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Review Article

A comprehensive review of the microbial aspects of enhancing the nutritional quality of ethnic fermented fish products in Asia

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Abstract
Fermentation has long been utilized as a preservation method that improves the safety, longevity, and overall nutritional and sensory quality of food items such as fish. In numerous Asian regions, fermented fish products are deeply embedded in culinary traditions and contribute significantly to local food industries. The fermentation process relies on specific microbial populations that drive biochemical changes, enhancing flavor and preservation while producing compounds with potential health-promoting effects. This review presents a current assessment of fermented fish varieties found throughout Asia, focusing on traditional preparation methods, dominant microbial species, and regional practices. It also examines the bioactive properties associated with these products, including their potential to exhibit anticancer, antimicrobial, antihypertensive, and anticoagulant activities. Emphasis is placed on the functional role of fermentation-associated bacteria in developing these health benefits. Additionally, this article outlines research priorities and underscores the necessity of in vivo experiments and toxicity evaluations to ensure safety before clinical or dietary use. Continued investigation in this area holds promise for advancing human nutrition and wellness and expanding innovation within the food processing sector.

Keywords: Bioactive compounds, Fermented fish, Functional foods, Microorganisms, Traditional fermentation

INTRODUCTION

Fish and fish-based products are excellent sources of polyunsaturated fatty acids, essential minerals, and vitamins. Aquatic animal foods contributed at least 20% of the per capita animal protein supply for approximately 3.2 billion people worldwide, underscoring their critical role in global nutrition and food security (FAO, 2024).

Fermented food was likely one of the first food consumed by humans, and fermentation could only occur in the presence of microbes. Fermentation word came from the Latin word "Fermentum," which means "boiling." It is a chemical digesting process that converts organic chemicals into simpler compounds (Zaman *et al.*, 2022). Fermentation is an ancient process used to make and preserve food (Soibam *et al.*, 2018), enriching and increasing food safety since the dawn of civilization. Preparing traditional fermented foods is one of the world's oldest biotechnological techniques (Roopashri *et al.*, 2023). It opens up a wide range of opportunities for improving food's nutritional and functional characteristics. It slipped out of favor as food processing processes improved. Fortunately, it is increasingly gaining popularity because of its health benefits. Fermentation is an intrinsic process that has an unavoidable impact on the global human food supply, and fermented foods are widely accepted worldwide because they result from the interaction between people and their microbial environment (Tanasupawat & Visessanguan, 2014).

Fermented foods have been an important contribution to diets as fermentation improves nutritional value, enhances sensory qualities, and is a cost-effective technology (Marco *et al.*, 2017). Traditionally, all fermented fish products were prepared based on empirical knowledge, without understanding the microbes' involvement before the advent of modern microbiology (Zang *et al.*, 2020). Tamang (2009) describes ethnic, fermented foods as food items produced by indigenous communities using their traditional knowledge and locally sourced plant or animal materials. These foods are naturally altered or processed with the addition of microorganism-containing starter cultures to create culturally and socially accepted edible products with new flavors and enhanced nutrients. Fermentation occurs when microbes modify specific dietary components to produce a drastically altered end product suitable for ingestion by humans (Kumari *et al.*, 2022). Food fermentation involves altering food through various bacteria, fungi, and the enzymes they generate (Katz, 2012).

Fermentation utilizes microbial metabolic processes to partially oxidize carbohydrates and other nutrients, resulting in various products such as alcohols, acids, amino acids, metabolites, antibiotics, and a small amount of energy (Tavman *et al.*, 2019). Microorganisms enzymatically alter fermented foods and beverages to enhance taste and aroma for human preference (Patel *et al.*, 2023), improve food palatability, and create new variations of foods (Rodgers, 2008).Fermented foods provide numerous advantages, including a distinctive taste, aroma, and texture. They also have an extended shelf life compared to the raw ingredients used in their preparation (Tavman *et al.*, 2019). Additionally, fermentation increases the concentration of secondary metabolites and bioactive compounds, contributing to the food's antimicrobial and antioxidant properties (Vijayendra & Halami, 2015). Additionally, fermented food products support the maintenance of a healthy gut microbiota that plays a key role in protecting against various illnesses and maintaining physiological balance (Rawat *et al.*, 2018). The microorganisms involved in fermentation are probiotic in nature; thus, they offer health benefits to consumers and are essential for maintaining a healthy gut microbiota (Melini *et al.*, 2022)

Northeast India covers approximately 8% of the total geographical area of India and is home to around 40 million individuals, or roughly 3.1% of India's total population. The tribes in this region primarily rely on agricultural cultivation, particularly 'Jhum or shifting' cultivation, to grow cereals, vegetables, and fruits (TERI, 2022). This area is known for its diverse physiography, including hills, valleys, plains, and mountains. Fermented foods and beverages have been traditionally produced and consumed within local markets in Northeast India. The climatic conditions also affect the fermented food product because of the region's tropical, subtropical, and temperate climates (E-Pao, 2025).

FERMENTED FISH OF ASIAN COUNTRIES

Although fermented fish has historical roots in Europe and North Africa, contemporary production is predominantly led by Southeast and East Asian countries. Notably, fermented fish is a distinct culinary speciality of Southeast Asia, differing significantly from fish products prepared in other regions. One of the key distinctions lies in the fermentation period; in Southeast Asia, the process typically spans several months or even years, depending on the type of fish, which is considerably longer than the fermentation durations practiced elsewhere (Han *et al.*, 2024; Li *et al.*, 2023). Native microbial flora plays a significant role in producing volatile flavor compounds in fermented fish. Several studies have shown that the ability of bacteria to produce enzymes like amylases, proteases, and lipases is linked to their role in flavor development. For instance, *Virgibacillus* sp. and *Staphylococcus* sp. strains used as starter cultures have been shown to improve the profile of desirable volatile compounds in fish sauce (Udomsil *et al.*, 2022). Additionally, lactic acid bacteria can convert peptides and oligopeptides into flavor precursors due to their high intracellular amino peptidase activity (Kouakou-Kouamé *et al.*, 2023). According to (Han *et al.*, 2024), *Tetragenococcus halophilus* plays a significant part in enhancing the flavor profile of fish sauce by generating various volatile compounds such as 2-methylpropanal, 2-methylbutanal, 3-methylbutanal, and benzaldehyde. Yeasts also contribute significantly to flavor development due to their strong lipolytic and proteolytic capabilities, and their application as starter cultures has been linked to the production of low-salt fish sauce with improved sensory properties (Ma *et al.*, 2022).

Asian markets offer various fermented fish products, such as whole fish, fish pieces, sauces, pastes, and more. Asians have traditionally made fermented fish sauces, and the practice is gaining traction on international markets every year. These sauces are referred to by a variety of names in various countries throughout the world. In the Philippines, Patis (Elegado *et al.*, 2016); Nampla (Daroonpunt *et al.*, 2016) in Thailand; Budu (Ahmad 2014) in Malaysia; Bakasang (Fatimah *et al.*, 2017) in Indonesia; and Yu-lin (Wang *et al.*, 2018) in China. Fermented fish products from different Asian countries are mentioned in Table 1. These products generally employ comparable basic mat erials, production techniques, and finished compositions. Fish sauce is typically made with just two key ingredients: fish and salt, often in a 3-5:1 ratio. However, some varieties may also include additional herbs and spices. Generally speaking, halophilic bacterial cultures are crucial to c reating these sauces.

Fish sauces are highly nutritious, usually containing all essential amino acids, vitamins, and minerals. However, their nutritional value may be a concern due to their high salt content, especially when consumed alongside other salty foods (Ibrahim *et al.*, 2022)

In addition to fish sauces, a range of fermented fish products can be found in Southeast Asia. Plaa-som, a fermented fish food, and suan yu, an ancient Chinese fermented fish product, both appear in Thai cuisine. Pekasam is a Malaysian fermented whole fish product. Shidal is a fermented food made from salt-free fish, particularly from species like punti (*Puntius sophore*) and phasa (*Setipinna phasa*). Hukuti maas is a well-known dish in Northeast India.

IMPORTANCE OF MICROORGANISMS IN FISH FERMENTATION

Microorganisms play a crucial role in the fermentation process of fish, significantly impacting its quality and taste. Lactic acid bacteria (LAB), such as *Lactobacillus*, *Tetragenococcus*, and *Weissella*, are instrumental in breaking down proteins and lipids, leading to the formation of flavor compounds like aldehydes and ketones (Han *et al.*, 2023). These metabolites enhance the sensory characteristics of fermented fish products, including aroma and umami taste (Han *et al.*, 2023). Also, LAB and related microbes produce antimicrobial substances such as organic acids, hydrogen peroxide, and bacteriocins, inhibiting the growth of pathogens like *E. coli* and *Listeria monocytogenes* (Cortés *et al.*, 2024. This contributes to the microbiological safety and preservation of fermented fish (Cai *et al.*, 2024). Furthermore, microbial populations vary with fermentation parameters such as salt concentration, fermentation time, and starter culture usage (Zhao *et al.*, 2022). Controlled fermentation using selected LAB strains improves consistency, flavor, and safety compared to spontaneous fermentation (Abdulkhair *et al.*, 2023).

Antimicrobial compounds produced by microorganisms during the fermentation process significantly contribute to the stability and quality of fish products, alongside the characteristics of the raw materials used. Compounds such as organic acids, ethanol, hydrogen peroxide, and bacteriocins are crucial in inhibiting or inactivating spoilage and pathogenic microorganisms (Bhattacharya *et al.*, 2022). Organic acids like lactic acid, acetic acid, and propanoic acid create an acidic environment that inhibits the growth of acid-sensitive spoilage microorganisms (Chittora *et al.*, 2022). In fermented fish products, acetic acid has been found to be particularly effective in suppressing the growth of yeasts, molds, and bacteria compared to lactic acid (Chittora *et al.*, 2022). Additionally, lactic acid bacteria (LAB) produce hydrogen peroxide during fermentation, contributing to antimicrobial activity (Bhattacharya *et al.*, 2022). The effectiveness of hydrogen peroxide in killing bacteria depends on its concentration and environmental factors like pH and temperature (Bhattacharya *et al.*, 2022). Bacteriocins, peptides or proteins with antimicrobial activity produced by various lactic acid bacetria (LAB), have been isolated from different fermented fish products. For instance, *Lactococcus lactis* strains have been identified as producers of bacteriocins with potential applications in the biopreservation of fish products (Marlida *et al.*, 2023).

The flavor plays a significant role in determining the quality of fermented fish and is a key factor in consumer purchasing choices. During fermentation, microbial communities have been noted to decompose proteins, lipids, and carbohydrates, forming alcohols, aldehydes, volatile fatty acids, and amino acids. The distinctive taste of fermented fish is primarily due to the equilibrium of microbial byproducts (Han *et al.*, 2024; Li *et al.*, 2023). Native microbial flora plays a significant role in producing volatile flavor compounds in fermented fish. Several studies have shown that the ability of bacteria to produce enzymes like amylases, proteases, and lipases is linked to their role in flavor development. For instance, Virgibacillus sp. and Staphylococcus sp. strains used as starter cultures have been shown to improve the profile of desirable volatile compounds in fish sauce (Udomsil *et al.*, 2022). Additionally, lactic acid bacteria can convert peptides and oligopeptides into flavor precursors due to their high intracellular amino peptidase activity (Kouakou-Kouamé *et al.*, 2023). According to Han *et al.* (2024), *Tetragenococcus halophilus* plays a significant part in enhancing the flavor profile of fish sauce by generating various volatile compounds such as 2-methylpropanal, 2-methylbutanal, 3-methylbutanal, and benzaldehyde. Yeasts also contribute significantly to flavor development due to their strong lipolytic and proteolytic capabilities, and their application as starter cultures has been linked to the

Table 1. Fermented fish products of Asian Countries

Name	Raw material	Fermentation time	Microbes used	Nutrient composition	State
Nam-pla	*Stolephorus spp. Cirrhinus spp. Ristrelliger spp.* salt	5 to12 Months	*Lactobacillus sp., Pseu-domonas sp., Corynebacterium sp., Micrococcus sp., Pediococcus sp., Bacillus sp., Halobacterium sp. Streptococcus sp.,Sarcina sp.*(Narzary *et al.*, 2021); *Tetragenococcus halo- philus, Bacillus subtilis* and *Staphylococcus sp.* (Fukui *et al.*, 2021); *Bacillus circulans, Bacillus cereus, Bacillus licheniformis and B. megaterium*	The sample contains 4.62% crude protein, 32.26% moisture, 0.80% fat, 0.32% lactic acid, and has a pH range of 5.3 to 6.7 (Zang *et al.*, 2020; Punyauppa-Path *et al.*, 2022).	Thailand
Yu-lu	Anchovies (*Engraulis japonicus*), snakehead, (fish sauce)	6 Months	LAB, Yeast and Halotolerant	The sample contains 66-81% moisture, 16-21% protein, 0.2-15% fat, 1.2-1.5% minerals, 0-0.5% carbohydrates. (Kari *et al.*, 2022)	China
Plaa-som	(Freshwater fish like *Puntius sophore)*, salt, palm sirup, boiled rice and garlic	8 to12 Days	*Pediococcus pentosaceus, Lactobacillus plantarum, Lactobacillus fermentum, Lactococcus garvieae, Weissella cibaria, Streptococcus bovis, Pediococcus cerevisiae, Lactobacillus brevis, Staphylococcus sp.,and Bacillus sp*	The sample contains 16.08–18.94% crude protein, 62.2–67.72% moisture, 0.71–3.20% fat, a pH range of 4.3–5.3, and no detectable lactic acid (Punyauppa-Path *et al.*, 2022).	Thailand
Suan yu	(*Cyprinus carpio*), roasted rice, salt and sugar	30 to 60 Days	*Saccharomyces cerevisiae, Hansenula anomal, L. plantarum, Pediococcus pentosaceus, Leuconostoc, Paralimentarius,*	The product contains a higher protein content of 17.2% to 22.9%, lower moisture range of 52.9% to 58.1%. pH is between 4.27 and 5.18 (Zeng *et al.*, 2013)	China
Hukoti	(*Puntius spp. Ticto barb*), green leaves , stem of *Colocasia esculenta*, ginger, salt	12 Months	*Lactococcus lactis ssp. lactis*	The sample contain 10.12% moisture, 41.51% crude protein, 13.97% crude fat, 4.77% crude fiber, and 20.11% ash. (Ahmed et at., 2019)	India
Jeotgal	*Engraulis japonicus* (anchovy) and / or *Ammodytes sp*	2 Months or May be one year	*Micrococcus, Pseudomonas, Staphylococcus, Sarcina, Saccharomyces, Torulopsis, Achromobacter, Bacillus, Brevibacterium, Flavobacterium, Halobacterium, Leuconostoc,*	59.1% moisture, 12.6% crude protein, 1.3% crude lipid, 21.2% ash, and 22.4% salinity.(Kim *et al.*, 2013)	Korean
Katsuobushi	Skipjack (*Euthynnus pelamis* or *Katsuwonus pelamis*), eastern little tuna (*E. affinis*), *frigate mackerel* (*Auxis rochei*), *frigate tuna* (*A. thazard*), oriental bonito (*Sarda orientalis*)	3 to 4 Months	*Aspergillus*, *Eurotium*	The product contain 48.25% moisture, 41.25% protein, 4.80% fat, 4.10% ash, and 1.60% carbohydrate. (Puspita *et al.*, 2020)	Japan
Narezushi	Crucian carp, horse mackerel, chub mackerel, salt, cooked rice	2 to 3 Months	The identified microorganisms include *Lactobacillus versmoldensis* and *Lactobacillus acidipiscis*. 4o mini	The product has a low pH and contains six different kinds of amino acids (Chan *et al.*, 2023). 4o mini	Japan

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Nappi	Shrimp paste is made from trash fish, including *Acetes* species and mysid shrimp.	7 to 10 Days	The identified microorganisms include *Vibrio cholerae*, *Salmonella typhi*, and *Salmonella paratyphi*.	The moisture content of the dried product ranges from 15.66% to 35.5%, with the highest ash content in the dry salted taki being 26% (Khan *et al.*, 2022). Additionally, another sample has 46.80% moisture, 47.46% protein, 25.38% salt, and a pH of 7.3	Bangladesh
Belacan	Shrimp paste is made from small shrimp, specifically from the *Acetes* species or mysid shrimp.	No fixed duration	The identified microorganisms include *Bacillus*, *Pediococcus*, *Lactobacillus*, *Micrococcus*, *Sarcina*, *Clostridium*, *Brevibacterium*, *Flavobacterium*, *Bacillus cereus*, *Staphylococcus aureus*, and *Corynebacterium*.	The composition includes 28.7–40% crude protein, 27–40% moisture, 1.4–2.6% fat, 2.0–3.4% calcium, 0.02% iron, and a pH range of 7.2–7.8 (Narzary *et al.*, 2021).	Malaysia
Cincalok	Shrimp paste is made by mixing small, fresh shrimp with salt and sugar.	3 to 7 Days	The identified microorganisms include endospore-forming bacteria, *Enterobacteriaceae*, *Bacillus cereus*, *Clostridium perfringens*, and *Staphylococcus aureus*.	The composition includes 69.76% moisture, 12.43% ash, 16.23% protein, and a pH of 4.82 (Surya *et al.*, 2024).	Indonesia
Kapi	Krill or small-sized shrimps (*Acetes vulgaris*)	12 Months	The identified microorganisms include *Bacillus*, *Clostridium*, *Staphylococcus*, and *Tetragenococcus* (Chuon *et al.*, 2014).	The sample contains 49.80% moisture, 43.45% protein, and 39.64% salt and has a pH of 7.8 (Damanik *et al.*, 2020).	Thailand
Kecap ikan	The marine fish mentioned include anchovy (*Stolephorus* sp.), herring (*Clupea* sp.), ponyfish (*Leiognathus* sp.), sardines (*Sardinella* sp.), and jack (*Caranx* sp.) (Ilyanie *et al.*, 2020).	4 to 12 Months	The identified microorganisms include *Bacillus* species, *Cladosporium herbarum*, *Aspergillus fumigatus*, and *Penicillium nonatum* (Ilyanie *et al.*, 2020).	The composition includes 66.67% moisture, 23.7% ash, and 10.17% protein (Surya *et al.*, 2024).	Indonesia
Kung-chom	The mixture consists of small shrimp, ground roasted rice, salt, and garlic.	3 to 5 Days	The microorganisms identified include *Tetragenococcus halophilus*, *Lactobacillus pentosus*, *Lactobacillus plantarum*, *Lactobacillus farciminis*, and *Staphylococcus piscifermentans*, along with *Saccharomyces cerevisiae* strains (Tanasupawa *et al.*, 2014).	The product has a moisture content of 60.7–73.2%, protein content ranging from 6.8–14.2%, fat content between 0.9–2.8%, fiber from trace amounts to 1.8%, ash content of 5.1–12.2%, sodium chloride (NaCl) levels of 3.2–9.4%, lactic acid content of 1.1–3.8%, and a pH range of 3.9 to 4.3 (Tanasupawa *et al.*, 2014).	Thailand
Pla ra	(*Crossocheilus sp.* (soi), *Channa striatus* (chorn), *Cyclocheilichthys sp.* (takok), *Labiobarbus leptocheilus* (soi), *Puntius gonionotus* (ta-pian), *Trichogaster sp.* (kra-dee))	6 to 10 Months	The microorganisms identified include *Tetragenococcus halophilus*, *Lactobacillus acidipiscis*, *Lactobacillus farciminis*, *Enterococcus faecalis*, and *Weissella thailandensis* (Tanasupawa *et al.*, 2014).	The product contains 28.9–68.3% moisture, 7.9–20.3% protein, trace to 6.3% fat, trace to 5.6% fiber, 12.5–28.0% ash, 11.5–23.9% NaCl, trace to 7.3% total invert sugar, 0.5–2.0% lactic acid, and has a pH ranging from 4.1 to 6.9 (Tanasupawa *et al.*, 2014).	Thailand

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Hentak	*Esomus danricus* and *Alocasia macrorrhizos*	15 to 20 Days	The microorganisms identified include *Enterococcus faecium, Lactobacillus fructosus, Lactobacillus amylophilus*, and *Bacillus subtilis* (Thapa *et al.*, 2004).	The composition includes 20.9% moisture, 52.86% crude protein, 17.10% crude fat, 8.10% ash, 39.6% free fatty acid (as oleic acid), a pH of 6.6, 1.1% non-protein nitrogen, and 99.85 mg% total volatile base nitrogen (Muzaddadi *et al.*, 2012).	Manipur
Shidal	*Puntius sophore*	Four to six months	*Staphylococcus aureus, Micrococcus sp., Bacillus sp., E. Coli* (Muzaddadi *et al.*, 2012)	The sample contains 27.2–38.35% protein, has a pH of 6.1–6.2, and a moisture content ranging from 33.44% to 37.52%.	Assam, Tripura, Arunachal Pradesh, and Nagaland,
Lona Ilisha	*Tenulosa ilisha*	4 to 6 Month	*Micrococcus* and *Bacillus* species were identified (Majumdar and Basu, 2010).	The sample contains 54% moisture, 15% salt, and has a pH of 5.4 (Panda *et al.*, 2011).	Bangali community and phillippines
Tungtap	*Puntius sp.* and *Danio sp.*.	4 to7 Days	The microorganisms identified include *Bacillus pumilus, Micrococcus, Bacillus cereus, Staphylococcus aureus, Candida*, and *Saccharomyces* (Thapa *et al.*, 2004).	The sample contains 67.44% moisture, 43.97% ash, 34.22% protein, and 2.38% fat (Ilyanie *et al.*, 2020).	Khasia and Jaintia tribes' community of Meghalaya
Trasi	Fresh Shrimp	No fixed timing	*Staphylococcus, Bacillus*, and *Proteus* were detected in the trasi, while *Salmonella, Vibrio, E. coli*, and *Clostridium* were not present.	The sample contains 25.89% crude protein, 12.13% moisture, 3.8% fat, 32–46% ash, and a pH range of 6.35 to 6.51 (Bozkurt *et al.*, 2016).	Indonesia
Bekasam	The ingredients include freshwater fish, specifically common carp (*Cyprinus carpio Linn.*), along with cooked rice and sticky rice.	8 Weeks	The list of available microorganisms includes *Enterobacter, Micrococcus, Lactobacillus, Moraxella, Eriococcids, Pseudomonas, Staphylococcus,* and *Streptococcus*.	The sample contains 4.81% crude protein, 66.95% moisture, 14.25% fat, 5.76% ash, and has a pH ranging from 6.35 to 6.51 (Surya *et al.*, 2024).	Indonesia
Bagoong	*Stolephorus sp., Sardinella fimbriata* and *Decapterus sp.*	3 to12 Months	*Bacillus sp., Pediococcus sp. Leuconostoc mesenteroides, Lactobacillus plantarum* [Orillo *et al.*, 1968] or *B. coagulans, B. megaterium and B. subtilis while B. licheniformis, Micrococcus colpogenes, M. roseus, M. varians* and species of *Staphylococcus* (SANCHEZ *et al.*, 1999; Tamang *et al.*, 2016)	The sample's composition, as reported by SANCHEZ *et al.* (1999) and Tamang *et al.* (2016), includes the following parameters: Total nitrogen: 2.26% Formol nitrogen: 1.31% Ammonia nitrogen: 0.31% Sodium chloride: 26.10% pH: 5.85% lactic acid content: 0.84%	Philippines
Balao- bala	*Penaeus indicus* or *Macrobrachium sp.*), adding salt (20% based on the shrimp weight	7 to10 Days	According to Banaay *et al.* (2013), the identified microbial species include *Leuconostoc mesenteroides, Pichia cerevisiae*, and *Lactobacillus plantarum.*	According to SANCHEZ *et al.* (1999) and Tamang *et al.* (2016), the sample has a pH range of 7.52–3.80, volatile acid (as acetic acid) levels between 0.03–0.1%, and titratable acidity (as lactic acid) ranging from 0.12–2.0%.	Philippines

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Ngapi	Fish and shrimp are the raw material used for preparation	3 to12 Months	Bacterial population found in Hmyin are *Aeromonas liquefaciens, Alcaligenes faecalis, Bacillus alvel, Bacillus badius, Bacillus brevis, Bacillus cereus, Bacillus circulans, Bacillus polymyxa, Bacillus firmus, Bacillus laterosporus, Bacillus lentus, Bacillus macerans, Bacillus pantothenticus, Bacillus stearothermophilus. Bacillus subtilis, Corynebacterium hoffmanni, Kurthia sp., Lactobacillus, streptobacterium, Pseudomonas fluorescens, Serratia marcescens* and *Staphylococcus epider- midis* (Myo *et al.*, 2004); *Tetragenococcus halophilus, Staphylococcus epidermidis, Tetragenococcus muriaticus, Halanaerobium fermentans, Tetragenococcus muriaticus, Clostridium sensu, Clostridium botuli- num, Halanaerobium fermentans* (Kobayashi *et al.*, 2016)	According to Myo *et al.* (2004), the sample contains 7.6% moisture, 41.9% protein, 8.4% fat, 37.95% NaCl, 0.17% free ammonia, 3.45% ash, and 0.5% sand.	Myanmar
Shottsuru	The raw material used for preparation are Anchovy, opossum shrimp, salt	6 Months	According to Tamang *et al.* (2016), microbial species such as *Aerococcus viridans*, *Halobacterium sp.*, halotolerant and halophilic yeasts, *Micrococcus, Corynebacterium, Streptococcus,* and *Bacillus* were found in environments with 2.5% NaCl, while *Halococcus, Halobacterium, Vibrionaceae,* and *Streptococcus* were detected in 20% NaCl.	According to Ma *et al.* (2022), the sample contains 26.2–30.4% salt, with a pH range of 4.54–5.56. The total nitrogen is 301–1598 mg/100 ml, and volatile basic nitrogen (VBN) ranges from 36.2–170 mg/100 ml.	Japan
Pedah	The fish species used as raw material is Mackerel (*Rastrelliger neglectus*)	2 to 3 Months	The microorganisms identified includes *Acinetobacter sp., Flavobacterium sp., Cytophaga sp., Halobacterium sp., Micrococcus sp., Staphylococcus sp.,* and *Corynebacterium sp.*	According to Surya *et al.* (2024), in a 100 g sample, the parameters are as follows: 46 g moisture, 28 g protein, 4 g fat, 174 mg calcium (Ca), 316 mg phosphorus (P), and 3.1 mg iron (Fe).	Indonesia
Budu	The fish species include Sea water or brackish water fish *Stolephorus indicus, Clupeoides sp., Sardinella sp., Anchoviella commersonii,* and *Anchoviella indica*	3 to 12 Months	*Lactobacillus plantarum*, *Staphylococcus arlettae*, *Saccharomyces cerevisiae* and *Candida glabrata* (Yuen *et al.*, 2009) *Acinetobacter sp., Flavobacterium sp., Cytophaga sp., Halobac- terium sp., Micrococcus sp., Staphylococcus sp.* and *Corynebacterium sp; Lactobacillus sp and Staphylococcus sp.*	According to Zang *et al.* (2020) and Punyauppa-Path *et al.* (2022), the sample contains 45–60.2% moisture, 12.1–13.2% crude protein, 1.3–1.8% crude fat, 0.2–0.4% fiber, 21.6–23.2% ash, with an acidity of 0.4–0.9%, and a pH range of 5.4–6.5.	Thailand and Malaysia
Pekasam	Freshwater fish, tamarind, and salt are commonly used, though marine fish is also utilized.	3 to 5 Days	Studies have revealed that commercial pekasam is contaminated with *Listeria ivanovii, Listeria innocua, Listeria seeligeri, Listeria welshimeri*, and *Listeria denitrificans*, likely due to improper handling practices.	The sample contains 15–25% crude protein, 57–73% moisture, 3.0–8.0% fat, 0.1–0.4% lactic acid, 6–14% ash, and has a pH range of 4.5–6.1.	Malaysia
Som-fak	The fish species include *Channa micropeltes*, *Notopterus chitala* or *Notopterus notopterus*.	3 to 5 Days	The microorganisms identified include *Lactobacillus pentosus, Lactobacillus plantarum, Lactobacillus sakei, Lactobacillus brevis, Pediococcus pentosaceus,* and *Enterococcus faecalis*.	According to Tanasupawat and Vissessanguan (2014), the product contains 62.4–76.3% moisture, 15.9–18.5% protein, trace to 4.8% fat, 0.1–1.0% fiber, 4.4–4.7% ash, 3.6–3.9% NaCl, and 1.2–1.5% lactic acid, with a pH range of 4.1–5.2.	Thailand

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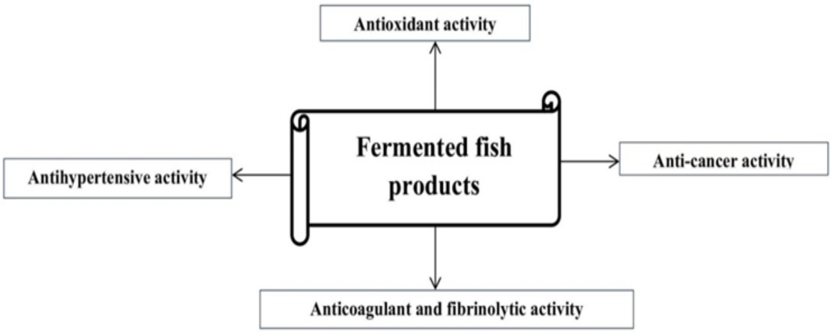

Fig. 1. *Health Benefit of fermented fish products*

production of low-salt fish sauce with improved sensory properties (Ma *et al.*, 2022).

HEALTH BENEFITS OF FERMENTED FISH PRODUCTS

Fermentation has long been a traditional method for preserving fresh fish. It now also produces various nutritious components with improved bioavailability in many cases. Je *et al.* (2005) and (Elegado *et al.*, 2016) report that the active compounds are primarily generated from the extensive breakdown of proteins during fermentation. These chemicals have been connected to numerous advantageous biological features (Je *et al.*, 2005; Elegado *et al.*, 2016).

Fish are rich in essential fatty acids, particularly linoleic and alpha-linolenic acids (Tewari *et al.*, 2022). Due to their unique sensory characteristics and nutritional advantages, fermented fish and other aquatic products are highly sought after globally (Ruddle & Ishige, 2010) Fermenting fish enhances its organoleptic properties and increases the absorption of minerals in the product (Şanlier *et al.*, 2019). Compared to fresh fish, fermented fish has lower levels of fatty acids (Freije *et al.*, 2020). Fermented fish oil is rich in EPA (Eicosapentaenoic acid) and DHA (Docosahexaenoic acid). According to (Han *et al.*, 2012), fermented fish oil containing DHA may offer relief from symptoms associated with atopic dermatitis.

Antioxidant activity

Natural antioxidants and vital minerals abound in fermented fish products, contributing significantly to human health (Liu *et al.*, 2024). Recent studies have identified bioactive peptides derived from fermented fish that exhibit potent antioxidant properties, effectively scavenging free radicals and reducing oxidative stress (Jin *et al.*, 2022). These peptides have demonstrated a range of biological activities, including immunomodulatory, antihypertensive, antimicrobial, and anticancer effects, largely influenced by their specific amino acid sequences (Jin *et al.*, 2022). For instance, through enzymatic hydrolysis, fermentation processes involving lactic acid bacteria have been shown to enhance the production of antioxidant peptides in fish products, such as *Labeo rohita* head sauce (Kanwate *et al.*, 2024). Additionally, comparative analyses of traditional Japanese condiments like shoyu (soy sauce) and gyoshoyu (fish sauce) have revealed significant antioxidant activities, attributed to their rich peptide content (Liu *et al.*, 2024). These antioxidants are crucial in neutralizing reactive oxygen species, thereby playing a vital role in mitigating aging processes and reducing the risk of cancer development (Jin *et al.*, 2022).

Fermented fish products are increasingly recognized as valuable sources of natural antioxidants and essential nutrients, significantly contributing to human health (Liu *et al.*, 2024). Recent studies have demonstrated that small peptides generated during fermentation exhibit robust free radical-scavenging activities, such as hydroxyl and DPPH radical elimination (Chaijan *et al.*, 2022). These bioactive peptides, influenced by specific amino acid sequences, show diverse biological properties, including antioxidant, antihypertensive, antimicrobial, immunomodulatory, and anticancer effects (Gaikwad *et al.*, 2021). For example, traditional fermented fish products like Loma have shown promise as functional food ingredients to help manage chronic illnesses associated with oxidative stress. Similarly, Shidal, a naturally fermented product, has been highlighted as a rich source of natural antioxidants and nutrients, particularly when processed using optimized enzymatic hydrolysis and lactic acid bacteria fermentation (Kanwate *et al.*, 2024).

A recent study on fermented *Labeo rohita* head sauce revealed that antioxidant activity significantly increased after 180 days of storage at 37°C compared to enzyme-treated samples, indicating that fermentation contributes to peptide enrichment (Kanwate *et al.*, 2024). Furthermore, hydrophobic amino acids produced during fermentation enhanced the free radical-scavenging capacity of fish hydrolysates (Liu *et al.*, 2024). Comparative evaluations of traditional Asian condiments such as shoyu (soy sauce) and gyoshoyu (fish sauce) have similarly confirmed their high antioxidant activities, primarily due to their dense bioactive peptide content (Bashir *et al.*, 2020). These antioxidants are crucial in neutralizing reactive oxygen species (ROS), which are closely linked to the onset of cancer and accelerated aging (Gaikwad *et al.*, 2021).

Antihypertensive activity

Peptides with significant antihypertensive effects can be found in fermented fish. Fermented fish can potentially have antihypertensive effects due to the abundance of peptides produced during manufacturing that show ACE inhibitory activity (Sørensen *et al.*, 2004; Itou and Akahane, 2004; Itou *et al.*, 2006). According to research, oligopeptides from "Katsuobushi," a traditional Japanese dish prepared from dried bonito, have shown promise in controlling blood pressure successfully without endangering human health (Fujita *et al.*, 2001; Ma *et al.*, 2022). Dried bonito is also acknowledged as a dietary supplement that might support the recuperation process after exertion. Additionally, studies have shown that narezushi, which is made by fermenting salted mackerel with boiling rice, has antihypertensive properties. (Khositanon *et al.*, 2021; Tamura *et al.*, 2022).

Anticancer activity

Peptide fractions derived from fermented fish products have demonstrated potential anticancer properties. For instance, peptides obtained from fish bone fermented with *Monascus purpureus* have been shown to induce apoptosis and autophagy in human colorectal cancer cells, suggesting a possible preventive effect against certain types of cancer (Chen *et al.*, 2023). Additionally, fermented fish products such as *bekasam*, an Indonesian fermented fish, have exhibited strong antiproliferative effects against various cancer cell lines, indicating their potential as anti-carcinogenic agents (Setiarto *et al.*, 2024). Furthermore, fish sauces produced from Pacific whiting have been recognized for their high concentrations of glutamic acid and peptides, contributing to their nutritional value and potential use in commercial dietary supplements (Kim *et al.*, 2023).

Anticoagulant and fibrinolytic activity

Anticoagulants and antiplatelet medications have traditionally been used to prevent blood clot formation. Certain seafood condiments contain various active compounds that effectively inhibit fibrin clotting, offering potential alternatives to synthetic drugs (Shao *et al.*, 2023). These active substances work by preventing fibrinogen from being affected by thrombin, thereby inhibiting the formation of blood clots (Ortizo *et al.*, 2023). With molecular weights ranging from 1 to 5 kDa, such compounds show promise for oral administration to prevent thrombotic diseases (Baraiya *et al.*, 2024). Fibrinolytic enzymes that break down fibrin and fibrinogen have also been identified in fermented small cyprinid fish (Gu *et al.*, 2023). Despite the proposed health benefits of fermented fish, further investigation—particularly involving clinical studies—is required to validate these effects in human populations (Daza-Rodríguez *et al.*, 2023). Research indicates that fermented fish can generate polysaccharides and bioactive metabolites such as lactoferrin and flavonoids from simple substrates during fermentation (Chaudhary *et al.*, 2023). These bioactive peptides function as antioxidant enzyme complex (ACE) inhibitors and antioxidants and exhibit antiproliferative properties against human lymphoma cells (Shao *et al.*, 2023; Baraiya *et al.*, 2024).

Future prospects

Globally, the demand for fermented fish has surged in the past few years. Many novel methods for studying bacteria during fermentation have been developed to understand microbial ecological groups better. However, most studies on microbes have been descriptive, focusing mainly on identifying microflora.

Next-generation sequencing (NGS) or high-throughput sequencing (HTS) can identify the whole microbial community of fermented fish. Through the analysis of microorganisms' nucleic acid sequences and their comparison with sequence data stored in databases, these methods reveal information about the identity and possible uses of many additional microbes. Since the majority of the taxonomy has been defined, the focus of the current study has changed from taxonomy to function. An improved comprehension of the microbiota of fermented fish is being obtained by examining distinct bacterial strains within a species and proteins produced.

How microbial metabolites control flavor production is still unknown. Traditional fermented fish products have a long production history, but only a few methods have been commercialized globally. Further research is needed to understand the impact of microbes on the quality of fermented fish. Additionally, assessing the safety and nutritional value of these products is essential. As demand for fermented products grows in domestic and international markets, gaining a deeper understanding of these processes becomes increasingly important.

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Conflict of interest

The authors declare that they have no conflict of interest.

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