BIODIVERSITAS
Volume 26, Number 10, October 2025
Pages: 4865-4873

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d261003

Habitat-driven variation in amino and fatty acid profiles of Rabbitfish from the Makassar Strait and Gulf of Bone, Sulawesi, Indonesia

IRMAN HALID[1,♥], ARHAM RUSLI[2,♥♥], PATAHIRUDDIN[3], SISWATI[3], MARHAYANA SYARIFUDDIN[3], WITNO[4], RIHADATUL AISYA AR RAZAK[5], IKBAL SYUKRONI[2]

[1]Postgraduate School of Fisheries Science, Universitas Andi Djemma. Jl. Malatobong No. 1, Palopo 91914, South Sulawesi, Indonesia. Tel.: +62-471-24506, ♥email: irmanhalid@unanda.ac.id
[2]Department of Agricultural Technology, Politeknik Pertanian Negeri Pangkep. Jl. Poros Makassar-Parepare Km. 83, Pangkep 90652, South Sulawesi, Indonesia. Tel.: +62-410-2312704, ♥♥email: arhamrusli@polipangkep.ac.id
[3]Department of Fisheries, Universitas Andi Djemma. Jl. Malatobong No. 1, Palopo 91914, South Sulawesi, Indonesia
[4]Department of Forestry, Universitas Andi Djemma. Jl. Malatobong No. 1, Palopo 91914, South Sulawesi, Indonesia
[5]Department of Fisheries, Faculty of Marine Sciences and Fisheries, Universitas Hasanuddin. Jl. Perintis Kemerdekaan KM. 10, Makassar 90245, South Sulawesi, Indonesia

Manuscript received: 7 June 2025. Revision accepted: 2 October 2025.

Abstract. *Halid I, Rusli A, Patahiruddin, Siswati, Syarifuddin M, Witno, Ar Razak RA, Syukroni I. 2025. Habitat-driven variation in amino and fatty acid profiles of Rabbitfish from the Makassar Strait and Gulf of Bone, Sulawesi, Indonesia. Biodiversitas 26: 4865-4873.* This study aimed to determine the amino and fatty acid profiles of Rabbitfish (*Siganus* spp.) inhabiting different marine environments, specifically the Makassar Strait and the Gulf of Bone, Indonesia. Samples were collected from four locations: Balang Lompo Island, Panikiang Island, Karang-Karangan, and Batu Lotong waters. Freshly caught specimens were transported to the laboratory in ice-cooled containers to maintain sample integrity before preparation and biochemical analysis. To assess the effect of habitat, the amino acid and fatty acid compositions of rabbitfish muscle tissues were quantified, and the data were statistically analyzed using One-Way ANOVA. The results revealed significant habitat-driven variation, with rabbitfish collected from Panikiang Island exhibiting the most complete and diverse amino acid profile. Both essential and non-essential amino acids showed significant differences compared to the other three sites, except for glycine and cysteine, which remained relatively consistent. Similarly, the fatty acid profiles of Panikiang Island samples were more comprehensive, with higher concentrations and diversity than those of fish from Balang Lompo, Karang-Karangan, and Batu Lotong. These findings demonstrate that habitat characteristics play an important role in shaping the biochemical composition of rabbitfish, providing valuable insights into ecological adaptation, nutritional quality, and potential implications for fisheries management and aquaculture development.

Keywords: Amino acids, fatty acids, Gulf of Bone, Makassar Strait, rabbitfish

Abbreviations: ANOVA: Analysis of Variance, ARA: Arachidonic Acid, DHA: Docosahexaenoic Acid, DPA: Docosapentaenoic Acid, EPA: Eicosapentaenoic Acid, LC-PUFA: Long-Chain Polyunsaturated Fatty acids (LC-PUFA)

INTRODUCTION

Rabbitfish (*Siganus canaliculatus* (Park, 1797)) is an essential marine fish in various habitats, including straits and gulf. It is known for its unique feeding behaviours and ecological roles in aquatic ecosystems. In addition, rabbitfish is an herbivorous fish that feeds on various algae and seagrass. Its eating habits make this fish play a crucial role in maintaining the balance of coral reefs and seagrass beds by controlling algae growth (Topor et al. 2019; Müller et al. 2021). Habitat type can influence feeding behavior and biochemical composition of rabbitfish. Studies have shown that differences in temperature, salinity, and food sources affect the levels of amino and fatty acids in marine fish (LaMonica et al. 2021).

According to previous studies, rabbitfish has high economic value and is a target of traditional fishermen in several regions in Indonesia, especially in the Makassar Strait and the Gulf of Bone. The tender meat and delicious flavor make it a favorite fish in traditional and modern cuisine. Rabbitfish fisheries support coastal livelihoods and supply local and regional markets, emphasizing their ecological and economic importance (Jaikumar 2012; Halid 2018; Kamilan et al. 2023; Awaluddin et al. 2024). However, the flavor and aroma of the meat in each region have distinct differences and characteristics, showing that the fish is endemic to certain waters.

The flavor of rabbitfish is greatly influenced by its amino acid content. Amino acids, especially those classified as non-essential, such as glutamic and aspartic, can enhance the meat's natural savory taste (umami). Collagen-derived peptides also influence the perception of sweet and bitter tastes (Hu et al. 2022). The influence of amino acid content on the aroma of fish meat can occur through various biochemical pathways and reactions. Amino acids serve as precursors for the formation of volatile compounds that contribute to the aroma profile (Zhang et al. 2022). For example, cysteine facilitates the formation of sulfur-containing

compounds, contributes to the aroma of meat, and reduces the bitter taste (Ding et al. 2023).

In addition to the amino acid content, the flavor and aroma of rabbitfish meat are also influenced by fatty acid content. The flavor is affected by Poly-Unsaturated Fatty Acids (PUFA). Due to the inability of fish to synthesize these fatty acids, the compounds are often obtained from their food. The fatty acid profile, including the balance of saturated, monounsaturated, and polyunsaturated fatty acids, significantly influences the flavor and perception of meat (Roy et al. 2022; Choudhury et al. 2023).

Amino and fatty acid profiles are crucial biochemical markers that reflect the nutritional status and ecological adaptations of marine organisms. Various factors, including the type of diet, habitat, and environmental conditions, influence these profiles. Understanding the profiles can provide valuable insights into the ecological roles and physiological adaptations, particularly those with significant environmental and economic importance. Environmental factors, such as water temperature, salinity, and nutrient availability, have been shown to alter the composition of amino and fatty acids in fish muscle (Keva et al. 2019; Bayissa et al. 2021; Fernandez-López et al. 2024).

Ecological factors, such as temperature, feed diet, salinity, and ecosystem conditions (Antonucci et al. 2019; Maikanov et al. 2020; Kondratiuk and Otchenashko 2021), can directly or indirectly influence the amino acid and fatty acid profiles of fish. Extreme increases in water temperature can lead to increased concentrations of free amino acids in various tissues, indicating a shift in amino acid metabolism in response to temperature stress (Wang et al. 2019). Temperature changes can also lead to changes in fatty acid profiles, such as an increase in PUFA, suggesting adaptive mechanisms to cope with the current condition (Antonucci et al. 2019). Global environmental changes, including warming and shifting nutrient ratios, can reduce the availability of PUFA in fish food webs, thereby reducing the nutritional quality (Lau et al. 2021). Nutrient availability, which varies significantly across different marine habitats, has a substantial impact on the fatty acid composition in marine fish (Ho et al. 2024). A low salinity of about 20 ppt increases the expression of key enzymes involved in fatty acid biosynthesis, thereby increasing the ability of fish to produce PUFA from food sources (Marrero et al. 2024).

Studies on amino and fatty acids profiles of rabbitfish in various habitats, especially the waters of the Makassar Strait and the Gulf of Bone, have never been conducted. This information is crucial in providing data related to the relationship between environmental factors and the profiles. Therefore, this study aims to examine the amino and fatty acid profiles of rabbitfish caught in the Makassar Strait and the water of the Gulf of Bone, Indonesia.

MATERIALS AND METHODS

Study area

Rabbitfish samples used in this study were obtained from 2 water locations, namely the Makassar Strait and the Gulf of Bone, Sulawesi, Indonesia. To enhance spatial resolution, samples from the Makassar Strait (Figure 1) were obtained explicitly from two fishing locations: Balang Lompo Island, Pangkajene Islands District (corresponding to point 4: 04°57'06.98"S, 119°23'37.98"E) and Panikiang Island, Barru District (corresponding to point 3: 04°21'32.94"S, 119°35'22.71"E). Similarly, samples from the Gulf of Bone (Figure 1) were obtained from Luwu District, specifically from two fishing locations: Karang-Karangan (corresponding to point 1: 03°07’41.45”S, 120°16’16.21”E) and Batu Lotong (corresponding to point 2: 03°32'37.90"S, 120°24'58.45"E).

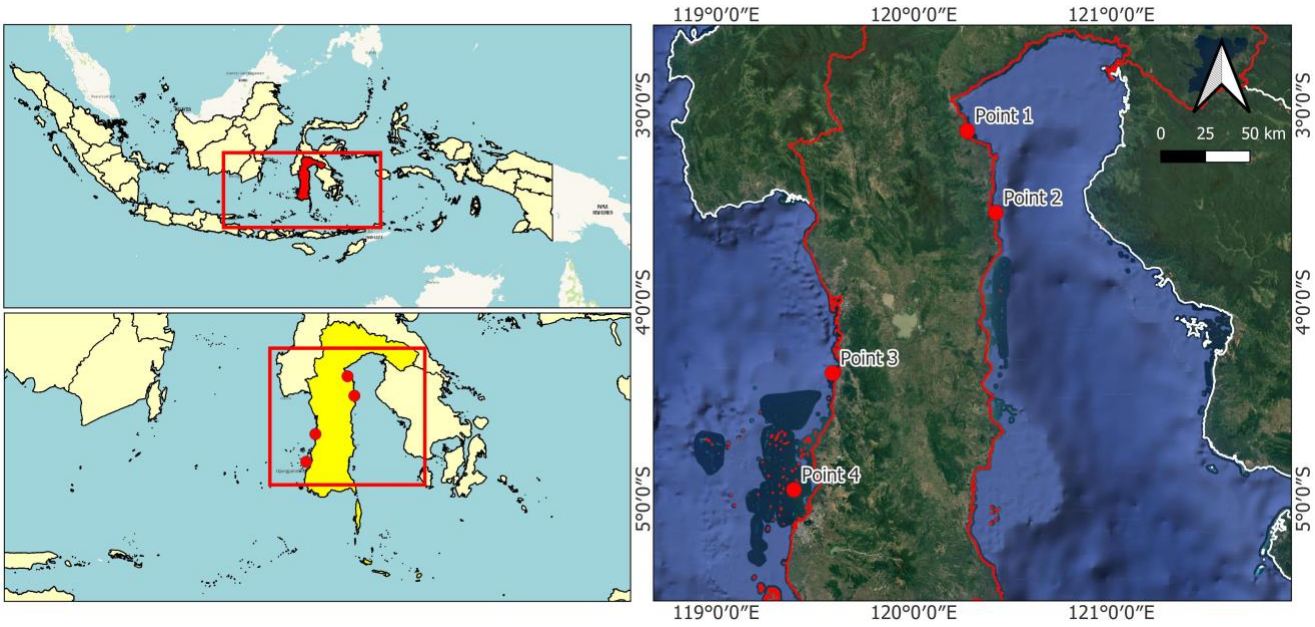

Figure 1. Satellite imagery Rabbitfish fishing location (habitat): Point 1 (03°07'41.45"S, 120°16'16.21"E), point 2 (03°32'37.90"S, 120°24'58.45"E), point 3 (04°21'32.94"S, 119°35'22.71"E), and point 4 (04°57'06.98"S, 119°23'37.98"E), Sulawesi, Indonesia

Procedures

Sample collection and species identification

A total of 50 individual rabbitfish were collected from each study location (Makassar Strait and Gulf of Bone). Approximately 25 fish were collected from each of these four specific sub-locations to ensure representative sampling across the broader study areas. Fish were collected using traditional fishing gear operated by local fishermen, ensuring the representation of locally harvested specimens. Upon collection, all fish were immediately placed into a cool box with a fish-to-ice ratio of 1:2 (w/w) to maintain the cold chain and preserve freshness until laboratory preparation. Sampling was carried out twice for each designated location.

Species identification was performed visually based on distinct morphological characteristics. The experienced local fishermen, familiar with the species, performed the initial identification. The fish identification was further carried out by observable traits such as body shape, coloration patterns (e.g., spots, stripes), and the presence of venomous dorsal and anal spines characteristic of *Siganus canaliculatus*.

Sample preparation

Fresh rabbitfish were filleted under sterile conditions to obtain muscle tissue. From each individual, 100 g of dorsal muscle meat was accurately weighed. This muscle tissue was then homogenized to ensure uniformity. The homogenized sample was subjected to a sequential solvent extraction process for lipid and amino acid analysis. The fish meat was macerated with acetone at a ratio of 1:4 (w/v) for 24 hours at room temperature (approximately 25°C), followed by sonication at 30°C for 60 minutes using an ultrasonic bath. The resulting filtrate was separated using nylon mesh (300 µm pore size). The residue was then subjected to a second extraction with n-hexane at a ratio of 1:4 (w/v), followed by another 24-hour maceration and 60-minute sonication at 30°C. This filtrate was also filtered through nylon mesh, followed by re-maceration using hexane on the remaining residue. All obtained filtrates were combined and concentrated under reduced pressure using a rotary evaporator at 40°C to remove the solvents, yielding a lipid-rich extract. The concentrated extract was then transferred into a sample bottle and stored at -20°C for subsequent analysis of amino acids and fatty acids.

Amino acids testing (Waters 2012)

Amino acid analysis was performed by preparing a single-point external standard solution supplemented with an internal standard to ensure accurate instrument calibration. Test samples were precisely weighed and subjected to acid hydrolysis with concentrated HCl to release free amino acids. The hydrolysate was quantitatively transferred to a 50 mL volumetric flask, diluted to volume with ultrapure water (Milli-Q grade), and homogenized thoroughly. The solution was then filtered through a 0.2 µm syringe filter to remove particulates, and the filtrate was collected in clean vials. An internal standard was added to the filtrate, followed by pre-column derivatization using the Waters AccQ•Tag Ultra kit. Derivatization was carried out with 6-aminoquinolyl-N-hydroxysuccinimidyl carbamate (AQC), which reacts with amino acids to form stable derivatives suitable for chromatographic separation.

Chromatographic separation and quantification were performed using a Waters ACQUITY UPLC system equipped with a Waters AccQ•Tag Ultra C18 column (1.7 µm, 2.1 × 100 or 150 mm). The mobile phase consisted of AccQ•Tag Ultra Eluent A and B in gradient mode, with the column maintained at 49°C. Detection was carried out using a Photo-Diode Array (PDA) detector at a wavelength of 260 nm. Chromatographic data were processed with Empower software to ensure accuracy and reproducibility. Amino acid levels in a sample using the ratio of the analyte area to the standard internal were calculated using the following formula:

$$\text{Standard or sample ratio (RS)} = \frac{A_{spl}}{A_{IS}}$$

$$\text{Amino Acid Levels (mg/Kg)} = \frac{\frac{\text{Sample ratio}}{\text{Standard ratio}} \times \frac{C_{std}}{1.000.000} \times BM \times Va \times Fp}{W_{spl}}$$

Where :

A_{spl} : Area of amino acids analyte

A_{IS} : Area of internal standard

C_{Std} : Concentration of amino acids standard solution (pmol/µL)

BM : Molecular weight of amino acids

Va : Final volume of the sample (µL)

Fp : Dilution factor

W_{spl} : Sample weight (g)

Fatty acids testing

Approximately 100 mg of the homogenized muscle sample was subjected to lipid extraction. The sample was combined with 100 mL of a 1:1 (v/v) methanol: chloroform mixture. Ultrasonic extraction was performed for 30 minutes at 55°C. Following extraction, the mixture was centrifuged (e.g., at 3000 rpm for 10 minutes) to separate the supernatant. The lipid-containing supernatant was then carefully transferred into a 3 mL vial for subsequent Gas Chromatography-Mass Spectrometry (GC-MS) analysis. Fatty Acid Methyl Esters (FAMEs) were analyzed using a Shimadzu GC-MS-QP2010 Ultra system. The GC-MS instrument conditions were set as follows: The injector temperature was maintained at 250°C in Splitless mode, with a pressure of 76.9 kPa and a flow rate of 14 mL/min. The ion source and interface temperatures were 200°C and 280°C, respectively. A solvent cut time of 3 minutes was applied, and the mass scan range was set from 400 to 700 m/z. Separation was achieved using an SH-Rxi-5Sil MS capillary column (30 m length, 0.25 mm inner diameter, 0.25 µm film thickness). The oven temperature program commenced at 70°C, held for 2 minutes, then increased to 200°C at a rate of 10°C/min, and finally ramped to 280°C at a rate of 50°C/min, holding for 9 minutes. The total analysis time was 36 minutes. Chromatographic data were processed and identified by comparing with the NIST 17 and Wiley 9 mass spectral libraries (Figure 2).

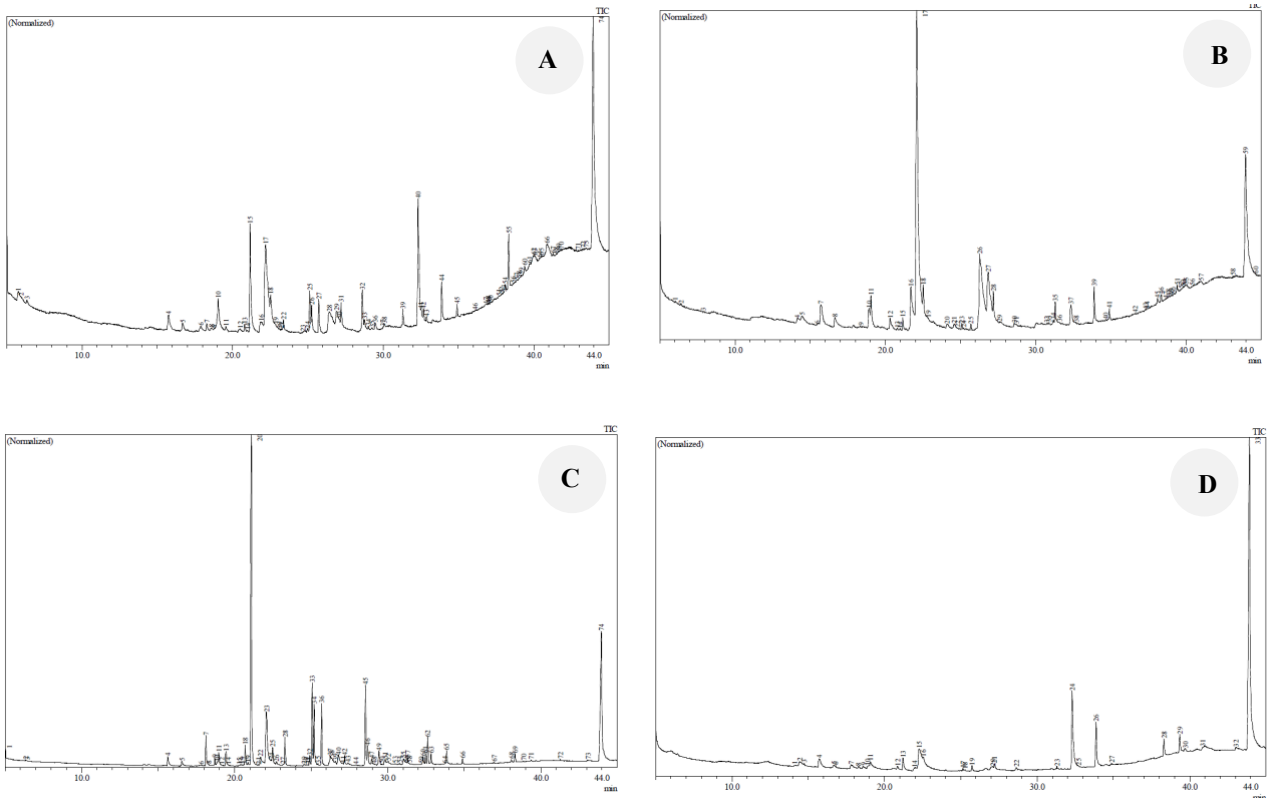

Figure 2. Chromatogram of fatty acids of rabbitfish collected from the: A. Makassar Strait 1, B. Makassar Strait 2, C. Gulf of Bone 1, and D. Gulf of Bone 2

Data analysis

Data was analyzed using SPSS Ver. 27 (SPSS Inc.) software using One-Way ANOVA to determine the influence of habitat on amino and fatty acids of rabbitfish. The Tukey test revealed significant differences in amino and fatty acids of rabbitfish based on their habitat.

RESULTS AND DISCUSSION

Amino acid profile

Marine fish have a high nutritional content, especially in the content of essential amino acids that are important for human health. The protein content of marine fish varied, but it generally contained all essential amino acids in sufficient proportions, making fish meat a complete source of protein. Furthermore, marine fish typically exhibit a low content of saturated fatty acids and a high content of omega-3 fatty acids, which contribute to human health benefits (Raja et al. 2024). The amino acid profile of rabbitfish from the Makassar Strait and the Gulf of Bone is presented in Table 1.

The results showed that the amino acid content of rabbitfish was significantly influenced by the habitat in which the fish lived, in terms of types and numbers. The amino acid composition of rabbitfish from the waters of the Makassar Strait 2 was more complete and higher than that of rabbitfish living in the waters of the Makassar Strait 1, Gulf of Bone 1, and Gulf of Bone 2. The rabbitfish from Panikiang Island (Makassar Strait 2) had significantly different essential and non-essential amino acids compared to those from other waters, except for glycine and cysteine.

Fatty acids profile

Factors affecting fish fatty acid profiles included temperature, salinity, type of food, geographic region, and season. The pelagic and demersal fish contained high levels of omega-3 and omega-6 polyunsaturated fatty acids, which are beneficial to human health (Ramesh and Venkateshwarlu 2022). The fatty acid profile of rabbitfish from the Makassar Strait and the Gulf of Bone was presented in Table 2.

The findings of the study showed that the habitat of rabbitfish affected their fatty acid profile. Rabbitfish from the Strait and the Gulf varied in the quantity and composition of fatty acids. In this study, the fatty acid content of rabbitfish from the Makassar Strait 2 was better than that collected from the other 3 study sites. Rabbitfish from Panikiang Island, Barru District, had only two undetected fatty acids. In comparison, those collected from Balang Lompo Island, Pangkep District (Makassar Strait 1), and Karang-Karangan, Luwu District (Gulf of Bone 1) exhibited 6 and 5 amino acids that were not detected, respectively. Rabbitfish caught in Batu Lotong, Larompong District, Luwu District (Gulf of Bone 2) only contained 3 types of fatty acids. An interesting result showed that the fatty acids of rabbitfish from Pangkep District differed from those of the other study sites.

Table 1. Amino acids profile (mg/g) of rabbitfish caught in the Makassar Strait and the Gulf of Bone, Sulawesi, Indonesia

Types of amino acids	Makassar Strait 1	Makassar Strait 2	Gulf of Bone 1	Gulf of Bone 2
Essential amino acids				
Phenylalanine	0.48±0.00^{b}	7.38±0.03^{d}	1.49±0.01^{c}	ND^{a}
Valine	1.03±0.00^{c}	9.23±0.04^{d}	2.70±0.02^{b}	0.59±0.00^{a}
Histidine	0.42±0.00^{c}	1.73±0.01^{d}	ND^{a}	0.34±0.00^{b}
Methionine	0.00±0.00^{a}	4.32±0.01^{c}	0.08±0.00^{b}	0.00±0.00^{a}
Isoleucine	0.66±0.00^{b}	6.50±0.04^{d}	1.65±0.01^{c}	0.27±0.00^{a}
Leucine	1.07±0.00^{b}	17.44±0.06^{d}	3.61±0.02^{c}	0.69±0.00^{a}
Lysine	0.71±0.00^{a}	7.76±0.03^{d}	2.84±0.01^{c}	1.11±0.00^{b}
Threonine	0.74±0.00^{b}	6.30±0.04^{d}	1.23±0.01^{c}	0.63±0.00^{a}
Tryptophan	ND^{a}	1.46±0.00^{b}	ND^{a}	ND^{a}
Non-essential amino acids				
Tyrosine	ND^{a}	4.45±0.03^{b}	ND^{a}	ND^{a}
Glycine	6.87±0.03^{b}	17.01±0.09^{c}	17.1±0.09^{c}	6.16±0.04^{a}
Alanine	3.2±0.01^{b}	16.56±0.09^{d}	9.86±0.04^{c}	2.10±0.01^{a}
Arginine	0.75±0.00^{b}	7.73±0.05^{d}	4.04±0.04^{c}	ND^{a}
Serina	3.36±0.01^{c}	7.08±0.04^{d}	2.23±0.02^{b}	1.15±0.00^{a}
Proline	1.96±0.01^{b}	10.06±0.09^{d}	9.40±0.05^{c}	0.55±0.00^{a}
Cystine	ND^{a}	2.85±0.00^{b}	3.61±0.02^{c}	ND^{a}
Glutamic acid	1.54±0.00^{a}	18.21±0.06^{d}	5.77±0.03^{c}	3.44±0.07^{b}
Aspartic acid	1.46±0.00^{b}	10.37±0.07^{d}	1.86±0.00^{c}	0.82±0.00^{a}

Note: Different superscript letters in the same row show significant differences at the 95% confidence level

Table 2. Fatty acid profile (g/100g) of rabbitfish caught in the Makassar Strait and the Gulf of Bone, Sulawesi, Indonesia

Types of fatty acids	Makassar Strait 1	Makassar Strait 2	Gulf of Bone 1	Gulf of Bone 2
Saturated fatty acids				
Miristic acid	ND^{a}	1,34±0,04^{c}	0,41±0,00^{b}	ND^{a}
Pentadecanoic acid	0,27±0,08^{b}	0,82±0,15^{c}	0,11±0,01^{b}	ND^{a}
Palmitic acid	12,00±1,16^{a}	30,30±2,13^{b}	7,36±0,03^{a}	7,06±1,20^{a}
Tridecanoic acid	0,19±0,02^{b}	ND^{a}	ND^{a}	ND^{a}
Margaric acid	ND^{a}	0,41±0,01^{b}	ND^{a}	ND^{a}
Stearic acid	12,05±0,88^{c}	7,85±0,66^{b}	1,87±0,06^{a}	1,45±0,16^{a}
Arachidonic acid	ND^{a}	1,54±0,35^{c}	0,59±0,07^{b}	ND^{a}
Unsaturated fatty acids				
Palmitoleic acid	1,51±0,02^{a}	4,80±0,11^{b}	1,01±0,03^{a}	0,97±0,41^{a}
Heptadecanoic acid	ND^{a}	0,42±0,01^{b}	ND^{a}	ND^{a}
Oleic acid	4,54 ±0,46^{b}	11,49±2,72^{c}	1,28±0,25^{b}	ND^{a}
Octadecanoic acid	ND^{a}	5,69±0,81^{c}	1,25±0,02^{b}	ND^{a}
Linoleic acid	0,08±0,04^{b}	ND^{a}	ND^{a}	ND^{a}
Thymnodonic acid (EPA)	ND^{a}	0,57±0,02^{b}	ND^{a}	ND^{a}

Note: Different superscript letters in the same row show significant differences at the 95% confidence level

Discussion

The difference in composition and content of amino acids in fish was closely related to the availability of food, fish-eating habits, and aquatic environmental conditions. The level of fertility or primary productivity of waters significantly affects the availability of food in the waters. The Makassar Strait typically exhibits higher primary productivity than many other bodies of water in Indonesia, including the Gulf of Bone. The concentration of chlorophyll in the Gulf of Bone ranges from 0.2 to 0.5 mg/m³, and the Makassar Strait from 0.4 to 0.7 mg/m³ (Rosdiana et al. 2017; Zainuddin et al. 2017; Musgamy et al. 2024). Variations in primary productivity also influence the quality of organic matter and the microbial communities attached to substrates such as seagrass and coral rubble, which serve as feeding grounds for herbivorous fish, including rabbitfish. Differences in food quality affect the amino acid pools and protein composition at the site-specific level (Jo et al. 2022). Habitats with different protein compositions can result in fish protein compositions. In addition, the physiological adaptation of fish to their environment can result in variations in amino acid synthesis and accumulation (Ryu et al. 2021). The reduced feeding activity of the deep-sea decapod *Aristeus antenatus*, a physiological adaptation to winter, resulted in the progressive hydrolysis of muscle proteins, as indicated by a higher free amino acid content. Previous studies have shown that the liberated amino acids enter the free amino acid pool and are available for energy production (Rosa and Nunes 2024).

Fish that lived in nutrient-rich environments had a more balanced amino acid profile due to their diverse diet. However, fish that lived in less favorable habitats could exhibit imbalances, leading to the accumulation of specific amino acids. Factors, such as sexual ripeness and biological differences, could further modulate the amino acid profile (Roques et al. 2020). The availability, composition of food sources, and eating habits of fish influence the amino acid profile of fish, as demonstrated by Loayza et al. (2023). Furthermore, *Orestias agassizii* fish had a lower histidine content and a higher concentration of taurine than the Orestias luteus fish, suggesting that variations in habitat and fish-eating behavior resulted in differences in amino acid accumulation. The omnivorous nature of both species, combined with their dependence on specific food sources such as amphibians, suggested that habitat quality and food availability directly impacted amino acid composition.

The influence of environmental factors such as temperature and oxygen levels on the amino acid profile of fish meat may occur because they affect metabolic processes within the fish's body. An increase in water temperature led to an increase in metabolic activity and oxygen consumption, which in turn impacted the rise in concentration of free amino acids in various tissues, including the brain, liver, and muscles of fish (Wang et al. 2019). Similarly, a study on rainbow trout revealed that different temperatures affected amino acid metabolism in the liver, with specific amino acids, such as phenylalanine and histidine, showing high concentrations at moderate temperatures, whereas high temperatures induced changes in other metabolic pathways (Tian et al. 2024). Studies in zebrafish have shown that prolonged exposure to higher temperatures increased amino acid catabolism, suggesting a shift in energy metabolism to cope with thermal stress (Aguilar et al. 2022).

The dissolved oxygen content in a body of water significantly affects the amino acid content and protein metabolism in fish. Hypoxia, characterized by low levels of dissolved oxygen, results in decreased protein synthesis in several tissues of fish, including the liver, muscles, and gills. Meanwhile, the heart remained less affected due to its preferred access to oxygen. This decrease in protein synthesis was accompanied by changes in protein degradation pathways, which were regulated differently in response to hypoxia, affecting the amino acid composition in fish meat tissue (Cassidy and Lamarre 2019). A low level of dissolved oxygen could decrease protein and amino acids retention and fish growth, suggesting that adequate oxygen levels were essential for optimal amino acids metabolism and retention in fish. Hypoxia could lead to oxidative stress, ultimately affecting amino acid metabolism by altering gene expression in metabolic pathways. Furthermore, the interaction between oxygen levels and the composition of dietary amino acids, such as lysine, may further modulate the amino acid profile and growth efficiency in fish (Gan et al. 2013; Wang et al. 2024).

Previous studies have shown that the aquatic habitat and environmental conditions significantly determine fish fatty acid content. These habitats and ecological conditions were closely related to the availability of food sources for fish, as food sources varied across different marine environments, resulting in distinct fatty acid profiles in fish (Mathieu-Resuge et al. 2024). Environmental conditions, population density, and food sources affected the lipid content of fish. Variations in habitat and ecological pressures significantly affected the fatty acid composition of marine fish. Environmental factors such as temperature, salinity, and food availability were crucial in determining the accumulation and quality of fatty acids in fish (Rajasilta et al. 2019). Moreover, water chemistry, particularly salinity and nutrients, influences algal fatty acid composition, which is then passed on through the food of herbivorous species, such as rabbitfish. Low-salinity enhances the expression of Fatty Acid Desaturase (FADS2) in *Siganus canaliculatus*, enabling higher biosynthesis of long-chain polyunsaturated fatty acids (e.g., EPA, DHA) from dietary precursors (Marrero et al. 2021).

The Gulf of Bone is a semi-enclosed water system that is sensitive to regional climate variability. The sea surface temperature in the Gulf of Bone was relatively high, averaging around 29 to 31°C, approaching the annual maximum typical of tropical regions. It reached around 30°C during the western season and slightly decreased during the eastern season or following strong winds. It is classified as a shallow bay that receives river water runoff from South Sulawesi, which results in lower surface salinity near the coast. The influx of this fresh river water significantly lowers local salinity in the Gulf of Bone, particularly during the rainy season. The concentration of chlorophyll a, a primary productivity indicator, ranges from 0.1 to 7 mg/m^3, with the highest values in coastal waters, especially after high wave events, indicating an increase in phytoplankton productivity following large waves (Rosalina et al. 2023; Musgamy et al. 2024).

In comparison, the Makassar Strait had a sea surface temperature ranging from 28 to 30°C, which tended to be cooler during the southeast monsoon season and warmer during the western monsoon season, with peak temperatures remaining around 29 to 30°C, exhibiting more noticeable variations due to the monsoon seasons. The Makassar Strait generally has higher salinity, which varies seasonally due to the influence of smaller river flows. During the West Monsoon season, the Indonesian Throughflow brought fresh water from the Java Sea, leading to a decrease in salinity. Meanwhile, during the southeast monsoon, the current introduced deep-sea water with high salinity, causing an increase in salinity levels (Rosdiana et al. 2017).

Temperature and salinity were the main abiotic factors affecting the fatty acid profile in fish. A combination of phylogenetic and ecomorphological factors contributed the most to the variation in EPA and DHA content. Lower temperatures significantly enhanced the accumulation of LC-PUFA in fish tissue. Furthermore, the interaction of food components also affected the fatty acid composition of fish (Gladyshev et al. 2018; Torno et al. 2019). Sea surface temperature and the concentrations of chlorophyll-a affected fatty acid profiles in albacore tuna, with an estimated reduction in essential fatty acids associated with increased sea surface temperatures (Pethybridge et al. 2015). These findings suggest that diet quality, substrate type (e.g., dominance of macroalgae or seagrass), and water chemistry

collectively determine the amino and fatty acid profiles of marine fish. Similar habitat-nutrient links have also been identified in rabbitfish; dietary plasticity among *Siganus* species closely corresponds to local resource availability, indicating strong ecological control over their biochemical variation (Zarco-Perello et al. 2024). Rabbitfish exhibits a unique ability among marine teleosts to synthesize Long-Chain Poly-Unsaturated Fatty Acids (LC-PUFA) from linolenic and linoleic acid precursors, enabling the utilization of plant-based oils in their diet, which can subsequently influence their fatty acid composition (Xie et al. 2016; Xie et al. 2018).

Fatty acid composition in rabbitfish included ARA, EPA, DPA, and DHA, with variations depending on the source of dietary fatty acids and the salinity of the aquatic environment. Fish fed a diet rich in linoleic and alpha-linolenic acid (D2-D4) showed higher levels of arachidonic acid in brackish water (10 ppt) compared to seawater (32 ppt). This study showed that the rabbitfish could convert this precursor of fatty acids into highly unsaturated fatty acids (Li et al. 2008).

The availability of food and the quality of the prey also played an essential role in determining the fatty acid composition of the fish. Fish adjust their fatty acid composition in response to environmental changes in food availability to optimize energy storage and utilization. For instance, mid-water fish species in the North Pacific exhibited varied lipid content and calorie density based on their environmental productivity, with lower lipid content in areas with lower food availability (Bailey and Robison 1986). The effect of food availability on fatty acid composition of fish meat was also found in farmed fish. Previous research has shown that replacing herring oil with high-oleic sunflower oil in the diets of coho salmon and rainbow trout significantly increases oleic acid concentrations in various tissues, notably resulting in a two-fold increase in muscle tissue. A significant increase in oleic acid concentration was observed in various tissues of coho salmon and rainbow trout fed a high-oleic sunflower oil diet. This effect was most pronounced in the muscle, where a two-fold increase occurred (Skonberg et al. 1994). A previous study by Mathieu-Resuge et al. (2024) demonstrated that different marine environments with varied food sources result in several fatty acid profiles in Sardines.

In conclusion, this study demonstrates significant habitat-driven variation in the amino and fatty acid profiles of rabbitfish. Instead, the profiles were primarily affected by environmental factors, particularly habitat characteristics, food availability, and physicochemical parameters such as temperature, salinity, and dissolved oxygen. These findings revealed the relationship between strong trophic and habitat levels, including the influence of preferred seagrass and the ability of species to synthesize long-chain polyunsaturated fatty acids. Nutritionally, rabbitfish represents a valuable source of essential amino acids and omega-3 fatty acids, underscoring its potential to promote dietary health and enhance food security. From a conservation and management perspective, maintaining healthy seagrass beds and water quality is critical to sustaining their nutritional quality and population resilience. Future studies should address seasonal, ontogenetic, and dietary variations, as well as explore feed optimization strategies to enhance the value of this resource for aquaculture and the livelihoods of coastal communities.

ACKNOWLEDGEMENTS

The authors are grateful to the Director of Research, Technology, and Community Service, Directorate General of Higher Education, Research, and Technology, Ministry of Education, Culture, Research, and Technology, for the financial support for the implementation of the study through the 2024 Fundamental Research Grant Program with contract number 840/UM.18/023/VI/2024. The authors are also grateful to the Rector and Head of the Research and Community Service Institution, Universitas Andi Djemma, Indonesia, for their support.

REFERENCES

Aguilar A, Mattos H, Carnicero B, Sanhueza N, Muñoz D, Teles M, Tort L, Boltaña S. 2022. Metabolomic profiling reveals changes in amino acid and energy metabolism pathways in liver, intestine and brain of zebrafish exposed to different thermal conditions. Front Mar Sci 9: 835379. DOI: 10.3389/fmars.2022.835379.

Antonucci M, Belghit I, Truzzi C, Illuminati S, Araujo P. 2019. Modeling the influence of time and temperature on the levels of fatty acids in the liver of Antarctic fish *Trematomus bernacchii*. Polar Biol 42: 2017-2030. DOI: 10.1007/s00300-019-02577-2.

Awaluddin, Budimawan, Nadiarti, Nafie YAL. 2024. Biodiversity and distribution of rabbitfish (Siganidae) in Tanakeke Island, South Sulawesi, Indonesia. Biodiversitas 25: 2756-2762. DOI: 10.13057/biodiv/d250849.

Bailey TG, Robison BH. 1986. Food availability as a selective factor on the chemical compositions of midwater fishes in the Eastern North Pacific. Mar Biol 91: 131-141. DOI: 10.1007/BF00397578.

Bayissa TN, Geerardyn M, Vanhauteghem D, Wakjira M, Janssens GPJ. 2021. Nutrient-related metabolite profiles explain differences in body composition and size in Nile tilapia (*Oreochromis niloticus*) from different lakes. Sci Rep 11 (1): 16824. DOI: 10.1038/s41598-021-96326-3.

Cassidy AA, Lamarre SG. 2019. Activation of oxygen-responsive pathways are associated with altered protein metabolism in Arctic char exposed to hypoxia. J Exp Biol 222: jeb203901. DOI: 10.1242/jeb.203901.

Choudhury S, Basuli D, Das T, Nandi S, Sarkar NS. 2023. Exploring fatty acid connections between estuarine fish *Chelon planiceps* and its diatom diet as taste and nutraceutical property influencing factor. Algal Res 72: 103116. DOI: 10.1016/j.algal.2023.103116.

Ding Y, Yan C, Dai W, Wang Y, Liu S, Zheng R, Zhou X. 2023. Flavor improving effects of cysteine in xylose-glycine-fish waste protein hydrolysates (FPHs) Maillard reaction system. Bioresour Bioprocess 10 (1): 95. DOI: 10.1186/s40643-023-00714-8.

Fernandez-López E, Panzera Y, Bessonart M, Marandino A, Féola F, Gadea J, Magnone L, Salhi M. 2024. Effect of salinity on fads2 and elovl gene expression and fatty acid profile of the euryhaline flatfish *Paralichthys orbignyanus*. Aquaculture 583: 740585. DOI: 10.1016/j.aquaculture.2024.740585.

Gan L, Liu Y-J, Tian L-X, Yue Y-R, Yang H-J, Liu F-J, Chen Y-J, Liang G-Y. 2013. Effects of dissolved oxygen and dietary lysine levels on growth performance, feed conversion ratio and body composition of grass carp, *Ctenopharyngodon idella*. Aquac Nutr 19 (6): 860-869. DOI: 10.1111/anu.12030.

Gladyshev MI, Sushchik NN, Tolomeev AP, Dgebuadze YY. 2018. Meta-analysis of factors associated with omega-3 fatty acid contents of wild fish. Rev Fish Biol Fish 28: 277-299. DOI: 10.1007/s11160-017-9511-0.

Halid I. 2018. Analysis of fisheries aspects of rabbitfish (*Siganus canaliculatus*) in the Gulf of Bone, Luwu Regency. Proceedings of the National Symposium on Marine Affairs and Fisheries. Faculty of

Marine Sciences and Fisheries, Universitas Hasanuddin, Makassar, 29 June 2018. [Indonesian]

Ho QT, Dahl L, Nedreaas K, Azad AM, Bank MS, Berg F, Wiech M, Frantzen S, Sanden M, Wehde H, Frøyland L, Maage A, Madsen L. 2024. Modelling seasonal and geographical n-3 polyunsaturated fatty acid contents in marine fish from the Northeast Atlantic Ocean. Environ Res 252: 119021. DOI: 10.1016/j.envres.2024.119021.

Hu Y, Xiao N, Ye Y, Shi W. 2022. Fish proteins as potential precursors of taste-active compounds: An in silico study. J Sci Food Agric 102 (14): 6404-6413. DOI: 10.1002/jsfa.12006.

Jaikumar M. 2012. A review on biology and aquaculture potential of rabbit fish in Tamilnadu (*Siganus canaliculatus*). Intl J Plant Anim Environ Sci 2 (2): 57-64.

Jo N, Youn S-H, Joo H, Jang HK, Kim Y, Park S, Kim J, Kim K, Kang JJ, Lee SH. 2022. Seasonal variations in biochemical (biomolecular and amino acid) compositions and protein quality of particulate organic matter in the Southwestern East/Japan Sea. Front Mar Sci 9: 979137. DOI: 10.3389/fmars.2022.979137.

Kamilan K, Ramang MS, Susilo H, Fitriyana F, Nurfadilah N, Auliansyah A. 2023. Economic benefits and governance of guiding barrier fishing gear in white-spotted spinefoot fish fishing activities (*Siganus canaliculatus*, Park 1797) Bontang City waters. ECSOFiM: J Econ Soc Fish Mar 11: 77-88. DOI: 10.21776/ub.ecsofim.2023.011.01.07.

Keva O, Tang P, Käkelä R, Hayden B, Taipale SJ, Harrod C, Kahilainen KK. 2019. Seasonal changes in European whitefish muscle and invertebrate prey fatty acid composition in a subarctic lake. Freshwater Biol 64 (11): 1908-1920. DOI: 10.1111/fwb.13381.

Kondratiuk V, Otchenashko V. 2021. Investigation of dependences of the morphological composition of body and amino acid composition of trout meat proteins (*Oncorhynchus mykiss*) on levels of the energy value of feeds. Potravinarstvo Slovak J Food Sci 15: 497-505. DOI: 10.5219/1601.

LaMonica LE, Fox RJ, Donelson JM. 2021. Thermal sensitivity of juvenile rabbitfishes *Siganus doliatus* and *S. lineatus* (*Siganidae*): A key role for habitat? Coral Reefs 40: 1307-1320. DOI: 10.1007/s00338-021-02146-2.

Lau DCP, Jonsson A, Isles PDF, Creed IF, Bergström A-K. 2021. Lowered nutritional quality of plankton caused by global environmental changes. Glob Change Biol 27: 6294-6306. DOI: 10.1111/gcb.15887.

Li Y-Y, Hu C-B, Zheng Y-J, Xia X-A, Xu W-J, Wang S-Q, Chen W-Z, Sun Z-W, Huang J-S. 2008. The effects of dietary fatty acids on liver fatty acid composition and Δ6-desaturase expression differ with ambient salinities in *Siganus canaliculatus*. Comp Biochem Physiol B: Biochem Mol Biol 151: 183-190. DOI: 10.1016/j.cbpb.2008.06.013.

Loayza E, Muñoz-Saravia A, De Troch M, Hendriks WH, Janssens GPJ. 2023. Detailed whole-body nutrient analysis identifies differences in feeding ecology between related fish species: The case of *Orestias* native Andean killifish in Lake Titicaca. J Anim Physiol Anim Nutr 107 (5): 1302-1310. DOI: 10.1111/jpn.13831.

Maikanov BS, Auteleyeva LT, Ismagulova GT, Wiśniewski J, Bełkot Z, Anusz K. 2020. Quality and safety of agricultural products in the Shuchinsk-Burabay Resort Zone. Fish. Med Weter 76 (10): 585-588. DOI: 10.21521/mw.6462.

Marrero M, Monroig Ó, Betancor M, Herrera M, Pérez JA, Garrido D, Galindo A, Giráldez I, Rodríguez C. 2021. Influence of dietary lipids and environmental salinity on the n-3 long-chain polyunsaturated fatty acids biosynthesis capacity of the marine teleost *Solea senegalensis*. Mar Drugs 19 (5): 254. DOI: 10.3390/md19050254.

Marrero M, Monroig Ó, Pérez JA, Betancor MB, Galindo A, Bolaños A, Acosta NG, Rodríguez C. 2024. Dietary LC-PUFA and environmental salinity modulate the fatty acid biosynthesis capacity of the euryhaline teleost thicklip grey mullet (*Chelon labrosus*). Comp Biochem Physiol B Biochem Mol Biol 269: 110865. DOI: 10.1016/j.cbpb.2023.110865.

Mathieu-Resuge M, Brosset P, Sardenne F, Soudant P, Le Grand F, Schull Q, Lebigre C. 2024. How membrane fatty acids influence sardine size across diverse marine environments. Prog Oceanogr 221: 103209. DOI: 10.1016/j.pocean.2024.103209.

Müller M, Staab CFK, Puk LD, Schoenig EM, Ferse SCA, Wild C. 2021. The rabbitfish *Siganus virgatus* as key macroalgae browser in coral reefs of the Gulf of Thailand. Diversity 13 (3): 123. DOI: 10.3390/d13030123.

Musgamy HK, Jasruddin J, Palloan P. 2024. Study of chlorophyll a variability in Bone Bay waters during high wave events. Adv Soc Hum Res 2 (8): 1036-1048. DOI: 10.46799/adv.v2i8.277.

Pethybridge HR, Parrish CC, Morrongiello J, Young JW, Farley JH, Gunasekera RM, Nichols PD. 2015. Spatial patterns and temperature predictions of tuna fatty acids: Tracing essential nutrients and changes in primary producers. PLoS One 10 (7): e0131598. DOI: 10.1371/journal.pone.0131598.

Raja K, Suresh K, Anbalagan S, Ragini YP, Kadirvel V. 2024. Investigating the nutritional viability of marine-derived protein for sustainable future development. Food Chem 448: 139087. DOI: 10.1016/j.foodchem.2024.139087.

Rajasilta M, Hänninen J, Laaksonen L, Laine P, Suomela J-P, Vuorinen I, Mäkinen K. 2019. Influence of environmental conditions, population density, and prey type on the lipid content in Baltic herring (*Clupea harengus membras*) from the northern Baltic Sea. Can J Fish Aquat Sci 76 (4): 576-585. DOI: 10.1139/cjfas-2017-0504.

Ramesh R, Venkateshwarlu G. 2022. Marine Fish Fatty Acids: Variation in Fatty Acid Profiles of Pelagic and Demersal Fishes. In: Advances in Fish Processing Technologies. Apple Academic Press, New York. DOI: 10.1201/9781003300595-12.

Roques S, Deborde C, Richard N, Skiba-Cassy S, Moing A, Fauconneau B. 2020. Metabolomics and fish nutrition: A review in the context of sustainable feed development. Rev Aquac 12 (1): 261-282. DOI: 10.1111/raq.12316.

Rosa R, Nunes ML. 2004. RNA, DNA and protein concentrations and amino acid profiles of deep-sea decapod *Aristeus antennatus*: An indication for seasonal variations of nutrition and growth. Aquat Living Resour 17 (1): 25-30. DOI: 10.1051/alr:2004003.

Rosalina D, Suleman Y, Shaliha A, Ruzuqi R. 2023. Bone Bay sea surface temperature distribution in 2021 using Terra MODIS satellite imagery. Jurnal Kelautan 16 (2): 110-116. DOI: 10.21107/jk.v16i2.18999. [Indonesian]

Rosdiana A, Prartono T, Atmadipoera AS, Zuraida R. 2017. Nutrient and chlorophyll a distribution in Makassar upwelling region: From MAJAFLOX CRUISE 2015. IOP Conf Ser: Earth Environ Sci 54: 012087. DOI: 10.1088/1755-1315/54/1/012087.

Roy J, Baranek E, Mercier Y, Larroquet L, Surget A, Ganot A, Sandres F, Lanuque A, Terrier F, Briand L. 2022. Involvement of taste receptors in the oro-sensory perception of nutrients in rainbow trout (*Oncorhynchus mykiss*) fed diets with different fatty acid profiles. Aquac Nutr 2022 (1): 1152463. DOI: 10.1155/2022/1152463.

Ryu B, Shin K-H, Kim S-K. 2021. Muscle protein hydrolysates and amino acid composition in fish. Mar Drugs 19 (7): 377. DOI: 10.3390/md19070377.

Skonberg DI, Rasco BA, Dong FM. 1994. Fatty acid composition of salmonid muscle changes in response to a high oleic acid diet. J Nutr 124 (9): 1628-1638. DOI: 10.1093/jn/124.9.1628.

Tian Y, Wang W, Jiang W, Zhang G, He J, Dong S, Zhou Y, Yang W, Tang Q, Yu Y, Gao Q. 2024. Non-targeted metabolomics provides insights into the distinct amino acid and lipid metabolism in liver tissues of rainbow trout (*Oncorhynchus mykiss*) cultured in seawater at different temperatures. Aquaculture 579: 740188. DOI: 10.1016/j.aquaculture.2023.740188.

Topor ZM, Rasher DB, Duffy JE, Brandl SJ. 2019. Marine protected areas enhance coral reef functioning by promoting fish biodiversity. Conserv Lett 12 (4): e12638. DOI: 10.1111/conl.12638.

Torno C, Staats S, Fickler A, De Pascual-Teresa S, Izquierdo MS, Rimbach G, Schulz C. 2019. Combined effects of nutritional, biochemical and environmental stimuli on growth performance and fatty acid composition of gilthead sea bream (*Sparus aurata*). PLoS One 14 (5): e0216611. DOI: 10.1371/journal.pone.0216611.

Wang M, Zhao S, Wang J, Nie L, Li L, Zhu X, Zhang L. 2024. Multi-omics analysis provides insight into liver metabolism in yellow catfish (*Pelteobagrus fulvidraco*) under hypoxic stress. Aquaculture 583: 740531. DOI: 10.1016/j.aquaculture.2023.740531.

Wang Y, Han G, Pham CV, Koyanagi K, Song Y, Sudo R, Lauwereyns J, Cockrem JF, Furuse M, Chowdhury VS. 2019. An acute increase in water temperature can increase free amino acid concentrations in the blood, brain, liver, and muscle in goldfish (*Carassius auratus*). Fish Physiol Biochem 45: 1343-1354. DOI: 10.1007/s10695-019-00642-5.

Waters. 2012. Acquity UPLC H-Class and H-Class Bio Amino Acid Analysis System Guide. Waters Coportation, Irlandia.

Xie D, Chen F, Lin S, You C, Wang S, Zhang Q, Monroig Ó, Tocher DR, Li Y. 2016. Long-chain polyunsaturated fatty acid biosynthesis in the euryhaline herbivorous teleost *Scatophagus argus*: Functional characterization, tissue expression and nutritional regulation of two fatty acyl elongases. Comp Biochem Phys Part B: Biochem Mol Biol 198: 37-45. DOI: 10.1016/j.cbpb.2016.03.009.

Xie D, Liu X, Wang S, You C, Li Y. 2018. Effects of dietary LNA/LA ratios on growth performance, fatty acid composition and expression levels of elovl5, Δ4 fad and Δ6/Δ5 fad in the marine teleost *Siganus canaliculatus*. Aquaculture 484: 309-316. DOI: 10.1016/j.aquaculture.2017.08.039.

Zainuddin M, Farhum A, Safruddin S, Selamat MB, Sudirman S, Nurdin N, Syamsuddin M, Ridwan M, Saitoh S-I. 2017. Detection of pelagic habitat hotspots for Skipjack tuna in the Gulf of Bone-Flores Sea, southwestern Coral Triangle tuna, Indonesia. PLoS One 12 (10): e0185601. DOI: 10.1371/journal.pone.0185601.

Zarco-Perello S, Martin SB, Hoey A. 2024. Biogeographical diet variation within and between the rabbitfishes *Siganus corallinus*, *Siganus doliatus*, *Siganus trispilos* and *Siganus virgatus*. Ecol Evol 14 (6): e11326. DOI: 10.1002/ece3.11326.

Zhang Z, Ji H, Zhang D, Liu S, Zheng X. 2022. The role of amino acids in the formation of aroma-active compounds during shrimp hot air drying by GC-MS and GC-IMS. Foods 11: 3264. DOI: 10.3390/foods11203264.