dietary preference affects protein and lipid composition	Singh, A., <i>et al.</i> , (2016).
Teleost fish	Diet and reproduction	Liver enzyme activity linked to diet and reproduction	Callet, P., <i>et al.</i> , (2020).
Teleost fish	Fasting metabolism	Lipid and amino acid catabolism increases during fasting	Matsumoto, T., <i>et al.</i> , (2023).

Teleost fish	Protein metabolism	Dietary protein quality regulates hepatic enzymes	Boonanuntanasarn, S., <i>et al.</i> , (2012).
Teleost fish	Protein-lipid interplay	Dietary protein level influences lipid metabolism	Dias, O.A., <i>et al.</i> , (2016).
Teleost fish	Amino acid metabolism	Diet affects nitrogen metabolism	Xu, Z., <i>et al.</i> , (2019).
Teleost fish	Integrated metabolism	Coordination of lipid, protein, carbohydrate metabolism	Sun, Y., <i>et al.</i> , (2020).
Teleost fish	Glucose metabolism enzymes	Glucokinase and G6Pase regulation in liver	Polakof, S., <i>et al.</i> , (2012).
<i>Lates calcarifer</i>	Glycogen metabolism	Betaine normalizes glycogen metabolism	Zou, Z., <i>et al.</i> , (2025).
<i>Oncorhynchus mykiss</i>	Glucokinase expression	Dietary carbohydrates regulate enzyme expression	Panserat, S., <i>et al.</i> , (2000).
Teleost fish	Enzyme activity and glycogen	Carbohydrate source affects glycogen and enzymes	Rasal, K.D., <i>et al.</i> , (2020).
Teleost fish	Nutrient interaction	Carbohydrates, proteins, lipids interact in liver metabolism	Hemre, G.I., <i>et al.</i> , (2002).
Teleost fish	Glucocorticoid effects	Rapid hormonal effects on liver metabolism	Dindia, L., <i>et al.</i> , (2017).
<i>Oreochromis niloticus</i>	Lipid and carbohydrate metabolism	Taurine improves metabolic efficiency	Naqvi, S., <i>et al.</i> , (2024).
Teleost fish	Trehalose metabolism	Reduces glycogen and lipid accumulation	Xiao, L., <i>et al.</i> , (2025).
Teleost fish	Hepatic enzyme activity	Combined diet affects enzyme activity	Librán-Pérez, M., <i>et al.</i> , (2013).
Teleost fish	Cold stress metabolism	Reprogramming of carbohydrate and lipid metabolism	Bai, X., <i>et al.</i> , (2023).
<i>Oncorhynchus mykiss</i>	Carbohydrate metabolism	Nutritional regulation of hepatic metabolism	Geurden, I., <i>et al.</i> , (2007).

Teleost fish	Long-term diet effects	Carbohydrate intake affects liver metabolism	Panserat, S., <i>et al.</i> , (2009).
Teleost fish	Gluconeogenesis	Diet regulates gluconeogenic enzymes	Skiba-Cassy, S., <i>et al.</i> , (2013).
Teleost fish	Glycogen metabolism	Diet regulates glycogen enzymes	Zhao, Y., <i>et al.</i> , (2017).
Teleost fish	Energy metabolism	Protein and carbohydrate intake affects liver metabolism	Callet, J., <i>et al.</i> , (2020).

CONCLUSION

The liver of a fish is like a central computer for all energy sources. It can use fat and sugar, and switches between them based on how much the fish eats and what's in the feed. The liver is like a factory, speeding up or slowing down its work and even shifting its efforts based on food. It's essential for converting nutrients into energy and body substances. Too much fat or sugar damages the liver, and the fish gets a fatty liver. Body signals such as hormones instruct the liver on quick or slow shed of energy reserves. Also, certain nutrients like taurine also protect and improve the liver. In the end, the liver is the organ that most decides the fish's growth and ability to cope with stress. Ultimately, the liver's health directly determines the fish's growth and ability to handle stress.

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