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Advances in the nutritional value, functional factors, and health benefits of tuna and its derived products

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ABSTRACT: Tuna is a popular deep-sea pelagic fish that is both flavorful and nutritious and contains polyunsaturated fatty acids, amino acids, selenium, oligopeptides, and other beneficial nutrients. As an important part of the dietary structure of Chinese residents, aquatic products play a key role in ensuring a supply of high-quality nutrients. In recent years, with the development of science and technology, researchers have discovered a variety of nutritional benefits in marine foods, including tuna. Owing to its rich nutrient content and health benefits, the growing popularity of tuna has not only led to an increase in the aquaculture industry but also stimulated the tuna-related food processing industry, including traditional canned tuna and emerging functional foods. This review focuses on the nutritional composition of tuna. Researchers have elucidated its various health-promoting functions, including anti-inflammatory, antioxidant, anticancer, antiobesity, immune-boosting, and antiaging properties. This review also discusses the processing directions for tuna meat and its byproducts, offering insights into the sustainable development of the tuna industry.

Keywords: Tuna; Nutritional effects; Lipids; Amino acids; Oligopeptide; Canned tuna

1. Introduction

Tuna are oceanic migratory fish that are distributed mainly in tropical waters. It belongs to the family Scombridae and order Perciformes, which includes the genera Thunnus and Katsuwonus (skipjack tuna). Tuna comprises eight primary species, including bigeye tuna (*Thunnus obesus*), albacore tuna (*Thunnus alalunga*), yellowfin tuna (*Thunnus albacares*), southern bluefin tuna (*Thunnus maccoyii*), Pacific bluefin tuna (*Thunnus orientalis*), Atlantic bluefin tuna (*Thunnus thynnus*), green gannet tuna (*Thunnus tonggol*), and skipjack tuna (*Katsuwonus pelamis*). More than eight million tons of tuna and tuna-like fish are caught annually worldwide [1]. According to the 2025 China Fisheries Statistical Yearbook, China's tuna catch is predominantly

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dependent on distant-water fishing—a model largely attributable to the warm-water migratory characteristics of tuna stocks. Specifically, in 2024, China's total tuna catch reached approximately 480,000 tons, with offshore fishing accounting for the overwhelming majority (440,000 tons). In contrast, coastal fishing contributed a mere 7.28% to the national total. Geographically, China's tuna resources are primarily distributed in the coastal waters off Hainan Province; this region alone contributed 67.61% of the nation's coastal tuna catch, securing its position as the top contributor.

Globally, the principal markets for tuna consumption are located in Europe, the United States, and Japan, whereas the leading regions for tuna production and processing include Thailand, Ecuador, Spain, and Japan[2]. Typically, tuna is frozen and subsequently processed into canned products and seasonings [3]. With improvements in living standards, tuna has gradually opened up in the Chinese market owing to its high nutritional value.

In Japan, fresh tuna is a staple for sushi and sashimi. Tuna meat is categorized into several portions [4]. The fat content of tuna meat varies considerably from one part of the fish to another, depending on the quality, sorting, and processing methods. Tuna meat is mostly processed into canned food. The byproducts of tuna processing, which constitute approximately 70% of the total weight, are efficiently utilized. For example, tuna byproducts are processed into a variety of nutritional products and fish feed because they are rich in nutrients, including tuna oil, protein, bone, and fish meal.

Tuna is recognized for its substantial nutritional value as a rich source of unsaturated fatty acids, trace elements, amino acids, active peptides, selenium, etc. [5]. It contains high levels of docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), along with a variety of hydrolyzed active peptides and selenium. These components collectively confer tuna with numerous health-promoting properties, including anti-inflammatory, antitumor, antiaging, antioxidant, and immune-enhancing effects, as well as regulation of the intestinal flora and metabolism of glucose and lipids[6, 7]. Therefore, consuming tuna can prevent and improve diseases and protect health. Concurrently, rapid advancements in the fisheries and food processing industries have facilitated the increased consumption of tuna worldwide.

2. Nutritional compositions of tuna

Tuna is a highly nutritious seafood that is rich in proteins, lipids, and various essential nutrients. Additionally, it is a significant source of polyunsaturated fatty acids and vital amino acids. Tuna is rich in vitamins and minerals, making it an ideal dietary choice. However, significant differences in lipid content between farmed and wild tuna have been reported, with farmed tuna exhibiting an increase in DHA content. This disparity in fatty acid composition is attributed primarily to the DHA levels in the feed provided to cultured tuna [4]. Table 1 lists the approximate nutrient compositions of the main tuna species caught.

Table 1 Basic nutritional composition of tuna meat

Species (%, wet basis)	Hydration	Protein	Lipid	Ash	Reference
Bigeye tuna (*Thunnus obesus*)	72.89 ± 0.63	23.72 ± 0.16	2.06 ± 0.57	1.77 ± 0.13	[1]
Albacore tuna	70.00 ± 0.20	27.30 ± 0.50	1.90 ± 0.20	1.50 ± 0.10	[2]

(*Thunnus alalunga*)					
Yellowfin tuna (*Thunnus.albacores*)	73.57 ± 0.55	23.52 ± 0.61	1.93 ± 0.13	1.54 ± 0.06	[1]
Pacific bluefin tuna (*Thunnus orientalis*)	68.60 ± 0.10	25.40 ± 0.60	0.60 ± 0.10	1.90 ± 0.30	[3]
cultured Pacific Bluefin tuna (cultured *Thunnus orientalis*)	62.90 ± 1.60	24.20 ± 0.30	9.50 ± 0.90	1.30 ± 0.10	[3]
Atlantic bluefin tuna (*Thunnus thynnus*)	63.28 ± 0.92	20.96 ± 0.45	11.04 ± 0.78	*	[4]
cultured Atlantic Bluefin tuna (cultured *Thunnus thynnus*)	59.50 ± 0.50	20.82 ± 0.70	16.78 ± 0.50	1.27 ± 0.10	[5]
Longtail Tuna (*Thunnus tonggol*)	52.50 ± 0.26	22.66 ± 0.57	14.91 ± 0.04	1.11 ± 0.00	[6]
Bonito (*Katsuwonus pelamis*)	71.76 ± 0.42	25.29 ± 0.00	0.60 ± 0.00	1.49 ± 0.14	[7]

*: Data not queried

2.1 Lipids

Lipids, which are essential nutrients in food, play crucial roles in the biological processes of living organisms. Lipids also improve the tenderness and flavor of meat. Tuna meat is very rich in lipids, up to (16.78 ± 0.5)%. Notably, lipids are not uniformly distributed in tuna, with the *o-toro* having the highest lipid content, followed by the ventral mid-*toro* and dorsal *akami* having the lowest lipid content [4]. The approximate fatty acid compositions of various tuna species are listed in Table 2. The sampling locations were primarily on the dorsal side, facilitating a more accurate comparison of fat composition differences among the different tuna species.

Table 2. Approximate fatty acid composition of different tuna species (% of total fatty acids).

Species	Bigeye tuna	Albacore tuna	Yellowfin tuna	Pacific bluefin tuna	cultured Pacific Bluefin tuna	Atlantic bluefin tuna	cultured Atlantic Bluefin tuna	Bonito
C14:0	1.66	3.49	1.30	2.90	3.20	2.92	6.30	1.74
C16:0	24.55	21.90	26.18	17.80	16.60	16.21	15.00	14.49
C18:0	8.43	3.50	14.50	6.20	7.30	4.95	4.50	7.57
C16:1	3.42	3.90	3.08	3.70	4.90	3.98	6.70	2.07
C18:1, n-9	24.19	12.70	20.32	15.50	20.60	25.85	12.00	7.74
C20:1, n-9	2.15	1.50	1.30	0.30	0.80	4.29	7.70	0.44
C22:1, n-9	0.85	0.30	0.55	5.70	1.30	3.51	12.00	0.08
C18:2, n-6	0.92	2.30	1.31	1.00	1.10	1.25	1.50	1.00
C20:2, n-6	0.49	0.40	0.38	0.10	0.20	0.00	0.24	0.18
C20:3, n-3	0.26	1.20	1.10	0.00	0.10	0.00	0.16	0.08
C20:4, n-6	4.03	0.30	5.04	1.30	2.40	1.05	0.91	1.31
C20:5, n-3	3.27	9.10	2.39	6.90	6.40	6.51	14.00	3.48
C22:5, n-3	1.07	1.90	1.25	0.80	2.20	1.74	0.00	0.00
C22:6, n-3	20.22	33.80	16.91	23.30	21.50	16.24	12.00	19.27
SAF	37.00	30.80	44.99	34.80	32.00	24.08	28.00	26.56
MUFA	32.40	18.90	26.66	25.50	28.10	37.63	42.00	10.72
PUFA	30.26	50.20	28.35	34.80	35.80	31.32	30.00	25.58
EPA +	23.49	42.90	19.30	30.20	27.90	22.75	26.00	22.75
Sampling position	Dorsal common torso muscles	Fish with two dorsal girdle muscles	Dorsal common torso muscles	Cephalal dorsal common muscle	Cephalal dorsal common dorsi	Common abdominal muscles	Male upper back muscles	Ordinary muscle
Reference	[1]	[8]	[1]	[9]	[9]	[10]	[11]	[7]

Tuna are rich in polyunsaturated fatty acids (PUFAs), which constitute approximately 30 % of lipids. DHA and EPA account for most PUFAs, with DHA being the most abundant, and the DHA:EPA ratio is high. The DHA:EPA ratios of different parts of albacore tuna (*Thunnus alalunga*) range from 3.0-6.6 [8], and the DHA content in the lumbar and dorsal muscles is as high as (33.8 ± 3.4)%. PUFAs are abundant not only in fish meat but also in fish byproducts such as the eyes, head, and viscera, which are good sources of PUFAs (especially DHA), and some studies have shown that the DHA content in tuna eyes is 33.44-34.96 %.

2.2 Proteins, oligopeptides, and amino acids

Tuna is characterized by its high protein content and diverse array of amino acids, with 18 common amino acids identified in yellowfin and bluefin tuna [9], highlighting the abundance of amino acids in tuna, including umami and branched-chain amino acids [5]. In yellowfin tuna, the protein mass fraction can account for (26.65 ± 0.15) % of the total mass, with essential amino acids constituting (38.64 ± 0.35) % [5], a proportion comparable to that found in eggs. The content of umami amino acids in tuna can account for approximately 35 % of the total amino acid content [5], surpassing that of pufferfish, a popular choice in East Asia [10], and contributes to the appeal of tuna among consumers. Branched-chain amino acids ameliorate fatty liver disease induced by a high-fat diet [11], although elevated blood levels of these amino acids have been linked to cardiovascular disease in adults [12]. Branched-chain amino acids (valine, leucine, isoleucine) account for 15.5 %, 15.59 % and 18.36 % of the total amino acid ratio in bigeye, yellowfin, and bluefin tuna, respectively [5]. Tuna also contains a variety of oligopeptides with active functions, including antioxidant peptides, angiotensin-converting enzymes (ACEs), and antiproliferative peptides[13, 14]. These oligopeptides can be directly absorbed and utilized by the human body without digestion and have active functions.

2.3 Phospholipid

Phospholipids are important components of lipids in living organisms, are major components of membranes, and play important roles in biological signaling. In addition to skipjack tuna, tuna contain a high proportion of phospholipids (26.41%-58.80 %) in total lipids, of which phosphatidylcholine (PC) is the main component [15]. Tuna phospholipids are rich in DHA. The phospholipid DHA (PL-DHA) effectively lowers the atherogenic index, improves lipid metabolism, and significantly increases DHA levels in the liver [16].

2.4 Other nutrients

Sulfated polysaccharides are important carbohydrates in tuna. [17]. Those extracted from tuna byproducts have good antioxidant and antimicrobial activities [17-19].

Tuna are rich in various vitamins and minerals, including sodium (Na), potassium (K), and calcium (Ca), as well as trace minerals, including zinc (Zn), iron (Fe), and selenium (Se), among others. Indeed, tuna is exceptionally rich in selenium [20], which has been shown to ameliorate methylmercury toxicity in animal models [21]. Se also possesses antioxidant, anticancer, and antiaging properties [20, 22, 23]. Selenoneine, the primary organic selenium compound in tuna [24], is the main compound responsible for the functional activity of selenium. The tuna liver is also a significant source of vitamin B_{12}, containing approximately 350 μg/100 g, a notably higher concentration than that found in bovine liver [25]. In bluefin tuna, the vitamin content is also high, with the contents of vitamins A, D, and E reaching 445, 37.3, and 790 μg/100 g, respectively.

3. Nutritional benefits of tuna

The health-promoting effects of tuna are attributable primarily to its high content of polyunsaturated fatty acids (PUFAs), active peptides, phospholipids, and minerals. PUFAs, in particular, offer a wide range of nutritional functions, including antidepressant effects [26], the inhibition of obesity [27], and the improvement of glucose–lipid metabolism [28]. Additionally, PUFAs are associated with the alleviation of pancreatic injury and kidney damage [29, 30] (Fig. 1). The production of active peptides through the hydrolysis of tuna meat yields numerous nutritional benefits, including antioxidant, blood pressure reduction, anticancer, and antiaging properties [31,32].

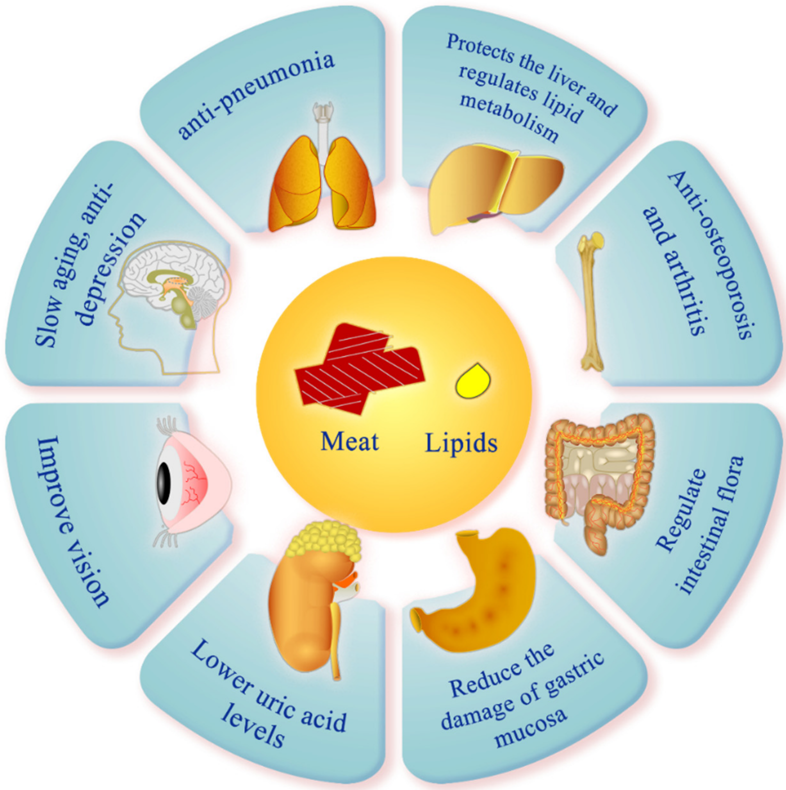

Fig. 1 The health benefits of tuna meat and lipids.

Research on the health benefits of tuna has focused primarily on its anti-inflammatory, antioxidant, anticancer, antiaging, antihypertensive, antidiabetic, lipid metabolism-regulating, and immune-enhancing properties, as well as its ability to improve micronutrient utilization. Studies have explored the potential of tuna in treating and ameliorating various organ-related diseases, including those affecting the liver, bones, brain, intestines, lungs, kidneys, stomach, skin, and reproductive system.

3.1 In vivo experimental studies

In *in vivo* experiments, researchers typically feed experimental animal tuna-derived feed in various forms, including tuna oil, tuna meat, tuna protein hydrolysate, and dried skipjack tuna soup. The primary experimental subjects were rats and mice, and researchers induced different models and added various forms of tuna to investigate their nutritional functions. Key areas of study include the antioxidant, anti-inflammatory, anticancer, and immune-modulating properties of fish oil and its active peptides, as well as the effects of tuna oil on glucose–lipid metabolism and the gut–brain axis. The *in vivo* health-promoting effects of tuna are shown in Table 3.

3.2 In vitro experiments

Fewer *in vitro* experiments have explored the active functions of tuna than *in vivo experiments*. These *in vitro* experiments aimed primarily to elucidate the mechanisms underlying the effects observed *in vitro* and to supplement the *in vitro* findings. *In vitro* studies have demonstrated that tuna possesses antioxidant, anti-inflammatory, blood pressure-lowering, anticancer, and antiaging properties. For a detailed summary of these characteristics, refer to Table 4.

Because tuna is a top predator in marine ecosystems, it tends to accumulate harmful substances from the ocean, including mercury, cadmium, lead, other toxic heavy metals, and polychlorinated dibenzo-p-dioxins (PCDDs) [33]. Consequently, there are also reports of health damage caused by tuna consumption (Table 5).

Extensive *in vitro* and *in vivo* experiments have demonstrated the positive health benefits of tuna. First, tuna oil has potent anti-inflammatory effects, primarily by inhibiting key inflammatory signaling pathways such as the NF-κB and MAPK pathways, thereby alleviating inflammation in models of otic edema, pneumonia, colitis, and arthritis. Second, tuna products exhibit protective effects on bone health, alleviating conditions such as osteoporosis and arthritis. Tuna exert systemic benefits by regulating the gut microbiota, slowing D-galactose-induced aging, and improving depressive behavior through the “gut-brain axis”. Additionally, tuna has promising effects on antitumor and immune regulation, various metabolic regulation, and neurological health.

Table 3. *In vivo* studies of the health effects of tuna.

Aspects	Tuna forms	Research target	Findings	Reference
Pneumonia/ anti-inflammatory /intestinal	Tuna oil	Cigarette smoke-induced lung inflammation in mice	Tuna oil supplementation (820mg/kg/day) for 30 days mitigated cigarette smoke-induced pneumonitis in mice by inhibiting NLRP3 inflammasome and NF-κB activation, enhancing antioxidant capacity, and improving gut microbiota and metabolites, including SCFAs and (R)-3-hydroxybutyrate.	[12]
Antitumor	Tuna oil (oil extracted from the orbital fat tissue)	Antitumor activity of 5-fluorouracil-induced sarcoma 180 mice	Daily supplementation with tuna oil for 14 days enhanced 5-fluorouracil-induced antitumor activity in Sarcoma 180-Bearing Mice without increasing side effects.	[13]
Cancer	Bigeye tuna dark muscle extract (STDME).	AOM/DSS-induced colitis-associated cancer (CAC) model in BALB/c mice	The STDME (4.71%) diet prevents colorectal cancer by inhibiting the accumulation of MDSC (myeloid-derived suppressor cells, which promote cancer development) in the spleen.	[14]
Highly covert aggressiveness	Dried bonito soup	Children with prenatal exposure to dioxin	A daily dose of 30 milliliters of dried bonito broth for 60 days for mothers and infants can improve children's exposure to dioxin.	[15]
anti-inflammatory	Skipjack tuna heart ethanol extract (THEE)	Croton oil-induced ear edema in ICR mice	THEE (250 mg/kg) exerts anti-inflammatory effects by decreasing the levels of NO and pro-inflammatory cytokines such as TNF-α, IL-6, and IL-1β without any cytotoxicity (in vitro experimental mechanism of action)	[16]
Anti-inflammator y	Tuna Eye Oil (TEO)	Croton oil-induced ear edema in ICR mice	At 250 mg/kg, ear edema formation was reduced by 35% compared to control. Mice were not killed by doses of TEO up to 5000 mg/kg body weight. TEO is non-toxic and can be safely used in humans at moderate doses.	[17]
Intestinal/Anti-Inf lammatory	Skipjack enzyme peptide (SEP, Leu-Leu-Phe-Thr-Thr-Gln)	A mouse ulcerative colitis model and a transgenic zebrafish inflammation model.	SEP has anti-inflammatory, anti-ulcerative colitis, and regulates intestinal flora structure	[18]
Obesity/anti-infla mmatory/lipid metabolism	Bonito Concentrate Fermented Extract (BoE)	HFD-60 high-fat diet in C57 BL 6/J mice	Three-month BoE supplementation (420 mg/kg/day) reduced weight gain, visceral fat, serum triglycerides and total cholesterol, and lowered inflammatory cytokines (IL-5, IL-6, IL-13).	[19]
Immunity	Tuna peptide selenium nanoparticles (TP-SeNP)	An experimental model of cyclophosphamide (CTX)-induced immunosuppression in mice.	TP-SeNP (72.92μgSe/kg) reverses CTX-induced immunosuppression by enhancing phagocytosis of mouse monocytes and increasing secretion of the immune factor TNF-α	[20]
Immunity/oncolo gy/intestinal	Albacore tuna (*Thunnus albacores*) protein hydrolysate (TPA)	Animal experiments in S180 tumor-bearing mice receiving 5-fluorouracil (5-FU) chemotherapy.	TPA (800 mg/kg/d), in combination with 5-FU for 15 days, enhanced tumor suppression and attenuated the damage to the small intestinal mucosa caused by 5-FU. TPA further improved the nutritional and survival status of the organism.	[21]
Aging/intestinal/b rain/microbiota-g ut-brain axis	Tuna oil	Animal experimental model of D-galactose-induced senescence in ICR mice	Tuna oil attenuates aging by modulating gut microbiota structure and brain protein expression, promoting beneficial bacteria and suppressing pathogens.	[22]
Brain/Antioxidant	Tuna Ovary DHA-PL	Lipid peroxidation in the mouse brain	Mice fed DHA-PL food had significantly lower lipid peroxide content in the brain and higher levels of tocopherols, DHA in PE, and dimethyl ethyl acetal.	[23]
Brain	Dried bonito soup	Fos expression in the rat brain	Enhancement of Fos expression in brain regions before and after gavage of dried skipjack tuna soup.	[24]

Kidney/hyperuricemia	*Katsuwonus pelamis* peptides and their complexes	1. A model of zebrafish hyperuricemia induced by the uricase inhibitor potassium oxonate. 2. Animal model of acute hyperuricemia in mice induced by oxolinic acid.	*Katsuwonus pelamis* peptide and its complex attenuated hyperuricemia in zebrafish and mice by inhibiting xanthine oxidase (XOD) activity and promoting renal uric acid excretion.	[25]
Kidney	Tuna	Effect of tuna consumption on the kidneys of subjects with type II diabetes mellitus.	GFR increased after subjects ingested 0.7 g/kg body weight of protein (cooked tuna and 100 ml of water).	[26]
Reproduction	Tuna red (black) meat, tuna white (regular) meat	Effect of tuna meat consumption on the reproductive system of rats	A 10% steamed tuna diet induced hyperuricemia, reproductive tract atrophy, testosterone reduction, and testicular oxidative stress in Wistar rats, elevating lipid peroxidation and antioxidant enzyme activities.	[27]
Hypertension/ cardiovascular diseases		Animal experiments on spontaneously hypertensive rats	Antihypertensive effects of hypotensive peptides from tuna black muscle hydrolysate.	[28]
Iron/trace elements	Raw tuna, boiled in brine, canned tuna in different processing conditions	Animal experiments on the utilization of dietary iron in rats	Iron bioavailability varied with tuna processing: raw tuna reduced fecal iron loss, while canned tuna (especially after 3-year storage or oleoresin sterilization) decreased iron absorption and increased fecal loss.	[29]
Anti-Inflammatory	tuna oil	Animal experiments on experimental periodontitis in mice	Dietary 10% tuna oil (35% n-3 PUFAs) elevated oral tissue n-3 PUFA levels and attenuated alveolar bone loss in a murine periodontitis model.	[30]
Bone/anti-inflammatory/intestinal	Tuna oil (TO)	Animal experiments on collagen-induced arthritis (CIA) in ICR mice	Tuna oil (960 mg/kg/day, 22 days) attenuated collagen-induced arthritis and bone erosion by inhibiting NF-κB and activating Wnt/β-catenin pathways, reducing inflammation, and restoring gut barrier and microbiota.	[31]
Bone/anti-inflammatory/intestinal	Tuna Bone Powder (TBP)	Glucocorticoid-induced osteoporosis (GIOP) in ICR mice in animals.	TBP exerted anti-osteoporotic effects via NF-κB inhibition and Wnt/β-catenin activation, enhanced gut barrier integrity, SCFA production, and anti-inflammatory microbiota.	[32]
Bones	Tuna bone meal	Animal experiments on the bone density of mammalian Sprague-Dawley rats and their offspring	Tuna bone meal (4 mg/kg, 4×/day, 14 days) elevated maternal and offspring bone mineral density and bone mass in lactating rats.	[33]
Bone/anti-inflammatory	Skipjack tuna elastin peptide (STEP)	Transgenic GFP zebrafish were used in a dexamethasone-induced cartilage damage model.	STEP (62.5 μg/mL) attenuates Osteoarthritis (OA) by suppressing inflammation and protecting cartilage tissue in zebrafish bodies	[34]
Bone/Motion	Calcium supplements prepared from tuna bone and tuna head oil	Bone damage caused by low calcium intake	Tuna bone calcium (0.4% w/w) exhibited higher bioavailability than $CaCO_3$, enhanced calcium absorption and bone formation via upregulation of serum $1,25(OH)_2D_3$, and attenuated calcium deficiency-induced osteoporosis.	[35]
Bone/anti-inflammatory/intestinal	Tuna elastin peptides	Freund′s complete adjuvant-induced adjuvant arthritis (AIA), AIA mouse model.	Tuna elastin peptide (500 mg / kg-d) alleviated murine AIA via suppressed IL-1β, IL-6, TNF-α, and IL-17, reduced bone erosion, restored gut microbiota, and elevated SCFAs over 42 days.	[36]
Depression / Anti-inflammatory / Intestinal / Brain	Tuna peptides (in tuna meat)	Animal experiments on depression-like behavior in mice due to chronic stress	Daily tuna peptide gavage (0.8 g/kg, 30 days) improved depression-like behavior and inflammation in mice, elevated hippocampal and intestinal 5-HT, reduced plasma LPS, and ameliorated dysbiosis.	[37]

ageing	Tuna oil (TO)	Animal experiments on D-galactose-induced senescence in mice.	Incorporation of tuna oil into the diet (TO: AO = 1:1, 1:2, or 1:3 ratio) attenuates D-galactose-induced senescence effects and improves the gut microbiota.	[38]
Liver/lipid metabolism	Tuna oil (TO)	Effects of lipid metabolism and fatty acid concentration in the rat liver	Tuna supplementation (100 mg/kg, 8 weeks) reduced hepatic and plasma TG/TC by suppressing HMG-CoA reductase expression, and increased n-3 PUFAs, DHA, and EPA in plasma, liver, and tissues.	[39]
Liver/anti-inflam matory	Bluefin tuna skin protein (TUS); tuna collagen peptide (TUCP)	Animal experiments on CCl4-induced hepatitis in mice	Dietary TUS or TUCP (1%, 3 weeks) attenuated CCl_4-induced hepatitis via anti-inflammatory effects, with hepatoprotection primarily mediated by TUCP.	[40]
Obesity/liver/lipi d metabolism	Boiled tuna extracts	Animal experiments on high-fat diet-induced obesity in mice	Cooked tuna extract (400 mg/kg) reduced epididymal fat and exerted anti-obesity effects by modulating hepatic lipogenic and adipogenic protein expression, enhancing fatty acid oxidation via AMPK upregulation, and inhibiting adipogenic enzymes.	[41]
Brain/fetus	Tuna oil	Fatty acid composition of brain and liver phospholipids in guinea pig fetal alcohol syndrome	Tuna oil elevated DHA in fetal brain phospholipids and altered hepatic phospholipid composition, attenuating ethanol-induced neurodevelopmental impairment.	[42]
Fatty acids	Tuna oil	Effect of TO supplementation of sows during gestation on fatty acid composition of piglets	Tuna oil supplementation at different times during the sow's pregnancy had a positive effect on piglet growth. However, it did not prevent the decline in 20:4 n-6 fatty acid status in the brain of piglets at birth.	[43]
Allergies	Tuna oil（TO）	Animal experiments in mice with peanut extract (PE) or whey-induced sensitization	Supplementation with 6% DHA oil (TO, 27.8% DHA) for 6 weeks effectively reduces allergic reactions and mmcp-1 and whey-specific IgE and IgG1 levels in PE- and whey-allergic mice.	[44]
Brain/Neurologic al	Skipjack tuna ovarian lipid (OLS)	Water immersion restraint stress (WIRS) as a chronic stressor in rats stress animals.	Adding 0.9% OLS to the diet for 28 days can alleviate anxiety and inhibit aggression by affecting the 5-hydroxytryptamine nervous system.	[45]
Brain/immunity/ mood	Dried bonito broth (dashi) DBD	PV-small serotonin immunoreactive neurons in the brain and emotional behavior in mice	DBD (10%， 100%) might modulate emotional behaviors by promoting PV-immunoreactive and/or GABAergic neurotransmission through antioxidants and histidine included in DBD, and the vagal nerve.	[46]
vasculature	Bonito extract (BE)	Animal experiments in a model of reduced blood flow induced by overcrowding	A single administration of BE might expand the vascular diameter by affecting the constriction of blood vessels induced by catecholamines， however, it did not affect the cutaneous perfusion rate in mice under normal conditions	[47]
Skin/Anti-Inflam matory	bonito oil and protease-undi-gested proteins (SDBR)	Mouse model of spontaneously occurring atopic dermatitis, NC/Nga mice	SDBR (233 g/kg diet) alleviates atopic dermatitis via modulation of gut microbiota and suppression of IgE and LTB4, mediated by skipjack tuna oil-derived EPA and DHA.	[48]

Table 4. *In vitro* studies of the health effects of tuna

Aspects	Active substance	Research objective	Finding	Reference
Liver/antioxidant	12 antioxidant peptides TRPH1~12: SGE, VDTR, AEM, QDHKA, TVM, QEAE, TEA, VEP, AEHNH, QEP, QAEP, and	*In vitro* study of H_2O_2-induced Chang liver cells	AEM, QDHKA, YEA, AEHNH, and YVM had the strongest free radical scavenging capacity, iron-reducing capacity, anti-lipid peroxidation capacity, and protection against H_2O_2-induced Chang hepatocytes.	[49]

	YVM from Skipjack tuna ovalbumin hydrolysate			
Anti-diabetic/antioxidant	70% ethanol tuna heart extract	*In vitro* antidiabetic and antioxidant effects	Inhibits the efficiency of PTP1B, α-glucosidase, and HRAR enzymes. Significant scavenging effect on free radicals such as DPPH, ABTS, ONOO-, ROS, etc.	[50]
Antioxidant	Thirteen oligopeptides with antioxidant activity, identified as GHHAAA, PHPR, AKHQ, GRVPRV, ADMYW, VDDDD, SVTEV, VKIYI, VRDQY, IRDDY, YREY, AQRPR, and SMDV from Skipjack tuna fish extract protein hydrolysate	*In vitro* study of human umbilical vein endothelial cells (HUVECs) with H_2O_2 oxidative damage	Peptides GHHAAA, PHPR, SVTEV, VRDQY, and SMDV protected HUVECs from H_2O_2-induced injury by enhancing viability, boosting antioxidant enzymes (SOD, GSH-Px), and reducing ROS and MDA.	[51]
Vasculature	Angiotensin-converting enzyme (ACE) inhibitory peptides, WGESF (TRP 3), IKSW (TRP 6), YSHM (TRP 9), and WSPGF (TRP 12) from tuna egg	*In vitro* study of H2O2-induced HUVECs.	ACE inhibition and regulation of NO/ET-1 improved endothelial function, alleviated oxidative stress, and inhibited apoptosis in HUVECs.	[52]
Vasculature	Fourteen ACEi peptides TE, AG, MWN, MEKS, VK, MQR, MKKS, VKRT, IPK, YNY, LPRS, FEK, IRR, WERGE from Skipjack tuna (K. pelamis) dark-colored muscle.	*In vitro* study of H2O2-induced HUVECs.	Peptides MWN, MEKS, MKKS, and LPRS exhibited ACE inhibitory activity and protected vascular endothelium by reversing NE-induced suppression of NO and stimulation of ET-1.	[53]
Lipid metabolism	Micro/nano colloids in bigeye tuna head soup	OA and PA (2:1) were used to establish FFA exposure in an in vitro study of the HepG2 cell model.	TG deposition was significantly reduced in HepG2 cells exposed to FFA	[54]
Anticancer	Skipjack tuna heart ethanol extract (THEE)	Lipopolysaccharide (LPS)-induced anti-inflammatory activity in RAW 264.7 cells	THEE attenuated LPS-induced inflammation in RAW 264.7 cells via suppressing NF-κB/MAPK pathways, reducing NO, TNF-α, IL-6, IL-1β, iNOS, and COX-2.	[16]
Anticancer	Tuna eyeball oil (TEO)	LPS-induced anti-inflammatory activity in RAW 264.7 cells	TEO was not cytotoxic to LPS-induced cell viability in RAW264.7 cells. TEO reduced levels of NO and pro-inflammatory cytokines by up to 50% in a dose-dependent manner. TEO inhibited the expression of NF-κB and MAPK as well as iNOS and COX-2 proteins.	[17]
Anticancer	Two antiproliferative peptides of tuna black muscle digest peptide are Leu-Pro-His-Val-Leu-Thr-Pro-Glu-Ala-Gly-Ala-Thr (1206 Da) and Pro-Thr-Ala-Glu-Gly-Gly-Val-Tyr-Met-Val-Thr (1124 Da)	Antiproliferative activity of human breast cancer cell line MCF-7	showed a dose-dependent inhibition of MCF-7 cells	[55]

Anti-cancer/lung	Freeze-dried tuna whole blood (TWBF) and freeze-dried tuna blood cells (TRBF)	Lung cancer A549 cell proliferation and apoptosis	TWBF and TRBF inhibited A549 proliferation and induced apoptosis via ROS accumulation and mitochondrial membrane potential disruption.	[56]
Cell activation	Skipjack tuna lecithin	In vitro activation of macrophages	Skipjack tuna phospholipids enhanced RAW264.7 macrophage immune function by elevating viability, phagocytosis, NO, SOD, and upregulating IL-1β, IL-6, iNOS, and TNF-α mRNA.	[57]
Cancer/Selenium	Selenoneine from tuna Dark Muscle Extract (STDME)	v-Ha-ras transfected BALB/c 3T3 cell line Bhas 42	STDME feeding increased IFN-γγ-(interferon) production and attenuated tumor transformation	[14]
Enzyme	Raw fish, degreased fish, alkaline and acid solutions as nitrogen sources	Extracellular lipase-producing ability of Staphylococcus epidermidis CMST Pi 2 isolated from the intestinal tract of Indian shrimp (Penaeus indicus)	Skimmed fish meat supports maximum lipase production	[58]
Anticancer	Peptides (LGVGSPPGK, GFDPSR, and PGAPGGGFDI)	Chondrocytes treated with three peptides	Positive regulation of inflammatory response and JAK 2/STAT 3 signaling pathway, and effective inhibition of ECM degeneration and chondrocyte apoptosis	[34]
Immunity	Yellowfin tuna head protein digest and graded fractions 10kD or more, 10-5kD, 5-3kD, 3-1kD, 1kD or less five grade fractions	Mice splenic lymphocytes	Fractions II (10–5 kDa) and V (<1 kDa) potently promoted murine splenocyte proliferation. Fraction V synergized with LPS/ConA to enhance lymphocyte proliferation and immunity.	[59]
Aging/Anti-Wrinkle	Tuna heart extract	Folding of Hs27 human fibroblasts mediated by inhibition of MMPs in skin cells.	Tuna heart extract exerted anti-aging and anti-wrinkle effects by upregulating TIMP-1, suppressing MMP and elastase activity, and stimulating collagen synthesis and fibroblast proliferation.	[60]

Table 5. Health damage from tuna consumption

Forms of tuna consumed	Subjects and Dosage	Damage to health	Reference
Skipjack tuna	Human children aged 3-6 years who regularly consume skipjack tuna	cause severe wheezing	[61]
Tuna fish	More than 1,000 pregnant women in Hong Kong eat every day	If you eat only tuna during pregnancy, it can cause your child's IQ to drop by 2.3 points	[62]
Canned tuna	AARP members between 50 and 71 years of age	Tuna intake was positively associated with the risk of malignant melanoma and melanoma in situ.	[63]
The red or white flesh of tuna	Male Wistar rats weighing approximately 250 g were steamed with 100 g of fresh muscle from blocks of red (dark) or white (normal) muscle and added to 1 kg of food pellets.	Tuna consumption may cause lead accumulation, hyperuricemia, and hepatotoxicity, evidenced by elevated AST/ALT, oxidative stress (increased lipid peroxidation and antioxidant enzymes), and histopathological abnormalities.	[64]
Reproduction Tuna red (black) meat, tuna white (regular) meat	250 g of male Wistar rats, steamed tuna meat was mixed into the diet at a ratio of 1:10	A 10% steamed tuna diet induced hyperuricemia, testicular lead accumulation, reproductive tract atrophy, reduced testosterone, impaired spermatogenesis, and testicular oxidative stress in Wistar rats.	[27]

4. Current status of tuna processing

Globally, tuna is not only consumed as a fresh food but also widely used in the production of canned products, which are popular in the global market [34]. However, during tuna processing, a significant number of byproducts are generated, accounting for approximately 50 % to 70 % of the total fish weight [35]. This waste highlights the need to utilize tuna-processing byproducts. Various parts of tuna, such as the head, skin, bones, offal, and other scraps, can be used to extract valuable nutrients, including fish oil, gelatin, and other active compounds [36] (Fig. 2). Therefore, tuna processing byproducts are considered valuable sources of nutrients and bioactive compounds.

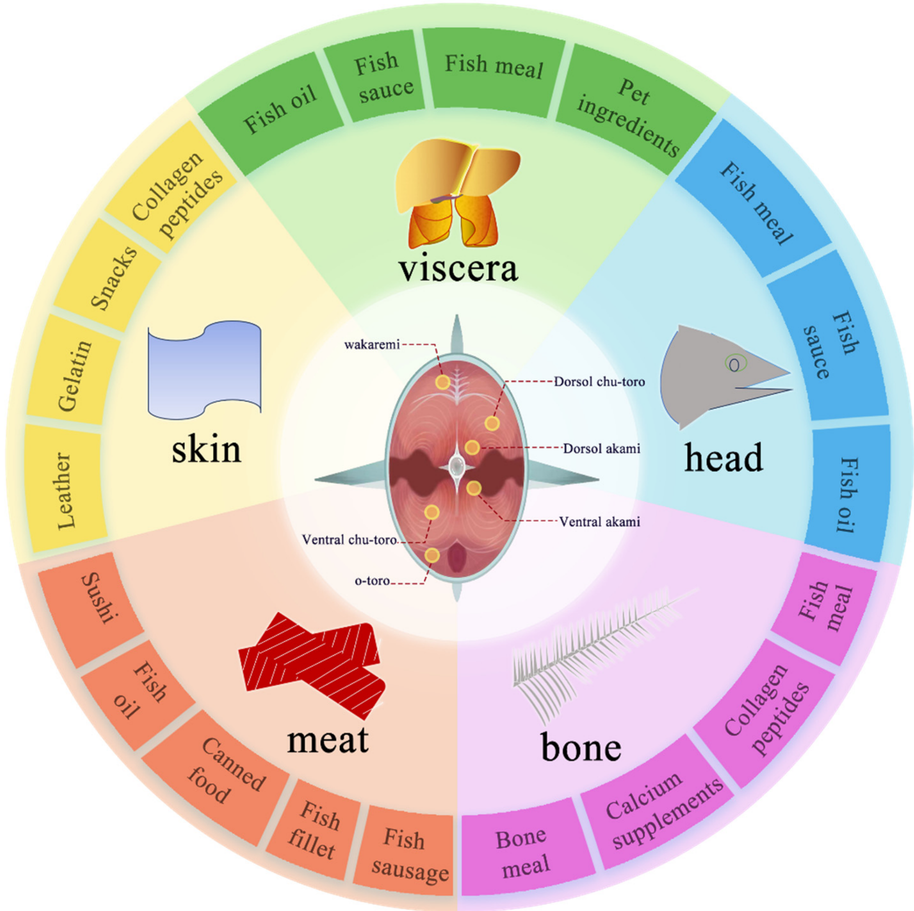

Fig. 2 The different processed products of tuna.

4.1 Preserved and raw tuna

Tuna meat is known for its delicious taste, high fat content, and excellent flavor when consumed fresh. Fresh tuna is particularly popular and highly sought after in the Japanese market, leading to significant price speculation for top-quality fresh tuna. Tuna quality is typically assessed on multiple criteria, including freshness, fat content, flesh color, and the absence of burnt tuna syndrome [37]. Fresh tuna is often quickly processed to make sashimi [38] and is commonly used in dishes such as sushi. Owing to the challenges of preserving tuna, which are often caught in distant oceans and are difficult to maintain during transportation [39], the industry faces the issue of maintaining freshness. As a result, there have been rapid developments in the maintenance and quality testing of fresh tuna. Traditional preservation methods often involve freezing [40].

However, in recent years, new technologies have emerged, including chitosan biopolymer coatings [41], edible cling films made with fish scale gelatin [42], subcooling techniques [43], and methods involving pulsed electric fields and oscillating magnetic fields. In addition to these preservation methods, advanced technologies, including portable handheld single-sided nuclear magnetic resonance (NMR) surface scanners [44, 45]; automated visual inspection systems, including SIVATUN [37]; computer-based visual inspection [46]; and other quality inspection techniques, are utilized to ensure the quality and freshness of tuna products on the market.

4.2 Canned tuna

Tuna meat processing is predominantly focused on producing canned tuna products. Research in this area has often focused on evaluating the quality of canned tuna under different processing conditions [47, 48] and identifying the tuna species present in the cans through DNA analysis [49-54]. Species identification is crucial for preventing adulteration, as different species of tuna have different commercial values. Notably, there is a loss of nutrients in canned tuna compared with raw tuna after processing. This loss includes a decline in total saturated fatty acids, omega-3 fatty acids, EPA, and DHA [55]. Immersion in oil is often used as a compensatory measure to address nutrient loss. However, canned tuna may also contain toxic heavy metals, histamines, and other harmful substances [56-59]. Therefore, there is an urgent need to improve canned tuna processing to address these concerns and ensure the safety and quality of the final product.

4.3 High-value utilization of tuna byproducts

Tuna processing byproducts include fish heads, gills, viscera, bones, skin, nonfillet flesh, and fins[60]. They contain fish oil, gelatin, taurine, calcium, and other nutrients. Fish sauce is a condiment made from aquatic products by fermenting fish with salt and other excipients. Tuna processing byproducts can be used to ferment fish sauces. Tuna viscera contain a large number of endogenous proteases that play significant roles in fermentation [61]. Ciou et al. [62] fermented fish sauce and improved its flavor by adding black bean sauce to tuna cooking juice. Haddar et al. [63] used alkaline protease to hydrolyze tuna skulls to extract gelatin; Yaowapha Waiprib et al. [64] used papain to extract chitosan from tuna heads; Ferdosh et al. [65, 66] used supercritical carbon dioxide to extract fish oil from tuna heads, skin, and viscera; Zhang et al. [67] used a single ultrahigh pressure pretreatment to extract fish oil from yellowfin tuna heads; Shahab Naghdi et al. [68] extracted sulfated polysaccharides from skipjack tuna heads; and biological hydroxyapatite was extracted from fish bones at 950 °C by Boutinguiza et al. [69]. Finally, tuna bones can be treated in various ways to prepare bone meal [70-72]. Tuna viscera contains enzymes [73], a large number of free amino acids with a fresh taste and sweetness, and a large amount of taurine [74], which can improve the palatability of bait, making it a good attractant [75]. In addition, tuna offal can be used to ferment fish sauce[61], replace fishmeal as feed [76], act as an enticement [77], and produce clean energy [78].

5. Conclusions and Outlook

Tuna are highly favored by global consumers not only for their taste but also for their rich nutritional composition. Tuna is known for its high lipid content and is particularly rich in docosahexaenoic acid and protein. It also contains an abundance of essential trace elements. Tuna consumption is associated with various health benefits, including anti-inflammatory, antioxidant, anticancer, metabolism-regulating, gut flora-regulating, bone health, liver health, brain health, and vision-protecting properties. However, there is a lack of research on safe consumption levels of tuna and the removal of harmful substances from tuna products, which may be an urgent issue for future research in relation to processing. Sashimi and canned tuna are traditional tuna products, and the future direction of food processing should be to develop other new products while maintaining the nutritional value of tuna.

Conflict of interest

The authors declared no competing interests in this paper.

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