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Review

Channel catfish, a species with potential deposition of human-beneficial fatty acids

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ABSTRACT. Fatty acids from fish are of great interest for human consumption, and the channel catfish (*Ictalurus punctatus*) is one of the most important aquaculture species in Mexico and perhaps in other countries with similar resource endowments. Channel catfish occupy a trophic level that theoretically and potentially allows the retention and de novo biosynthesis of long-chain fatty acids (FAs), essential for human nutrition and health. Here, we present an overview of the main features of FAs, their reported average levels and extreme values in channel catfish assessments, and their correlations. The importance of FAs for human consumption and some implications for future research are discussed.

Keywords: *Ictalurus punctatus*; channel catfish; lipids; MUFAs; PUFAs; trophic level

INTRODUCTION

The channel catfish (*Ictalurus punctatus* Rafinesque, 1818) is a freshwater fish in the family Ictaluridae (North American catfish), which includes seven genera and approximately 45 species (Parra-Bracamonte et al. 2023). Channel catfish is one of the most important species for aquaculture in Mexico after tilapia (*Oreochromis* spp.), carp (*Cyprinus carpio* Linnaeus, 1758), and rainbow trout (*Oncorhynchus mykiss* Walbaum, 1792). Channel catfish farming in Mexico began in the 1970s, and the species has become an essential freshwater resource produced under farm conditions (de la Rosa Reyna et al. 2014, Lara-Rivera et al. 2015).

The channel catfish is native to northeast Mexico, including Tamaulipas, Nuevo León Coahuila, and Chihuahua, where environmental conditions are optimal for its reproduction and growth. Although native varieties of this species are available, different importation events during the 1970s introduced channel catfish aquaculture farming in Tamaulipas and later in 20 additional Mexican states (Lara-Rivera et al. 2015) mainly for the growth and production of animal protein due to its increasing acceptance and consumption. During the first decade of the 2000s, peak production was achieved, and soon after, production decreased from 9000 t of product estimated in 2007 to approximately 2000 t in 2015 (FAO 2019). By 2016, the estimated production was 4000 t (INAPESCA 2018),

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positioning the species relevant to the country's aquaculture sector.

The catfish meat production sector indicated that growth traits are essential for establishing production and genetic improvement programs (Lara-Rivera et al. 2015). However, it was suggested that the identification of variability related to meat quality traits such as fatty acid (FA) deposition would help encourage competition with other more recognized species in Mexico and, above all, expand the market, which is limited to certain Mexican states (Mendoza-Pacheco et al. 2018).

Lipids and their FAs are important organic components of fish and play a critical role as sources of metabolic energy for growth, reproduction, and migratory movement. In addition, some fish FAs are rich in long chains of omega-3 unsaturated FAs (n-3 polyunsaturated fatty acids (PUFAs)) that have an important role in animal nutrition, including fish and humans; this reflects their role in physiological processes. Fish are the main source of long-chain PUFAs (LC-PUFAs, >C18) for human consumption (Xu et al. 2020). These FAs are generally associated with nutritional advantages and confer the status of functional foods to products that contain them and may also provide added value or greater competitiveness in the market for the aquaculture industry.

The present study aimed to provide an overview of the average levels of FAs in reviewed document reports of channel catfish meat and to highlight the importance of human-beneficial FAs and their implications for the Mexican aquaculture industry.

Features of fish FA use and biosynthesis

Food refers to anything that, when consumed, provides the necessary nutrients for the metabolism of a given organism. Some foods exhibit health benefits beyond their nutritional characteristics; these advantages can be either natural or the result of human intervention. Foods possessing different health benefits beyond fundamental nutrition are called functional foods. Essential FAs (EFAs) are among the most popular functional foods. An FA is an organic molecule with a carboxylic acid group at the end of an aliphatic chain containing four or more carbons, usually an even number of up to 24. The aliphatic chain can be "saturated", where all carbon-carbon linkages are single bonds, and all other carbon bonds are taken by hydrogen, or "unsaturated", where some carbons are linked by double bonds (Castro et al. 2016). EFAs are polyunsaturated FAs necessary for human health. Nevertheless, the human body cannot synthesize them, and therefore they must be consumed with the diet, such as α-linolenic acid (ALA, 18:3[n-3]) and linoleic acid (LA, 18:2[omega-6, n-6]). ALA and LA can be converted to other n-3 and n-6 FAs, respectively, although this depends on the presence and expression of genes involved in FA desaturation and elongation.

Castro et al. (2016) provided a general description of FA biosynthesis involving the primary pathway of lipogenesis as the biosynthesis of FA, which can be catalyzed by two cytosolic enzyme systems: acetyl-CoA carboxylase and the multienzyme fatty acid synthase (FAS) complex that uses acetyl-CoA as the carbon source to produce saturated FAs, primarily 16:0 in animals and 18:0 in plants. FA elongation is another major pathway in the production of FAs; the elongation of FAs to produce FAs with chain lengths of 18 carbons involves four sequential reactions to add 2-carbon units. These reactions are analogous to de novo synthesis (condensation, first reduction, dehydration, and second reduction). They are catalyzed by four membrane-bound enzymes, namely, elongation of very long-chain FAs (Elovl) proteins (condensing enzyme), β-ketoacyl-CoA reductase, β-hydroxy acyl-CoA dehydratase, and trans-2-enoyl-CoA reductase. Posteriorly, the biosynthesis of unsaturated FAs can occur by two pathways that involve the enzymatic fatty acyl desaturase (Fad) and Elovl processes of desaturation and elongation, respectively (Castro et al. 2016, Fig. 1).

Fish are one of the main sources of n-6 and n-3 EFAs. However, in some cases, depending on their biosynthesis capacity, fish cannot synthesize these FAs either, and the proportion of n-6 and n-3 depends greatly on the foods they consume (Taşbozan & Gökçe 2017). The typical FA composition of marine fish oils results from the FA composition of marine phytoplankton. These FAs reach the fish via the food web (Steffens 1997), which means that some variation is expected in the FA composition of different fish of the same species. Still, there is also a great difference in the FA composition between marine and freshwater fishes. It is important to note that the production of LC-PUFAs in most animals, and definitely in all vertebrates, is restricted to biosynthesis from preexisting (i.e. dietary) C18-PUFAs, given the lack of enzymes capable of producing C18-PUFAs from monounsaturated FAs (Castro et al. 2016). Therefore, species-specific metabolic differences and FA-specific metabolic pathways, such as selective incorporation, β-oxidation, and de novo synthesis/lipogenic activity, influence the incorporation of dietary FAs into fish tissues (Tocher 2015, Xu et al. 2020). Hence, a key feature of fish is their ability to synthesize LC-PUFAs. However, fish vary in their ability to meet the physiological demand

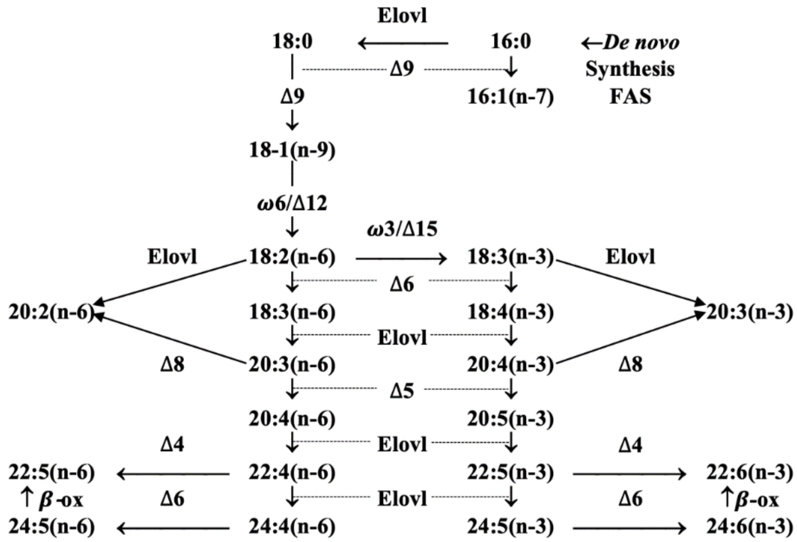

Figure 1. Biosynthetic pathways of polyunsaturated fatty acids (FAs). Desaturation reactions are described with "ω" or "Δ", which indicate, respectively, the carbon position at which the incipient double bond is located within the methyl (ω) and front (Δ) ends of the fatty acyl chain elongation of very long-chain FAs (Elovl) catalyzes elongation reactions. *De novo* biosynthesis of stearic acid (from 16:0, palmitic acid) by fatty acid synthase (FAs) complex system and subsequent Δ9 unsaturation by stearoyl-CoA desaturase are also shown. Production of 22:6n-3 and 22:5n-6 occurs through partial β-oxidation of 24:6n-3 and 24:5n-6, respectively. Adapted from Castro et al. (2016) and Xu et al. (2020).

for LC-PUFAs (i.e. 20:4(n-6), 20:5[n-3], and 22:6(n-3)) via elongation and desaturation of C18-PUFA [i.e. 18:2(n-6) and 18:3(n-3)] precursors (Trushenski & Rombenso 2020). In this case, it is considered that C18-PUFAS are nutritionally essential, if not physiologically essential, in their role as a biosynthetic precursor to LC-PUFAs (Trushenski & Rombenso 2020).

It has been hypothesized that marine species that have evolved in an LC-PUFA-rich environment have low evolutionary pressure to retain the ability to produce LC-PUFAs endogenously. In contrast, lower levels of LC-PUFAs in the food chain may have been the selective pressure driving freshwater species to retain the ability to biosynthesize LC-PUFAs to satisfy their physiological requirements (Xu et al. 2020). As a general rule, temperature and salinity have been suggested to be predictive of this major role of physiological patterns in FA essentiality; however, the demand for LC-PUFAs has been suggested to be more a function of species phylogeny (Garrido et al. 2019) or trophic level, that is, the position in the food web hierarchy, on a scale of 1-5, where 1 is a primary producer, and 5 is an apex predator (Trushenski & Rombenso 2020).

Generally, freshwater and salmonid species have been regarded as having a high capacity for LC-PUFA biosynthesis, whereas marine teleost species show a limited ability to biosynthesize LC-PUFAs (Xu et al. 2020). In the case of the channel catfish, its condition as an omnivorous species exhibiting a trophic level between 3.1 and 4.3 (Froese & Pauly 2022) might indicate the biological capacity to synthesize PUFAs (Trushenski et al. 2020), and additional information on enzymatic expression may support this hypothesis.

FA deposition in channel catfish meat

One of the important issues in applied sciences is to know the variation boundaries determining a phenotype because having this information reveals the true possibility of achieving improvement. From a broad literature review of published information on FA deposition in channel catfish (i.e. fillet or muscle), the descriptive statistics of the reported main FAs and their maximum and minimum amplitudes of occurrence were estimated (Table 1). Three saturated FAs (SFAs) are more frequently reported in channel catfish studies: myristic acid (14:0), palmitic acid (16:0), and stearic acid (18:0). In contrast, arachidic and eicosanoid acids are less frequently reported. The mean reported SFA

Table 1. Fatty acid content (%) statistics in channel catfish fillets from different studies. n: sample size. Estimated from data reported by Stickney & Andrews (1972), Worthington et al. (1972), Worthington & Lovell (1973), Mustafa & Medeiros (1985), Nettleton et al. (1990), Akoh & Hearnsberger (1993), Conrad et al. (1995), Morris et al. (1995), Robinson et al. (2001), Hedrick et al. (2005), Li et al. (2009), Zhang et al. (2015), Young et al. (2016), Betchel et al. (2017), Trushenski et al. (2020). SD: standard deviation.

Fatty acid	Common name	n	Mean	SD	Minimum	Maximum
14:00	Myristic	81	1.99	2.26	0.42	11.94
16:00	Palmitic	81	19.28	3.36	10.30	25.54
18:00	Stearic	81	5.50	2.15	1.20	11.09
20:00	Arachidic	10	0.32	0.19	0.10	0.63
22:00	Eicosanoid	8	0.32	0.34	0.10	0.98
16:1	Palmitoleic	81	3.51	1.93	0.65	9.00
18:1(n-7)	Vaccenic	17	2.05	1.40	0.19	4.90
18:1(n-9)	Oleic	84	39.09	8.55	25.80	59.50
20:1(n-9)	11-Eicosanoid	56	1.49	0.70	0.78	4.92
18:2(n-6)	Linoleic	89	13.15	4.84	2.80	38.60
18:3(n-3)	Alpha-linolenic	86	1.59	3.14	0.16	28.30
18:4(n-3)	Stearidonic	20	0.34	0.30	0.04	0.79
20:2(n-6)	Eicosadienoic	54	1.00	0.33	0.30	1.81
20:3(n-3)	Eicosatrienoic	16	0.77	0.88	0.08	3.60
20:3(n-6)	Dihomo-γ-linolenic	71	1.35	0.70	0.49	3.55
20:3(n-9)	Eicosatrienoic	26	1.13	0.74	0.10	2.80
20:4(n-3)	Eicosatetranoic	28	0.43	0.52	0.00	2.10
20:4(n-6)	Araquiquidonic (ARA)	68	3.78	3.59	0.40	13.22
20:5(n-3)	Eicosapentanoic (EPA)	79	1.21	1.32	0.00	9.40
22:4(n-6)	Adrenic	22	0.38	0.33	0.00	1.10
22:5(n-3)	Docosapentaenoic (n-3 DPA)	75	0.81	0.56	0.00	4.20
22:5(n-6)	Docosapentaenoic (n-6 DPA)	36	1.22	1.06	0.00	4.66
22:6(n-3)	Docosahexanoic (DHA)	81	3.80	2.83	0.75	16.00
SFA	Saturated	46	28.22	4.39	23.21	36.08
MUFA	Monounsaturated	46	39.53	8.10	24.94	57.00
PUFA	Polyunsaturated	44	30.59	8.99	10.50	50.30

content was 28.22 ± 4.39%, and palmitic acid was the most abundant, with a mean of 19.28 ± 3.36%. For monounsaturated FAs (MUFAs), the mean reported MUFA content was 39.53 ± 8.10%, and palmitoleic acid (16:1), oleic acid [18:1(n-7)] and 11-eicosanoid acid [20:1(n-9)] were the most frequently reported. However, vaccenic acid [18:1(n-7)] was occasionally reported [18:1(n-7)]. Of these MUFAs, the most abundant FA was oleic acid, with a mean content of 39.09 ± 8.55%.

Regarding PUFA content, linoleic [C18:2 (n-6)] and alpha-linolenic [18:3(n-3)] acids are more frequently reported, with linoleic acid being the most abundant, with a mean content of 13.15 ± 4.84%. Stearidonic acid [C18:4(n-3)] is occasionally reported as well. In contrast, LC-PUFAs are more frequently reported, including mostly n-3 and n-6 LC-PUFAs. For n-3 FAs, the most frequent are eicosapentaenoic acid [EPA, 20:5(n-3)], docosapentaenoic acid [DPA, 22:5(n-3)], and docosahexaenoic acid [DHA, 22:6(n-3)] and occasionally eicosatrienoic acid [20:3(n-3)] and eicosatetraenoic acid [20:4(n-3)]. Regarding n-6 FAs, eicosadienoic acid [20:2(n-6)], dihomo-g-linolenic acid [20:3(n-6)], and the essential arachidonic acid [ARA, 20:4(n-6)] are the most frequent (Table 1). The least frequent but also mentioned are adrenic acid [22:4(n-6)] and the n-6 isomer of DPA. The LC-PUFAs have a mean total deposition of 30.59 ± 8.99%, and according to published reports, the highest deposition levels are found for, interestingly, DHA and ARA (Table 1).

As this evidence suggests, the most frequent FAs in channel catfish meat are palmitic acid, oleic acid, linolenic acid, ARA, and DHA. These are the major FAs in percentage among the saturated or unsaturated FA types. Generally, large variation was found, as suggested by standard deviation estimates (Table 1) and the minimum and maximum amplitude values. In some cases, maximum levels are over three standard deviations from the mean (Table 1). The origin and sources of variation in published studies are diverse and large, even though selected studies were chosen based on their reporting of the same tissue, FA extraction method, and unit of measurement (i.e. percentage). However, most studies were nutritional experiments.

As most of the literature suggests, nutrition is the main source of variation in FA biosynthesis and deposition processes (Stickney & Andrews 1972, Worthington & Lovell 1973, Morris et al. 1995, Hedrick et al. 2005, Li et al. 2009, Zhang et al. 2015, Young et al. 2016, Trushenski et al. 2020). Worthington & Lovell (1973) indicated that more than 93% of the variance in FA deposition is explained by diet and suggested that low levels of natural variability in FA among catfish demonstrate that genetic and other factors are of minor importance compared to diet in determining FA composition. Evidence presented in this work partly agrees with their results since the high variability in the maximum levels found is likely the result of experimental diet differences. However, almost all published comparisons of FA deposition are related to nutrition assessment; therefore, more information regarding inherent (i.e. genetic) variation is needed.

Important Pearson correlations were estimated for the most frequent FAs reported in the literature (Table 2). A high and significant correlation for total SFA content indicated that palmitic acid determined a large percentage of these FAs. Additionally, a negative (r = -0.76) and significant (P < 0.0001) relationship was found between stearic acid and palmitoleic acid. Similarly, oleic acid negatively correlated (r = - 0.67, P < 0.0001) with total SFA content. This pattern was also found for total MUFA content (r = -0.74, P < 0.0001).

Among PUFAs, eicosadienoic acid positively correlated with dihomo-γ-linolenic acid (r = 0.64, P = 0.0001). ARA revealed interesting and significant relationships with SFA and MUFA deposition (Table 2). Significant ($P \leq 0.0003$) positive correlations of this FA with palmitic acid, stearic acid, and total SFA were observed (0.62, 0.70, and 0.78, respectively). Conversely, the association between oleic acid and total MUFA content was high and negative (-0.74 and -0.81, respectively). Similarly, EPA showed a positive correlation with total SFA content (r = 0.70, P < 0.0001) and a negative correlation with total MUFA content (r = -0.66, P < 0.0001). DHA showed a positive and significant (P < 0.0001) correlation with n-3 EPA, DPA, and total PUFA content (0.67, 0.66, and 0.60, respectively). Finally, the total PUFA content was highly, significantly, and negatively correlated with the oleic and total MUFA contents (-0.85 and -0.91, respectively).

In general, the direct relationship of biosynthesis could explain the correlations between FAs (Fig. 1). As observed, n-3 and n-6 FAs tend to be correlated with their more desaturated counterparts. In addition, nutritional management can significantly modulate deposition changes; for instance, Trushenski et al. (2020) indicated that providing diets enriched with n-3 LC-PUFAs to channel catfish would interfere with de novo production of n-6 LC-PUFAs in these species and may induce 20:4(n-6) deficiency.

Beneficial effects of FAs

FAs play diverse and important roles in the health of animals, including humans. EFAs affect the fluidity, flexibility, and permeability of the cell membranes, and they are the precursors of eicosanoids, which are needed for maintaining the impermeability of the skin barrier and are involved in cholesterol transport and metabolism (Steffens 1997). FAs also play a role as components of storage lipids and function as a reserve of energy. It has also been noted that some FAs play a functional role as regulators of metabolism at the extracellular level of tissues or intracellularly as ligands for transcription factors that control gene expression (Tocher 2015). FAs, especially PUFAs, play important physiological roles as substrates for the synthesis of LC-PUFAs with known physiological functions in the production of eicosanoids (prostaglandins, thromboxanes, leukotrienes, and others derived from ARA and EPA) and docosanoids (resolvins and neuroprotectins derived from EPA and DHA, respectively) (Trushenski & Rombenso 2020). Since EFAs are also a constituent of synaptic membranes, they are believed to play an integral role in neurological functioning. Their role in conditions such as schizophrenia, bipolar disorder, major depressive disorder, dementia, postpartum depression, and borderline personality disorder has been widely studied (Holub & Holub 2004, Sanchez-Villegas et al. 2007).

The first studies exploring the beneficial effect of eating fish on the incidence of heart attacks were performed in the 1970s and lasted 20 years. Those projects showed that fish consumption could reduce the risk of ischemic heart disease (Nelson 1972, Kromhout et al. 1985). For a long time, there has been controversy about n-6:n-3 ratios and how they may negatively affect human health. For instance, n-6 FAs, which can be found in corn and safflower oils, have been found to act as precursors involved in the growth of mammary tumors when fed to animals, whereas n-3 FAs, found primarily in fish oils, have shown inhibitory effects on different breast cancers (Bagga et al. 1997, Kim et al.

Table 2. Pearson correlation coefficients (above diagonal) and their significance (below diagonal) of fatty acids deposition percentage reported in the meat of channel catfish. SFAs: saturated fatty acids, MUFAs: monounsaturated fatty acids, PUFAs: polyunsaturated fatty acids.

	14:0	16:0	18:0	SFAs	16:1	18:1(n-9)	20:1(n-9)	MUFAs	18:2(n-6)	18:3(n-3)	20:2(n-6)	20:3(n-6)	20:4(n-6)	20:5(n-3)	22:5(n-3)	22:6(n-3)	PUFAs
14:0		-0.01	-0.39	0.68	0.65	-0.09	0.38	-0.15	-0.18	0.07	-0.53	-0.24	-0.12	0.20	0.11	-0.08	-0.26
16:0	0.9145		0.44	0.94	-0.17	-0.28	-0.34	-0.52	0.06	-0.44	-0.46	-0.51	0.62	0.06	0.02	0.14	0.05
18:0	0.0004	<.0001		0.47	-0.76	-0.55	-0.44	-0.74	0.04	-0.34	0.41	0.23	0.70	-0.13	-0.15	0.31	0.39
SFAs	<.0001	<.0001	0.002		0.02	-0.67	-0.55	-0.74	0.32	-0.30	-0.44	-0.45	0.78	0.70	0.39	0.41	0.45
16:1	<.0001	0.126	<.0001	0.8901		0.41	0.41	0.41	-0.35	0.07	-0.54	-0.34	-0.43	0.30	0.31	-0.21	-0.56
18:1(n-9)	0.4479	0.0114	<.0001	<.0001	0.0001		0.10	0.98	-0.19	-0.02	-0.05	-0.15	-0.74	-0.39	-0.31	-0.69	-0.85
20:1(n-9)	0.0034	0.0106	0.0007	0.0003	0.0018	0.474		0.13	-0.31	0.17	0.39	0.57	-0.52	0.40	0.36	0.04	0.19
MUFAs	0.3476	0.0004	<. 0001	<.0001	0.0081	<.0001	0.4244		-0.25	0.05	-0.06	-0.08	-0.81	-0.66	-0.45	-0.69	-0.91
18:2(n-6)	0.1149	0.6212	0.7437	0.0283	0.0015	0.0885	0.0211	0.094		-0.07	-0.07	-0.33	0.04	-0.21	-0.34	-0.08	0.56
18:3(n-3)	0.5206	<.0001	0.0021	0.0463	0.5612	0.8882	0.2065	0.7502	0.5512		0.07	0.11	-0.24	0.06	0.07	-0.01	0.29
20:2(n-6)	<.0001	0.0009	0.0031	0.0028	<.0001	0.755	0.0087	0.6742	0.6112	0.6035		0.64	-0.17	-0.30	-0.25	0.07	0.73
20:3(n-6)	0.0531	<.0001	0.0619	0.0016	0.0048	0.2341	<.0001	0.5945	0.0051	0.3546	<.0001		0.02	-0.08	-0.01	0.08	0.44
20:4(n-6)	0.3495	<.0001	<.0001	<.0001	0.0004	<.0001	0.0003	<.0001	0.7669	0.0447	0.2378	0.8759		0.16	0.07	0.42	0.41
20:5(n-3)	0.0911	0.5892	0.2637	<.0001	0.0095	0.0007	0.0033	<.0001	0.0587	0.6103	0.0322	0.504	0.194		0.93	0.67	0.36
22:5(n-3)	0.326	0.8422	0.1971	0.012	0.0071	0.0065	0.0069	0.004	0.0026	0.5279	0.0866	0.9487	0.57	<.0001		0.66	0.20
22:6(n-3)	0.4895	0.2182	0.0063	0.0054	0.0711	<.0001	0.7512	<.0001	0.5032	0.8956	0.6145	0.5282	0.0004	<.0001	<.0001		0.60
PUFAs	0.0931	0.7681	0.0096	0.0089	<.0001	<.0001	0.2947	<.0001	<.0001	0.0552	<.0001	0.0102	0.0059	0.0177	0.1931	<.0001	

2009). Additionally, some studies have been able to relate the consumption of n-3 FAs with an increased risk of type 2 diabetes (Djousse et al. 2011). The diet in North America varies from 8:1 to 20:1 n-6:n-3. This excess consumption of n-6 FAs has been widely related to obesity (Simopoulos 2016) and the risk of cardiac disease.

Multiple studies support the concept that fish-based diets, such as Mediterranean diets, help prevent coronary heart disease through the protective benefits of ALA. A study conducted with the Inuit people (Quebec) showed that their diet provides several thousand milligrams of n-3 FAs in the form of EPA and DHA combined by consuming marine mammals and fishes. When compared to the Danish population, the Inuit population showed a significantly lower rate of death from acute myocardial infarction (Bang & Dyerburg 1980). The Japanese population offers another good example of a diet based on fish consumption; their intake of EPA/DHA is approximately 1500 mg d^{-1}, compared to 130 mg d^{-1} in North America. Those higher amounts of consumption have been associated with lower rates of acute myocardial infarction, another ischemic heart disease, and atherosclerosis despite only moderately lower blood cholesterol levels being detected in the Japanese and Inuit populations.

Numerous recent studies support the beneficial effects of EPA and DHA consumption on human health (Table 3). Direct consumption of EPA and DHA via fish meat could reduce many chronic diseases involving inflammatory processes, such as cardiovascular disease, inflammatory bowel disease, cancer, and rheumatoid arthritis (Wall et al. 2010). Overall, the therapeutic effects of FAs on cardiovascular disease appear to be due to the suppression of fatal arrhythmia. Consumption of EPA has been associated with inflammation reduction (Duvall & Levy 2016), cardiovascular health improvement (Nelson & Raskin 2019), support in managing mood disorders such as depression and anxiety (Messamore et al. 2017), and reduction of certain types of cancer (Liu & Ma 2014, Jump et al. 2015, Zárate et al. 2017, Djuricic & Calder 2021). Similarly, consumption of DHA has been related to improvement of brain health and cognitive function at all stages of life (Carlson et al. 2013, Dighriri et al. 2022), reduced risk of cardiovascular disease (del Gobbo et al. 2016, Kleber et al. 2016), and prevention of neurodegenerative disorders such as Alzheimer's disease (Lorente-Cebrián et al. 2015, Balakrishnan et al. 2021). At doses >3 g d^{-1}, EPA plus DHA improved cardiovascular disease risk factors, including decreasing plasma triacylglycerols, blood pressure, platelet aggregation, and inflammation while improving vascular reactivity (Breslow 2006). Additionally, combined consumption of EPA and DHA has been associated with a reduction in blood triglyceride levels (Jain et al. 2015, Leslie et al. 2015, Zhang et al. 2019), anti-inflammatory benefits in chronic inflammatory diseases, such as rheumatoid arthritis (Calder 2015) and prevention of bone density loss (Mangano et al. 2013, Sharma & Mandal 2020), among other benefits (Table 3).

Implications

The available information on FA deposition in channel catfish meat, mostly from farming and nutritional experiments, was reviewed. These findings revealed that n-3 FAs (ALA, EPA, and DHA) are constantly available in important amounts in channel catfish meat, representing great potential for human consumption and health enhancement.

As discussed previously, channel catfish display omnivorous characteristics and occupy a trophic level that theoretically would allow the species to perform de novo biosynthesis of LC-PUFAs. However, this ultimately depends on whether their diet allows FA retention and biosynthesis. Stream food webs are generally highly enriched with n-3 LC-PUFAs, particularly EPA and DHA. Algae from temperate rivers show higher EPA contents than algae from subtropical rivers. Stream invertebrates from temperate and subtropical rivers preferentially retain algal EPA, and their PUFAs vary with algal PUFAs. The reasons for DHA and EPA trophic retention still need to be better understood. Still, an analysis suggests that consumers selectively incorporate algal PUFAs and possibly also bioconvert dietary ALA and EPA into DHA in a wide range of fish taxa (Guo et al. 2017). Martínez et al. (2006) suggested that a Mexican cultured silverside (*Chirostoma estor*) may convert EPA or other n-3 FAs to DHA.

Determining the process and level of essentiality or requirement of certain FAs is a key issue for aquaculture species. Defining nutritional FA essentiality in fish is complex given the wide variability among species subjected to different selective pressures and with different trophic levels and environmental tolerances and given the different experimental conditions and differences in feed formulation and manufacturing techniques involved, all of which can influence absolute requirements (Trushenski & Rombenso 2020) and deposition of FAs. Tocher (2015) notes that the balance between different PUFAs and

Table 3. Reported benefits of fatty acids, eicosapentanoic (EPA) and docosahexanoic (DHA), consumption in human health. References: 1) Duvall & Levy (2016); 2) Nelson & Raskin (2019); 3) Messamore et al. (2017); 4) Djuricic & Calder (2021); 5) Jump et al. (2015); 6) Liu & Ma (2014); 7) Zárate et al. (2017); 8) Lauritzen et al. (2016); 9) Carlson et al. (2013); 10) Dighriri et al. (2022); 11) Richard & Calder (2016); 12) Carlson & Colombo (2016); 13) Kleber et al. (2016); 14) del Gobbo et al. (2016); 15) Balakrishnan et al. (2021); 16) Lorente-Cebrián et al. (2015); 17) Jain et al. (2015); 18) Leslie et al. (2015); 19) Zhang et al. (2019); 20) McCusker et al. (2016); 21) Souied et al. (2016); 22) Calder (2015); 23) Kumar et al. (2016); 24) Wendell et al. (2014); 25) Mangano et al. (2013); 26) Sharma & Mandal (2020); 27) Calder (2019).

Fatty acid	Reported benefits	Reference
EPA	Reduced inflammation in the body	1
	Improves cardiovascular health	2
	Support in managing mood disorders, such as depression and anxiety	3
	Possible role in reducing the risk of certain types of cancer	4, 5, 6, 7
DHA	Brain development and function	8
	Improved brain health and cognitive function at all stages of life	9, 10
	Support in visual development, especially in infants and children	11, 12
	Reduced risk of cardiovascular disease	13, 14
	Potential benefits in preventing neurodegenerative diseases, such as Alzheimer's	15, 16
EPA and DHA	Reduction of blood triglyceride levels	17, 18, 19
	Support in eye health and prevention of age-related macular degeneration	20, 21
	Anti-inflammatory benefits in chronic inflammatory diseases, such as rheumatoid arthritis	22
	Improved lung function in people with asthma	23, 24
	Support in bone health and prevention of bone density loss	25, 26
	Brain and eye development and function	27

LC-PUFAs is important and defining is challenging, so ideal levels and balances are still not well understood, particularly concerning fish health and between wild versus farmed fish; however, efforts need to be focused on the de novo production of n-3 LC-PUFAs.

Differences between wild and farmed channel catfish have been proposed. Evidence of changes in FA deposition supports these assumptions. Young et al. (2014) found decreases in n-3 and C18 PUFAs in all tissues and increases in MUFAs over time when channel catfish were moved from the wild to farms. Since most reviewed studies included farmed channel catfish, that study demonstrates that FA signatures change over time in response to diet and habitat shifts and can be useful for tracking the timing of diet changes. However, other studies suggest that shreds of evidence do not support the notion that wild fish are higher in n-3 FA than cultivated fish (Nettleton 2000). Therefore, further research into cultivated and wild origin differences is needed to achieve conclusive results.

Studies such as the present one have many strengths but also some limitations. Estimations of correlations represent a phenotypic expression of traits involving the environmental (mainly diet) and genetic components. Further studies for these components dissection would enlighten the extreme values and interactions in the reviewed literature. Additionally, conforming to a more complete dataset to elucidate the main sources of variation is also a challenge. The reviewed studies involve different countries, management systems, diet formulations, tissues, sample origins, and fish ages, adding more variability to the assessment and accuracy of the estimated means. Therefore, a more complete assessment, including complex statistical models or meta-analysis to fit these factors, could be more helpful in understanding FA expression in channel catfish as a reference for future studies.

Channel catfish is one of the most important aquaculture species in Mexico, and farming production is still insufficient to match the demand for the product. In recent years, the reduction in channel catfish farming in some regions has been attributed to different reasons (Lara-Rivera et al. 2015). Additionally, a proportion of the fish consumed originated from wild catches from different available reservoirs, mostly in the north-eastern states of Mexico. The particularities and differences in management, availability of feed resources, water quality, weather, and genetic background of native varieties might reveal the purported important role of the trophic level occupied by the species, allowing the retention of important quantities of essential FAs from the rich diet. From the trophic perspective of FA essentiality and deposition, it could be hypothesized that the southern boundaries of the distribution of native channel catfish might act as an evolutionary advantage for the deposition of higher PUFA contents; however, this remains to be confirmed by further research. Hence, in states such as Tamaulipas, where the species occurs naturally, the large availability of water reservoirs used for aquaculture, which are frequently managed with grow-out cages, may allow comparison of farmed versus wild-caught channel catfish to help reveal the tissues that are sources of high-quality PUFAs.

Finally, the undeniable importance of certain FAs to human health supports the need to seek new sources of these nutrients, potentially increasing the consumption of channel catfish meat and supporting the aquaculture sector, which is associated with rural regions and exhibits a worrying socioeconomic lag locally.

CONCLUSIONS

FAs from fish are of great interest for human consumption, and channel catfish is one of the most important species in aquaculture in Mexico and perhaps in other countries with similar resources. The most common FAs found in channel catfish are MUFAs and PUFAs. Important quantities of ARA, EPA, and DHA are reported in this species, with broad variability and FA interactions mostly due to the published studies being predominantly nutrition experiments. Given its trophic level, de novo biosynthesis in channel catfish might be important for LC-PUFA deposition, and further research comparing wild versus farmed fish and assessing the specific expression of different FAs will confirm this potential.

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REFERENCES

Akoh, C.C. & Hearnsberger, J.O. 1993. Fatty acid profiles of farm-raised catfish fillet: total lipids and phospholipid classes. Journal of Aquatic Food Product Technology, 1: 43-55. doi: 10.1300/J030v01n02_06

Bagga, D., Capone, S., Wang, H.J., Heber, D., Lill, M., Chap, L., et al. 1997. Dietary modulation of omega-3/omega-6 polyunsaturated fatty acid ratios in patients with breast cancer. Journal of the National Cancer Institute, 89: 1123-1131. doi: 1093/jnci/89.15.1123

Balakrishnan, J., Kannan, S. & Govindasamy, A. 2021. Structured form of DHA prevents neurodegenerative disorders: a better insight into the pathophysiology and the mechanism of DHA transport to the brain. Nutrition Research, 85: 119-134. doi: 10.1016/j.nutres.2020.12.003

Bang, H.O. & Dyerburg, J. 1980. Lipid metabolism and ischemic heart disease in Greenland Eskimos. In: Draper, H.H. (Ed.). Advances in nutrition research. Plenum Press, New York, pp. 1-22.

Bechtel, P.J., Bland, J.M., Bett-Garber, K.L., Grimm, C.C., Brasher, S.S., Lloyd, S.W., et al. 2017. Chemical and nutritional properties of channel and hybrid catfish byproducts. Food Science & Nutrition, 5: 981-988. doi: 10.1002/fsn3.483

Breslow, J.L. 2006. n-3 fatty acids and cardiovascular disease. American Journal of Clinical Nutrition, 83: 1477S-1482S. doi: 10.1093/ajcn/83.6.1477S

Calder, P.C. 2015. Marine omega-3 fatty acids and inflammatory processes: effects, mechanisms and clinical relevance. Biochimica et Biophysica Acta (BBA)-Molecular and Cell Biology of Lipids, 1851: 469-484. doi: 10.1016/j.bbalip.2014.08.010

Calder, P.C. 2019. Conference on 'The future of animal products in the human diet: health and environmental concerns' Plenary Lecture 3 n-3 PUFA and health: fact, fiction and the future very long-chain n-3 fatty acids and human health: fact, fiction and the future. Proceedings of the Nutrition Society, 77: 52-72.

Carlson, S.E. & Colombo, J. 2016. Docosahexaenoic acid and arachidonic acid nutrition in early development. Advances in Pediatrics, 63: 453-471. doi: 10.1016/j.yapd.2016.04.011

Carlson, S.J., Fallon, E.M., Kalish, B.T., Gura, K.M. & Puder, M. 2013. The role of the ω-3 fatty acid DHA in the human life cycle. Journal of Parenteral and Enteral Nutrition, 37: 15-22. doi: 10.1177/0148607112467821

Castro, L.F.C., Tocher, D.R. & Monroig, O. 2016. Long-chain polyunsaturated fatty acid biosynthesis in chordates: insights into the evolution of Fads and Elovl gene repertoire. Progress in Lipid Research, 62: 25-40. doi: 10.1016/j.plipres.2016.01.001

Conrad, K.M., Mast, M.G. & MacNeil, J.H. 1995. Fatty acid composition of channel catfish (*Ictalurus punctatus*) fed diets containing dried waste eggs.

Journal of Aquatic Food Product Technology, 4: 23-33. doi: 10.1300/J030v04n03_03

de La Rosa-Reyna, X.F., Sifuentes-Rincón, A.M., Parra-Bracamonte, G.M. & Arellano-Vera, W. 2014. Identification of two channel catfish stocks, *Ictalurus punctatus*, cultivated in northeast Mexico. Journal of the World Aquaculture Society, 45: 104-114. doi: 10.1111/jwas.12109

del Gobbo, L.C., Imamura, F., Aslibekyan, S., Marklund, M., Virtanen, J.K., Wennberg, M., et al. 2016. ω-3 polyunsaturated fatty acid biomarkers and coronary heart disease: pooling project of 19 cohort studies. JAMA Internal Medicine, 176: 1155-1166. doi: 10.1001/jamainternmed.2016.2925

Dighriri, I.M., Alsubaie, A.M., Hakami, F.M., Hamithi, D.M., Alshekh, M.M., Khobrani, F.A., et al. 2022. Effects of omega-3 polyunsaturated fatty acids on brain functions: a systematic review. Cureus, 14: 10. doi: 10.7759/cureus.30091

Djousse, L., Gaziano, J.M., Buring, J.E. & Lee, I.M. 2011. Dietary omega-3 fatty acids and fish consumption and risk of type 2 diabetes. American Journal of Clinical Nutrition, 93: 143-150. doi: 10.3945/ajcn.110.005603

Djuricic, I. & Calder, P.C. 2021. Beneficial outcomes of omega-6 and omega-3 polyunsaturated fatty acids on human health: an update for 2021. Nutrients, 13: 2421. doi: 10.3390/nu13072421

Duvall, M.G. & Levy, B.D. 2016. DHA-and EPA-derived resolvins, protectins, and maresins in airway inflammation. European Journal of Pharmacology, 785: 144-155. doi: 10.1016/j.ejphar.2015.11.001

Food and Agriculture Organization (FAO). 2019. The state of world fisheries and aquaculture. FAO, Rome.

Froese, R. & Pauly, D. 2022. FishBase. World Wide Web electronic publication. [www.fishbase.org]. Reviewed: March 2, 2023.

Garrido, D., Kabeya, N., Betancor, M.B., Pérez, J.A., Acosta, N.G., Tocher, D.R., et al. 2019. Functional diversification of teleost Fads2 fatty acyl desaturases occurs independently of the trophic level. Scientific Reports, 9: 11199. doi: 10.1038/s41598-019-47709-0

Guo, F., Bunn, S.E., Brett, M.T. & Kainz, M.J. 2017. Polyunsaturated fatty acids in stream food webs-high dissimilarity among producers and consumers. Freshwater Biology, 62: 1325-1334. doi: 10.1111/fwb.12956

Hedrick, R.L., Popma, T.J. & Davis, D.A. 2005. Pond production and fatty acid profiles of the fillets of channel catfish reared on diets with different protein sources. North American Journal of Aquaculture, 67: 304-311. doi: 10.1577/A05-021.1

Holub, D.J. & Holub, B.J. 2004. Omega-3 fatty acids from fish oils and cardiovascular disease. Molecular and Cellular Biochemistry, 263: 217-225. doi: 10.1023/b:mcbi.0000041863.11248.8d

Instituto Nacional de la Pesca (INAPESCA). 2018. Acuacultura bagre de canal. Acuacultura comercial. [https://www.gob.mx/inapesca/acciones-y-programas/bagre-de-canal]. Reviewed: April 5, 2023.

Jain, A.P., Aggarwal, K.K. & Zhang, P.Y. 2015. Omega-3 fatty acids and cardiovascular disease. European Review for Medical and Pharmacological Sciences, 19: 441-445.

Jump, D.B., Depner, C.M., Tripathy, S. & Lytle, K.A. 2015. Potential for dietary ω-3 fatty acids to prevent nonalcoholic fatty liver disease and reduce the risk of primary liver cancer. Advances in Nutrition, 6: 694-702. doi: 10.3945/an.115.009423

Kim, J., Lim, S.Y., Shin, A., Sung, M.K., Ro, J., Kang, H.S., et al. 2009. Fatty fish and fish omega-3 fatty acid intakes decrease the breast cancer risk: a case-control study. BMC Cancer, 9: 1-10. doi: 10.1186/1471-2407-9-216

Kleber, M.E., Delgado, G.E., Lorkowski, S., März, W. & von Schacky, C. 2016. Omega-3 fatty acids and mortality in patients referred for coronary angiography. The Ludwigshafen risk and cardiovascular health study. Atherosclerosis, 252: 175-181. doi: 10.1016/j.atherosclerosis.2016.06.049

Kromhout, D., Bosschieter, E.B. & Coulander, C. 1985. The inverse relation between fish consumption and 20-year mortality from coronary heart disease. New England Journal of Medicine, 12: 1206-1209. doi: 10.1056/nejm198505093121901

Kumar, A., Mastana, S.S. & Lindley, M.R. 2016. n-3 fatty acids and asthma. Nutrition Research Reviews, 29: 1-16. doi: 10.1017/S0954422415000116

Lara-Rivera, A.L., Parra-Bracamonte, G.M., Sifuentes-Rincón, A.M., Gojón-Báez, H.H., Rodríguez-González, H. & Montelongo-Alfaro, I.O. 2015. El bagre de canal (*Ictalurus punctatus* Rafinesque, 1818): estado actual y problemática en México. Latin American Journal of Aquatic Research, 43: 424-434. doi: 10.3856/vol43-issue3-fulltext-4

Lauritzen, L., Brambilla, P., Mazzocchi, A., Harsløf, L.B., Ciappolino, V. & Agostoni, C. 2016. DHA effects in brain development and function. Nutrients, 8: 6. doi: 10.3390/nu8010006

Leslie, M.A., Cohen, D.J., Liddle, D.M., Robinson, L.E. & Ma, D.W. 2015. A review of the effect of omega-3 polyunsaturated fatty acids on blood triacylglycerol levels in normolipidemic and borderline hyperlipidemic individuals. Lipids in Health and Disease, 14: 1-18. doi: 10.1186/s12944-015-0049-7

Li, M.H., Robinson, E.H., Tucker, C.S., Manning, B.B. & Khoo, L. 2009. Effects of dried algae *Schizochytrium* sp., a rich source of docosahexaenoic acid, on growth, fatty acid composition, and sensory quality of channel catfish *Ictalurus punctatus*. Aquaculture, 292: 232-236. doi: 10.1016/j.aquaculture.2009.04.033

Liu, J. & Ma, D.W. 2014. The role of n-3 polyunsaturated fatty acids in the prevention and treatment of breast cancer. Nutrients, 6: 5184-5223. doi: 10.3390/nu61 15184

Lorente-Cebrián, S., Costa, A.G., Navas-Carretero, S., Zabala, M., Laiglesia, L.M., Martínez, J.A., et al. 2015. An update on the role of omega-3 fatty acids on inflammatory and degenerative diseases. Journal of Physiology and Biochemistry, 71: 341-349. doi: 10.1007/s13105-015-0395-y

Mangano, K.M., Sahni, S., Kerstetter, J.E., Kenny, A.M. & Hannan, M.T. 2013. Polyunsaturated fatty acids and their relation with bone and muscle health in adults. Current Osteoporosis Reports, 11: 203-212. doi: 10.1007/s11914-013-0149-0

Martínez, C.A., Racotta, I.S., Ríos-Durán, M.G., Palacios, E., Toledo-Cuevas, M. & Ross, L.G. 2006. Advances in applied research for the culture of Mexican silversides (Chirostoma, Atherinopsidae). Biocell, 30: 137-148.

McCusker, M.M., Durrani, K., Payette, M.J. & Suchecki, J. 2016. An eye on nutrition: the role of vitamins, essential fatty acids, and antioxidants in age-related macular degeneration, dry eye syndrome, and cataracts. Clinics in Dermatology, 34: 276-285. doi: 10.1016/j.clindermatol.2015. 11.009

Mendoza-Pacheco, O., Parra-Bracamonte, G.M., de la Rosa-Reyna, X.F., Rincón, A.M.S., Morales, P.A. & Medina, V.R.M. 2018. Genes candidatos para mejorar la deposición de ácidos grasos en carne de bagre de canal (*Ictalurus punctatus*). Revista AquaTIC, 51: 1-15.

Messamore, E., Almeida, D.M., Jandacek, R.J. & McNamara, R.K. 2017. Polyunsaturated fatty acids and recurrent mood disorders: phenomenology, mechanisms, and clinical application. Progress in Lipid Research, 66: 1-13. doi: 10.1016/j.plipres.2017. 01.001

Mustafa, F.A. & Medeiros, D.M. 1985. Proximate composition, mineral content, and fatty acids of catfish (*Ictalurus punctatus*, Rafinesque) for different seasons and cooking methods. Journal of Food Science, 50: 585-588. doi: 10.1111/j.1365-2621.1985.tb13749.x

Morris, C.A., Haynes, K.C., Keeton, J.T. & Gatlin, D.M. 1995. Fish oil dietary effects on fatty acid composition and flavor of channel catfish. Journal of Food Science, 60: 1225-1227. doi: 10.1111/j.1365-2621.1995.tb045 61.x

Nelson, A.M. 1972. Diet therapy in coronary disease: effect on mortality of high-protein, high-seafood, fat-controlled diet. Geriatrics, 27: 103-116.

Nelson, J.R. & Raskin, S. 2019. The eicosapentaenoic acid: arachidonic acid ratio and its clinical utility in cardiovascular disease. Postgraduate Medicine, 131: 268-277. doi: 10.1080/00325481.2019. 1607414

Nettleton, J.A., Allen Jr., W.H., Klatt, L.V., Ratnayake, W.M.N. & Ackman, R.G., 1990. Nutrients and chemical residues in one-to two-pound Mississippi farm-raised channel catfish (*Ictalurus punctatus*). Journal of Food Science, 55: 954-958. doi: 10.1111/ j.1365-2621.1990.tb01573.x

Nettleton, J.A. 2000. Fatty acids in cultivated and wild fish. Oregon State University, Oregon.

Parra-Bracamonte, G.M., de la Rosa-Reyna, X.F. & Lara-Rivera, A.L. 2023. Bagre de canal: diversidad genética e importancia comercial. In: La biodiversidad en Tamaulipas. Estudio de Estado. Vol. II. CONABIO, Ciudad de México, pp. 346-353.

Richard, C. & Calder, P.C. 2016. Docosahexaenoic acid. Advances in Nutrition, 7: 1139-1141. doi: 10.3945/an. 116.012963

Robinson, E.H., Li, M.H. & Oberle, D.F. 2001. Nutrient characteristics of pond-raised channel catfish. Beaumont, MS, USA: Mississippi Agricultural & Forestry Experiment Station. Research Report 22: 1-6.

Sanchez-Villegas, A., Henríquez, P., Figueiras, A., Ortuño, F., Lahortiga, F. & Martínez-González, M.A. 2007. Long chain omega-3 fatty acids intake, fish consumption and mental disorders in the SUN cohort study. European Journal of Nutrition, 46: 337-346. doi: 10.1007/s00394-007-0671-x

Sharma, T. & Mandal, C.C. 2020. Omega-3 fatty acids in pathological calcification and bone health. Journal of Food Biochemistry, 44: e13333. doi: 10.1111/jfbc. 13333

Simopoulos, A.P. 2016. An increase in the omega-6/omega-3 fatty acid ratio increases the risk for obesity. Nutrients, 8: 128. doi: 10.3390/nu8030128

Souied, E.H., Aslam, T., Garcia-Layana, A., Holz, F.G., Leys, A., Silva, R., et al. 2016. Omega-3 fatty acids and age-related macular degeneration. Ophthalmic Research, 55: 62-69. doi: 10.1159/000441359

Steffens, W. 1997. Effects of variation in essential FA in fish feeds on nutritive value of freshwater fish for humans. Aquaculture, 151: 97-119. doi: 10.1016/S0044-8486(96)01493-7

Stickney, R.R. & Andrews, J.W. 1972. Effects of dietary lipids on growth, food conversion, lipid and fatty acid composition of channel catfish. Journal of Nutrition, 102: 249-257. doi: 10.1093/jn/102.2.249

Taşbozan, O. & Gökçe, M.A. 2017. Fatty acids in fish. Fatty Acids, 1: 143-159. doi: 10.5772/68048

Tocher, D.R. 2015. Omega-3 long-chain polyunsaturated fatty acids and aquaculture in perspective. Aquaculture, 449: 94-107. doi: 10.1016/j.aquaculture.2015.01.010

Trushenski, J.T. & Rombenso, A.N. 2020. Trophic levels predict the nutritional essentiality of polyunsaturated fatty acids in fish-introduction to a special section and a brief synthesis. American Journal of Aquaculture, 82: 241-250. doi: 10.1002/naaq.10137

Trushenski, J.T., Rombenso, A.N. & Jackson, C.J. 2020. Reevaluating polyunsaturated fatty acid essentiality in channel catfish. North American Journal of Aquaculture, 82: 265-277. doi: 10.1002/naaq.10136

Wall, R., Ross, R.P., Fitzgerald, G.F. & Stanton, C. 2010. Fatty acids from fish: the anti-inflammatory potential of long-chain omega-3 fatty acids. Nutrition Reviews, 68: 280-289. doi: 10.1111/j.1753-4887.2010.00287.x

Wendell, S.G., Baffi, C. & Holguin, F. 2014. Fatty acids, inflammation, and asthma. Journal of Allergy and Clinical Immunology, 133: 1255-1264. doi: 10.1016/j.jaci.2013.12.1087

Worthington, R.E. & Lovell, R.T. 1973. Fatty acids of channel catfish (*Ictalurus punctatus*): variance components related to diet, replications within diets, and variability among fish. Journal of the Fisheries Board of Canada, 30: 1604-1608. doi: 10.1139/f73-257

Worthington, R.E., Boggess Jr., T.S. & Heaton, E.K. 1972. Fatty acids of channel catfish (*Ictalurus punctatus*). Journal of the Fisheries Board of Canada, 29: 113-115. doi: 10.1139/f72-018

Xu, H., Turchini, G.M., Francis, D.S., Liang, M., Mock, T.S., Rombenso, A., et al. 2020. Are fish what they eat? A fatty acid's perspective. Progress in Lipid Research, 80: 101064. doi: 10.1016/j.plipres.2020.101064

Young, M.P., Whitledge, G.W. & Trushenski, J.T. 2014. Changes in fatty acid profiles of three tissue types in channel catfish *Ictalurus punctatus* (Rafinesque, 1818) transferred from river to pond environments. Journal of Applied Ichthyology, 30: 895-905. doi: 10.1111/jai.12485

Young, M.P., Whitledge, G.W. & Trushenski, J.T. 2016. Fatty acid profiles distinguish channel catfish from three reaches of the Lower Kaskaskia River and its floodplain lakes. River Research and Applications, 32: 362-372.

Zárate, R., el Jaber-Vazdekis, N., Tejera, N., Pérez, J.A. & Rodríguez, C. 2017. Significance of long-chain polyunsaturated fatty acids in human health. Clinical and Translational Medicine, 6: 1-19. doi: 10.1186/s40169-017-0153-6

Zhang, T.T., Xu, J., Wang, Y.M. & Xue, C.H. 2019. Health benefits of dietary marine DHA/EPA-enriched glycerophospholipids. Progress in Lipid Research, 75: 100997. doi: 10.1016/j.plipres.2019.100997

Zhang, Y.B.P., Zhou, Y.B., Sang, B.Y., Wan, X.C., Yang, Y.O., Zhang, J.L., et al. 2015. Effect of dietary Chinese tea on growth performance, disease resistance and muscle fatty acid profile of channel catfish (*Ictalurus punctatus*). Aquaculture International, 23: 683-698. doi: 10.1007/s10499

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