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Review

Drying and smoking of fish: nutritional significance, safety concerns and emerging technologies for food security

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Abstract
The global demand for fish and fishery products has heightened the need for effective preservation methods to ensure food security and reduce post-harvest losses. Among these, drying and smoking remain the most widely practiced, traditional yet scientifically important techniques, particularly in regions lacking modern refrigeration. Drying, achieved through sun drying, solar or mechanical dryers, reduces microbial activity and enzymatic degradation, while smoking, through cold, warm or hot methods, imparts flavour and enhances preservation. These products are rich in high-quality protein, omega-3 fatty acids, vitamins and minerals, contributing significantly to human health and nutrition. However, microbial contamination, lipid oxidation, pesticide residues and heavy metal accumulation present safety concerns, especially under unhygienic processing conditions. Modern innovations such as vacuum packaging, automated smoking systems and electrostatic smoking improve safety and quality, while climate change poses new risks to traditional sun drying and smoking. Consumer perception is shifting towards safer and more hygienic products, while international regulations and standards such as Codex Alimentarius, EU directives and FSSAI guidelines play a crucial role in ensuring compliance and supporting trade. Furthermore, dried and smoked fish hold nutraceutical potential as affordable sources of protein and bioactive compounds in functional foods and supplements. Emerging technologies, including intelligent packaging, vacuum and liquid smoking and AI- or IoT-enabled dryers, offer sustainable solutions for consistent quality and extended shelf life. By integrating traditional practices with modern innovations and regulatory frameworks, dried and smoked fish can continue to play a pivotal role in ensuring global food and nutritional security.

Keywords: dried fish; food safety; fish nutrition; processed fish; smoked fish

1 | INTRODUCTION

Global aquaculture production has witnessed remarkable growth in recent decades, reaching 130.9 million tonnes in 2022 and accounting for approximately 59% of total global fisheries production, with an estimated value of USD 312.8 billion (FAO 2024). This significant expansion highlights aquaculture's growing contribution to global food systems and its potential to meet the increasing demand for aquatic food resources. Fish plays a pivotal role in ensuring global food and nutritional security due to its high-quality protein, essential amino acids and abundance of omega-3 polyunsaturated fatty acids (PUFAs), which are vital for human health (Balami *et al.* 2019; Tacon 2020). Compared to terrestrial animal production, fish farming is often more resource-efficient and sustainable, with a lower environmental footprint and higher feed conversion efficiency (Froehlich *et al.* 2018). Moreover, fish remains one of the most affordable and accessible sources of animal protein, especially in developing nations where it contributes significantly to dietary diversity and livelihood support (Béné *et al.* 2015; FAO 2022). The continued global expansion of aquaculture thus represents a cornerstone for achieving the United Nations Sustainable Development Goals (SDGs) related to food security, nutrition and sustainable livelihoods worldwide (FAO 2024).

Fish is a rich source of important nutrients, including good-quality fats and protein (macronutrients), vitamins (e.g. vitamin A, vitamin B12, coenzyme Q10, choline and folic acid) and minerals (e.g. Cd, Cu, Ca, Zn, I, Se and Cr^{3+}), all of which are crucial for global food and nutrition security (Maulu *et al.* 2021). However, its highly perishable in nature, owing to its biological composition, makes it susceptible to rapid spoilage if not properly handled or preserved. Effective preservation methods are essential to preserve the fish's quality and extend its shelf life, particularly in regions where modern refrigeration is inaccessible. Among these methods, drying and smoking have emerged as time-tested techniques, widely practiced in developing countries including India, for preserving fish and minimisng post-harvest losses. Approximately 27% of fish in India is consumed fresh, while the remaining 73% is preserved through traditional methods such as smoking, drying and salting (Andhikawati and Pratiwi 2021). The history of drying and smoking fish dates back thousands of years. Evidence suggests that sun-drying meat was practiced as early as 20,000 BC, with signs of fish drying recorded in France around 10,000 years ago (Clavel and Arbogast 2007). In Bengali culture, dried fish, locally referred to as "shutki," holds significant culinary and cultural value. The tradition of smoking fish is believed to have originated among the indigenous peoples of North America and has since been adapted globally to suit diverse tastes and preferences (Grandidier 1899).

One of the most cost-effective and traditional methods to preserve food is drying (Figure 1), which prolongs the shelf life of fish by significantly reducing its moisture content and thereby inhibiting microbial growth and enzymatic spoilage (Fitri *et al.* 2022) Common drying methods include sun drying, solar dryers, and mechanical drying systems, each varying in efficiency and hygiene depending on the technology and environment used (Al-Rubai 2020). This preservation technique is extensively applied to freshwater fish species such as rohu and catla, as well as small pelagic fishes including bombay ducks, mackerel and sardines, which are important in local fisheries and food security (Islam *et al.* 2025). Dried fish acts as a nutrient-dense food source rich in proteins and minerals, offering a highly concentrated product that is both economical and profitable, especially for communities reliant on artisanal fisheries (Sivertsvik 2021; Fitri *et al.* 2022). The drying process not only reduces microbial activity but also slows down enzymatic and chemical reactions, ensuring extended shelf stability and safety of the product while lowering production costs (Al-Rubai 2020). Furthermore, improved drying technologies like convective dryers optimize drying time and protect the product from environmental contamination, increasing product quality and shelf life (Fitri *et al.* 2022). Dried fish production also contributes to reducing postharvest losses, a major concern in fisheries, thereby strengthening food availability and livelihoods (FAO 2019). Thus, drying remains a sustainable preservation method with significant practical and economic benefits for fish producers worldwide.

Smoking (Figure 1), on the other hand, involves exposing fish to volatile compounds generated from the incomplete combustion of wood, which not only imparts distinctive flavors and aromas but also acts as a preservative by inhibiting microbial growth and oxidative spoilage (Doe 1998; Stolyhwo and Sikorski 2005). The process is influenced by factors such as temperature, wood type, smoking duration and salting conditions, which collectively determine the sensory and physicochemical properties of the final product (Stolyhwo and Sikorski 2005). The temperature at which smoking is performed determines the type of product obtained, generally categorised as cold, warm or hot smoking.

Cold smoking, conducted at temperatures below 30°C, produces fish with a reduced moisture content, a delicate smoky flavour and higher salt levels due to the interaction of NaCl and smoke constituents. This process partially denatures proteins, inactivates enzymes and yields a moderately smoky product with a firmer texture (Varlet *et al.* 2007). In contrast, hot smoking, performed at temperatures ranging from 70°C to 80°C, causes complete protein denaturation and lipid oxidation, resulting in a soft, juicy texture with an intense smoky aroma (Alasalvar *et al.* 2010; Adeyeye 2019). Warm smoking (30 – 60°C) is sometimes used as an intermediate process, combining partial cooking with extended shelf life (Gómez-Guillén *et al.* 2009). Among these, cold-smoked fish is particularly valued for its versatility, as it can be consumed directly or after further heat treatment depending on the fish species, size and salt concentration (Cardinal *et al.* 2001; Baltic *et al.* 2009). Moreover, the antimicrobial and antioxidant properties of smoke components such as phenols, formaldehyde and organic acids contribute significantly to product safety and extended storage stability (Varlet *et al.* 2007; Gómez-Guillén *et al.* 2009).

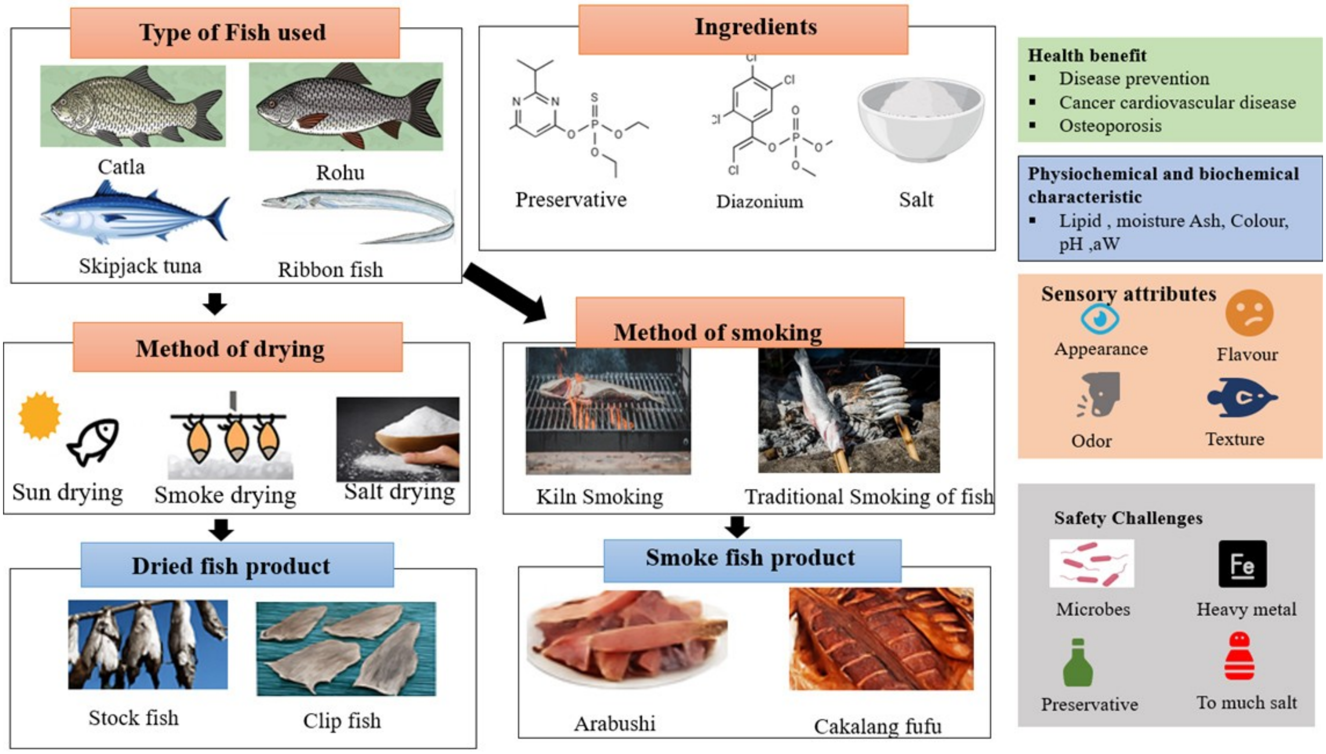

FIGURE 1 Graphical representation of fish drying methods, raw materials, dried and smoked fish products and their characteristics, health benefits and safety challenges.

Traditional fish drying and smoking methods (Figure 2) have persisted through centuries due to their ease of use, strong cultural significance and effectiveness in preserving fish by extending shelf life (Ghaly *et al.* 2010). These traditional techniques provide affordable and nutritious food options while also playing a key role in minimising post-harvest losses, thus significantly contributing to food security, especially in resource-constrained regions (FAO 2018). As the global community grows increasingly focused on sustainable and accessible food systems, the lasting importance of these preservation methods continues to gain recognition (Adeyeye *et al.* 2017).

2 | NUTRITIONAL COMPOSITION OF FISH

Fish is a highly nutritious food, containing 12 – 24% protein, 0.1 – 20% lipid, 0.8 – 5% ash and 63 – 85% moisture (Ninawe and Ratnakumar 2008). The high-quality protein in fish provides essential amino acids necessary for growth, repair and maintenance of body tissues. Additionally, fish is a rich source of omega-3 polyunsaturated fatty acids (PUFAs), particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which play crucial roles in cardiovascular health, brain function and the immune system (Kris-Etherton *et al.* 2002). Omega-3 fatty acids have been shown to lower the risk of coronary heart disease by reducing inflammation, lowering blood triglycerides, and improving endothelial function (Mozaffarian and Wu 2011). Importantly, consumption during pregnancy supports fetal brain development, promoting cognitive function and visual acuity in infants (Innis 2007).

Fish also contains a range of vitamins such as A, D and B-complex vitamins, and minerals including iodine, selenium and zinc, which contribute to overall health and metabolic processes (Tacon and Metian 2009). Its relatively low caloric content, combined with high nutrient density, makes fish valuable for dietary interventions aimed at improving nutrition and preventing chronic diseases (FAO 2022).

Despite its benefits and affordability relative to other animal proteins in many regions, socioeconomic factors such as income, education and availability strongly influence fish consumption patterns, potentially limiting access in certain populations (Thilsted *et al.* 2016). Addressing these factors is essential for maximising fish's role in global nutrition security.

FIGURE 2 Traditional fish drying and processing activities at the Kakinada dried fish landing centre of India.

3 | COMMONLY USED SPECIES FOR DRYING AND SMOKING

Dried fish production is largely influenced by geographical location and the seasonal availability of fish species. Since fresh fish is highly perishable, drying remains one of the most effective and widely adopted preservation methods. A diverse range of fish species is utilised for this purpose, depending on regional preferences and resource availability. In Asian countries, species such as Alaska pollock (*Gadus chalcogrammus*), Pacific saury (*Cololabis saira*), skipjack tuna (*Katsuwonus pelamis*) iridescent shark catfish (*Pangasius hypophthalmus*) and many other small indigenous species are commonly processed into dried fish products (Samad *et al.* 2009; Flowra *et al.* 2010). In contrast, European nations, particularly Portugal, utilise cod species including Atlantic cod (*Gadus morhua*), Pacific cod (*Gadus macrocephalus*), and Alaska pollock (*Theragra chalcogramma*) for the production of salted and dried cod, a traditional delicacy known as "bacalhau" (Fitri *et al.* 2022; FAO 2023).

In tropical regions such as South and Southeast Asia, small pelagic species like anchovies (*Stolephorus* spp.), sardines (*Sardinella* spp.) and mackerels (*Rastrelliger* spp.) are widely dried due to their abundance and high consumer demand (FAO 2021). Smoking, on the other hand, is extensively practiced for species such as herring (*Clupea harengus*), tilapia (*Oreochromis* spp.) and catfish (*Clarias* spp.). This method not only extends the shelf life of the product but also imparts distinctive flavour and aroma, making smoked fish valuable in both subsistence and commercial markets (Odeyemi *et al.* 2020; FAO 2023). Studies conducted on smoked *Clarias gariepinus* and *Oreochromis niloticus* have revealed significant improvements in microbiological stability and sensory quality compared to fresh fish, emphasising the importance of smoking as a preservation technique (Umar *et al.* 2021).

4 | METHODS OF DRYING

Dehydration of fish is accomplished by lowering the moisture level, which prevents microbial activity and degradation. There are several drying techniques available, of which sun drying and solar drying are most common in India.

4.1 Sun drying

The most popular technique for drying fish among artisan fisherman is open sun drying (Kituu *et al.* 2010). Agricultural items have been naturally sun-dried since prehistoric times. The most practical and affordable method of preserving fish and fish products is sun drying (Jain and Pathare 2007; Immaculate *et al.* 2012), especially in tropical and subtropical nations where solar radiation is plentiful, limitless and environmentally benign (Szulmayer 1971).

4.2 Solar drying

Fish and fish items are frequently dried using solar dryers. An improvement on sun drying, solar drying is an energy-efficient method (Zaman and Bala 1989). In addition to saving energy, solar drying also saves a lot of time, takes up less drying space, enhances the quality of the finished goods, increases process efficiency, and protects the environment (Vijaya Venkata Raman *et al.* 2012). The solar dryer is an enclosed device that efficiently uses heat by trapping it inside, which sets it apart from open sun drying (Immaculate *et al.* 2012).

4.3 Heat pump drying
Since the 1970s, heat pump dryers have found extensive industrial use, especially in the food drying and agricultural sectors. Compared to traditional drying, heat pump drying may function more effectively and at lower temperatures (Alves-Filho and Strømmen 1996). Heat pump drying enhances overall thermal performance by recovering both sensible and latent heat from the humid drier exhaust.

4.4 Freeze-drying
Food has been dried via freeze-drying, also known as lyophilisation, since the end of the 1800s (Babić *et al.* 2009). In contrast to traditional drying techniques that depend on capillary action and the evaporation of liquid water for drying, freeze-drying is a novel drying technology that uses the sublimation of ice as its primary drying mechanism.

4.5 Osmotic dehydration
One of the best complementary therapies and food preservation methods for handling dehydrated food is osmotic dehydration (Alakali *et al.* 2006). It is a typical phase in conventional procedures like marinating, smoking and salting, among others (Collignan *et al.* 2001). To create seasoned dried fish products, osmotic dehydration is also frequently used as a seasoning phase in conjunction with other drying techniques (Uribe *et al.* 2011; Wang *et al.* 2011).

5 | METHODS OF SMOKING
Smoking refers to the method of infusing the surface of meat or fish products with a volatile compound produced by the thermal breakdown of wood (Adeyeye 2019). Smoking can be carried by different means, uncluding wood smoking, charcoal smoking and liquid smoke. Cold smoking is a method that does not elevate the temperature sufficiently to cause any cooking of fish flesh, even partially. In contrast, hot smoking involves higher smoke temperature, which cooks the fish flesh to some degree and can even lead to partial sterilisation.

5.1 Hot smoking
It is a technique that requires keeping the temperature over 30°C, usually between 70 and 80°C. Hot smoking cooks the fish, making it ready to eat without the need for extra cooking (Adeyeye 2019).

5.2 Cold smoking
This approach involves keeping the temperature below 30°C. Unlike hot smoking, the fish is left uncooked and is smoked primarily to improve its flavour. As a result, it has to be cooked before consumption. Cold smoking is frequent in temperate locations with relatively low ambient temperatures (Adeyeye 2019).

5.3 Liquid smoking
is a modern practice that uses condensed smoke to Flavour food. This approach is preferred over traditional smoking because it provides for greater control of hazardous chemicals resulting from combustion processes (Rupert and Morgan 2005).

5.4 Electrostatic smoking
Developed and popularised in the Soviet Union, it depends on the electrokinetic characteristics of smoke in a high-voltage field of at least 40 kW (FISH 1948). The salted and rinsed fish are then run through a drying chamber, which is heated by infrared lights on either side of the feeder belt. After being exposed to temperatures between 40°C and 50°C for three to four minutes, the fish lose roughly 5% of their body weight. Conveyors are used to move the fish to the electrostatic smoking oven following this first drying phase. The technique has several advantages, such as continuous operation with mechanical equipment, significant time savings (the entire process takes about 20 minutes), reduced losses because of the short processing time, and an increase in output as a result (Balachandran 2018).

6 | HEALTH BENEFITS OF DRIED AND SMOKED FISH
Fish contain lipids and their constituent fatty acids, including omega-3 fatty acids and essential fats—mainly DHA and EPA—which are highly nutritious and essential for preserving heart health (Figure 3). They help decrease blood pressure, reduce inflammation, minimise the risk of heart disease, and support brain health by lowering the risk of neurodegenerative illnesses and enhancing cognitive performance (Domingo 2007). High-quality protein is necessary for muscle growth and general body maintenance. Fish contains every necessary amino acid that the body cannot produce on its own, making it a complete protein source vital for maintaining healthy muscles, skin and tissues (Yean *et al.* 2017).

Several vitamins and minerals, such as vitamin D, which is vital for healthy bones and the immune system, and Vitamin B12, which is crucial for nerve function and the production of DNA and red blood cells (Doe 1998). The combination of omega-3 fatty acids, selenium and vitamin D helps build a robust immune system, helps reduce inflammation, enhances immune response, and protects against infections and chronic diseases (Mendivil 2020).

7 | CONSUMER PERCEPTION, ACCEPTANCE AND MARKETING CHANNEL
The acceptance of dried and smoked fish products is shaped not only by nutritional value but also by cultural heritage, sensory attributes and perceived safety. In

South Asia, dried fish products such as shutki in Bengal are integral to traditional cuisines, while in Portugal, salted and dried cod (bacalhau) continues to be a staple food with deep cultural significance (Fitri *et al.* 2022). With increasing urbanisation and consumer awareness, preferences are shifting towards hygienically processed, low-contaminant products. A growing segment of consumers now demands naturally smoked products rather than chemically treated or heavily preserved varieties (Andhikawati and Pratiwi 2021). Moreover, value-added forms such as dried fish powder incorporated into soups, snacks and fortified foods have gained traction for their convenience and nutritional benefits, particularly in addressing protein-energy malnutrition in developing countries. Marketing channel of dried and smoked fish and fundctions of different market actors are shown in Figure 4.

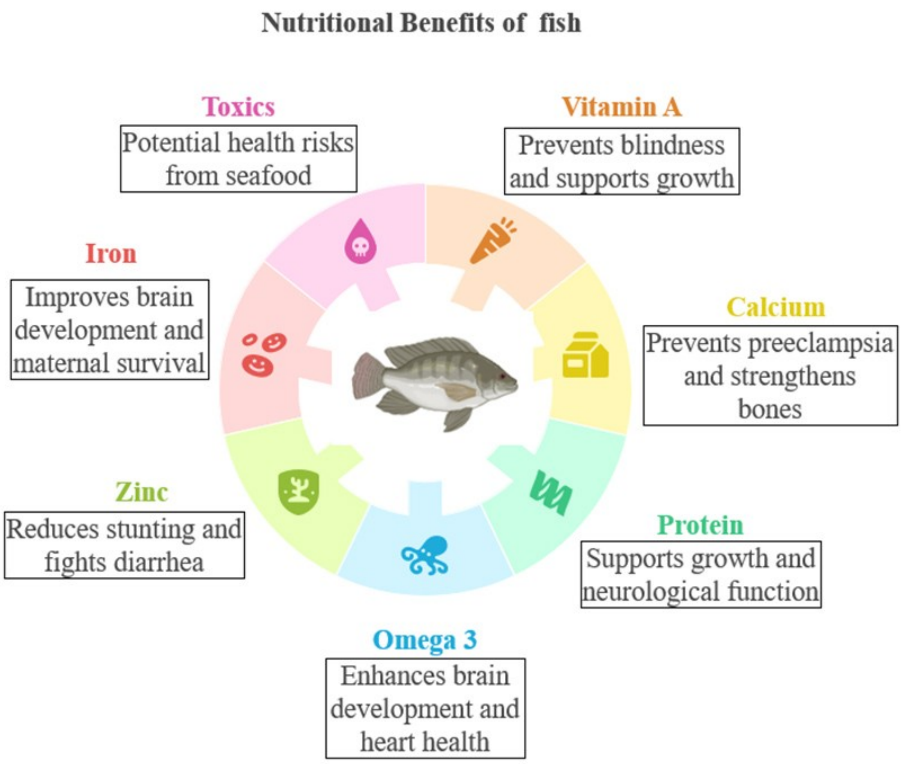

FIGURE 3 Health benefits of fish nutrients in humans.

8 | HAZARDS ASSOCIATED WITH DRIED AND SMOKED FISH

Dried and smoked fishes are susceptible to numerous spoilages, insect infestation and the presence of dirt and filth, which diminishes customer acceptability and has an impact on consumers' health. In addition, a lack of awareness about adequate sanitary handling and sanitation maintenance throughout drying, smoking and selling of smoked and dried fish through fish processors and fish farmers has become a major concern, especially in developing countries (Samad *et al.* 2009). Chemical hazards, such as aquaculture drugs, heavy metals and processing risks, are typically easier to manage since the pathways of contamination are well-defined. In contrast, biological hazards, particularly bacteria like *Listeria monocytogenes*, Enterobacteriaceae and *Clostridium* spp., are more challenging to control. Due to the large variation and diversity of smoked and dried fish, it becomes challenging to establish universal guidelines for food safety and health risks associated with this category of products. The producer has to ensure the product it is producing is free from any type of contamination and is safe for the consumer. Many nations began updating their fish inspection systems as early as 1980 to switch from end-product sampling and inspection to preventative safety and quality systems based on Hazard Analysis Critical Control Points (HACCP) (Lahsen 2007).

8.1 Microbiological hazards

In recent years, consumers have become increasingly concerned about the quality, safety and hygiene of dried and smoked fish products. Due to traditional drying, storage and distribution practices, various microorganisms can significantly affect the microbiological quality and shelf life of dried fishery products (Umar *et al.* 2021). The presence of pathogenic microbial loads in dried fish has become a major safety concern, as these microorganisms can compromise both product quality and public health. Generally, the acceptable total viable bacterial count (TVC) in fresh, frozen or cold-smoked fish should not exceed 7 log CFU g^{-1}; products with counts above this threshold are considered unfit for human consumption

(FAO/WHO 2021).

The detection of *Salmonella* spp. and *Escherichia coli* in some dried fish samples often indicates unhygienic handling and contamination during the drying or post-processing stages (Bedane *et al.* 2022). Traditionally sun-dried fish, particularly small indigenous species, have been reported to contain bacterial loads ranging between 8.10 and 8.45 log CFU g^{-1}, exceeding the permissible limit (Jahan *et al.* 2019). Pathogenic bacteria such as *E. coli*, *Salmonella*, *Shigella* and *Staphylococcus aureus* are frequently detected in dried and smoked fish, especially when processed under poor sanitary conditions or sourced from fecally contaminated waters (Rasul *et al.* 2022). Additionally, exposure of dried and smoked fish to high humidity or poor storage environments at marketplaces promotes moisture absorption, leading to microbial reactivation and spoilage (Fasuan *et al.* 2022).

FIGURE 3 Marketing channel of dried and smoked fish summarising activities of different market actors.

8.2 Chemical hazards

Lipid oxidation in dried and smoked fish: Fatty fishes that contain high levels of fatty acids undergo lipid oxidation when exposed to air or come in contact with oxygen, which alters the flavour and aromatic characters of the fish and imparts a rancid flavour and taste, which is considered unacceptable for consumption. Although it is a fundamental deteriorative response in many food types, fish are more affected because of the large concentration of highly polyunsaturated fatty acids present in marine species (Akman 1980).

Harmful pesticides and insecticides in dried fish: During the drying process, insect infestation and microbial contamination are among the major challenges affecting the quality and safety of dried fish. To prevent such infestations, many fish processors resort to the use of chemical pesticides and insecticides, some of which pose significant risks to human health. Studies have shown that compounds such as DDT (dichlorodiphenyltrichloroethane) and nogos (an organophosphate insecticide) are frequently applied to dried fish to repel insects during storage and marketing (Hossain *et al.* 2014). However, the maximum residue limit (MRL) of DDT in food products is set at 50 ppb by international food safety authorities (FAO/WHO 2023). Excessive or improper use of these chemicals can lead to bioaccumulation and cause chronic health issues such as neurological disorders, endocrine disruption and carcinogenic effects in consumers (Encarnação *et al.* 2019; Shekhar *et al.* 2024).

8.3 Environmental hazards

Environmental pollutants, including heavy metals such as lead (Pb), mercury (Hg) and cadmium (Cd), are examples of trace elements that can exert toxic effects on human health when present in elevated concentrations (Tchounwou *et al.* 2012). Certain trace elements like copper (Cu), nickel (Ni), iron (Fe) and cobalt (Co) are essential micronutrients, performing vital physiological functions at low concentrations; however, excessive accumulation leads to toxicity (Magaye *et al.* 2012). Even at low exposure levels, heavy metals such as Pb, Cd and Hg are known to cause serious health effects in humans (Chowdhury *et al.* 2024). The International Agency for Research on Cancer (IARC 2012) classified lead as possibly carcinogenic to humans (Group 2B), while cadmium and inorganic arsenic were categorised as carcinogenic to humans (Group 1). Chronic bioaccumulation of these metals in aquatic organisms can result in adverse impacts on the digestive, renal, cardiovascular, immune, and reproductive systems of consumers (Jamil Emon *et al.* 2023). The European Commission (EC 2006) established a maximum permissible limit of 0.3 mg kg^{-1} for lead in fish muscle, whereas the limits for cadmium vary from 0.05 to 1.0 mg kg^{-1} in meat products depending on the species and tissue type. For tuna (*Thunnus* spp., *Euthynnus* spp.), bi-clique (*Sicyopterus lagocephalus*) and mackerel (*Scomber* spp.), the maximum allowable concentration of cadmium in muscle tissue is 0.1 mg kg^{-1} (EC 2006).

9 | REGULATORY FRAMEWORK AND FOOD SAFETY STANDARDS

Ensuring the safety of dried and smoked fish requires strong adherence to internationally recognized standards. Regulatory frameworks such as the Codex Alimentarius Commission provide guidelines for maximum residue levels (MRLs) of pesticides, heavy metals, and microbial contamination in fishery products (FAO/WHO 2011). In the European Union, strict limits for contaminants such as cadmium, lead, and mercury in fish muscle have been established to protect consumers (EC 2006). In India, the Food Safety and Standards Authority of India (FSSAI) oversees quality and safety requirements for fish and fishery products, while the implementation of Hazard Analysis and Critical Control Points (HACCP) is increasingly emphasized to minimize risks along the processing chain (Lahsen 2007). Adoption of these regulatory measures not only ensures consumer safety but also facilitates international trade of dried and smoked fish by aligning with export market standards.

10 | CHALLENGES FACED BY THE DRIED AND SMOKED FISH SECTOR REGARDING PROCESSING, PRODUCTION AND MARKETING

Fish processing encompasses the various measures involved in fish and fishery products from the moment they are harvested until the final product reaches the customer (Hall 1997). Fish production is a highly intricate process that involves capturing fish, raising them in optimal conditions, preserving their eggs for future generations and processing them while adhering to microbiological, hydrobiological, chemical and other relevant factors (Bregnballe *et al.* 2024). Whereas Marketing of Fish refers to the process of congregating in public spaces to buy and sell goods, including fish and fish products. It represents the moment when a farmer's products, such as fish, are exchanged for income. The distribution of fish or fish products from the producer to the final customer, including the several processes required to get these items there, is all included in the marketing of fish (Asogwa and Asogwa 2019).

10.1 Processing challenges

Inefficient traditional methods that require extensive time and resources. Health risks associated with poor ventilation and exposure to harmful substances during processing. Lack of modern facilities and technologies that can enhance efficiency and safety.

10.2 Production challenges

Insufficient supply of fish to meet growing demand, particularly in regions like the Niger Delta. Dependence on traditional preservation methods due to inadequate cold storage facilities. Gender inequities, as women predominantly handle processing and face additional barriers in accessing resources.

10.3 Marketing challenges

The dried and smoked fish sector faces numerous marketing challenges that limit its growth and sustainability. Small-scale producers often experience restricted market access due to inadequate infrastructure, poor road connectivity, and limited transportation facilities, which constrain their ability to reach distant or urban markets (Cabugao 2024). In addition, seasonal fluctuations in fish availability significantly affect the consistency of supply, leading to unstable pricing and reduced consumer confidence (FAO 2023). The situation is further exacerbated by competition from larger industrial processing units, which are typically better equipped with modern preservation technologies and focus primarily on export-oriented markets, thereby marginalising small-scale and traditional processors (Naudé 2023). Moreover, insufficient access to market information, weak bargaining power, and lack of value addition or branding limit the profitability and competitiveness of local producers (Hara and Njaya 2016). Addressing these challenges requires coordinated interventions focusing on infrastructure improvement, market linkage development, and capacity-building initiatives for small-scale operators.

11 | MODERN INNOVATIONS

Vacuum packing, a static type of hypobaric storage, is commonly employed in the food sector to reduce oxidative reactions in the product at relatively lower costs (Gopal *et al.* 1999). Vacuum packaging is also known as hypobaric storage. It involves enclosing a product having low-oxygen permeability material and sealing it tightly after removing air (Kumar and Ganguly 2014). Vacuum packing has been demonstrated to extend shelf life up to six days because microbes like bacteria, mould and yeast cannot develop in a vacuum, and foods retain their texture and appearance. For vacuum packing, the packaging film should be strong enough to prevent damage when being handled and should have properties like heat sealability, high oxygen barrier, water vapour barrier, oil resistance and chemical resistance. Vacuum packing with gas-impermeable and heat-stable materials offers several benefits, including reduced post-pasteurization contamination hazards and easy handling. The packing material's oxygen barrier qualities prevent the growth of aerobic spoiling organisms and slow down oxidative reactions in food during storage, because they do not come into touch with air, foods that are vacuum packed retain their freshness and taste for 3 – 5 times longer than those that are stored using traditional techniques (Nagarajarao 2016).

There are many preservation techniques used to minimise post-harvest fish losses, which involve drying, salting and smoking. Fish smoking is a traditional and popular technique known for its unique flavour and colour. Smoked fish can be added whole or powdered to meals, making it considered "ready-to-eat" (Stein-er-Asiedu *et al.* 1991).

11.1 Traditional smoking vs. modern innovations

Traditional smoking includes exposing fish to smoke, which is produced by the combustion of wood or other organic materials, which can be done cold or hot. Cold smoking includes smoking fish at low temperatures, often less than 30°C (86°F), whereas hot smoking cooks fish at temperatures varying from 65°C to 85°C (149°F to 185°F). However, conventional smoking methods can be time-consuming, labour-intensive and inconsistent in quality.

11.2 Automated smoking systems

The automation of the smoking process is one of the biggest technological advances. Manual control over temperature, humidity and smoke density is frequently necessary when using traditional smoking techniques. However, precise control over these factors is now possible with modern automated smoking systems, leading to more reliable and effective manufacturing.

11.3 Smoker ovens with smoke generators

The effectiveness and caliber of smoking have significantly increased due to modern smoker ovens with smoke generators. These ovens enable the use of pellets or wood chips that burn under regulated conditions to create a steady stream of smoke. These sophisticated ovens provide consistency in temperature and smoke dispersion, in contrast to conventional techniques where the smoke may be irregular or inadequate.

11.4 Vacuum smoking

Fish are smoked in a vacuum-sealed atmosphere using an innovative technique called vacuum smoking. Compared to conventionally smoked fish, this method produces a product that is moister, delicate and less dry fish while allowing for a more effective infusion of smoke flavour.

12 | IMPACT OF CLIMATE CHANGE ON DRYING AND SMOKING

Climate change has a direct influence on post-harvest handling and preservation of fish. Rising global temperatures, irregular rainfall and increasing humidity significantly affect traditional preservation methods like sun drying and open smoking. High ambient moisture levels during the monsoon season prolong drying time, encourage mould infestation and promote microbial contamination, leading to food safety risks (Fitri *et al.* 2022). Conversely, extremely high temperatures accelerate lipid oxidation in fatty fish, causing rancidity and nutrient degradation. In tropical countries like India, small-scale processors rely heavily on climate-dependent sun drying, making them vulnerable to unpredictable weather conditions (Rasul *et al.* 2022). Adoption of climate-smart technologies such as solar-hybrid dryers, tunnel dryers, and controlled-environment smoking kilns is therefore essential to maintain product safety and quality in the face of climatic variability.

13 | FUTURE DIRECTIONS AND EMERGING TECHNOLOGIES

The modernisation of drying and smoking technologies is crucial for reducing post-harvest losses and ensuring consistent product quality. Intelligent packaging systems incorporating oxygen scavengers, moisture absorbers and antimicrobial films are being developed to extend shelf life and improve safety (Sampels 2015). Automated smoking chambers and electrostatic smoking systems provide precise control of temperature, humidity and smoke density, thereby improving uniformity and reducing harmful byproducts (Balachandran 2018). Vacuum smoking and liquid smoke technology are increasingly preferred due to their ability to produce moist, tender products with lower levels of polycyclic aromatic hydrocarbons (PAHs). Additionally, the integration of Internet of Things (IoT)-enabled solar dryers and AI-based quality monitoring systems promises to revolutionize traditional fish preservation by allowing real-time monitoring of drying parameters and microbial safety (Nagarajarao 2016). These innovations, coupled with climate-smart strategies, will pave the way for sustainable and safe production of dried and smoked fish.

14 | ECONOMIC ASPECTS OF DRIED AND SMOKED FISH IN INDIA

India is the third-largest fish-producing country in the world, accounting for 7.56% of global food production (Ministry of Fisheries, Animal Husbandry and Dairying, Government of India 2023). Fish production in India is expected to increase from 17.4 million tonnes in 2022–2023 to 22 million tonnes by 2024–2025. Andhra Pradesh is now considered the largest fish-producing state of India. During 2021, Indian smoked and dried fish market was 9.1%, which has increased to $ 1.8 billion in 2024 (Tractor Junction 2025). Approximately 32% of all marine landings in India are consumed as dried fish and 17% of all catches are used for the production of dried fish (Ministry of Fisheries, Animal Husbandry and Dairying, Government of India 2023). According to Volza Global Import data, the world imported 1971 shipments of dried fish from India between March 2023 and February 2024 (Trailing Twelve Months, TMM; Volza 2023). During this period, the world imported 149 dried fish shipments from India in February 2024 alone. Countries including the United States, Sri Lanka and China are the topmost importers that import dried fish from India globally, of which the US contributes to 24722 shipments of dried fish, followed by Sri Lanka with 10500 shipments and China ranks in third position with 9854 shipments of dried fish (Samant *et al.* 2025). Vietnam, India, and Peru are the world's top three dried fish exporters. Vietnam leads the globe in dried fish exports with 32,536 shipments, followed by India with 29,107 shipments and Peru in third place with 8,573 shipments. The world imported 6,753 shipments of smoked fish between March 2023 and February 2024 (TTM), according to Volza's Global Import data (Volza 2024). During this period, the world imported 582 shipments of smoked fish from India in February 2024 alone. Countries such as Ukraine, Uganda, and Russia are top importers of smoked fish. Sri Lanka, the Ivory Coast and Germany are the top exporters of smoked fish (Volza 2024).

15 | CONCLUSIONS

Fish is one of the most perishable foods, and preservation through drying and smoking remains one of the most effective and traditional methods to extend shelf life while enhancing nutritional concentration and imparting desirable sensory qualities. The nutritional value of dried and smoked fish varies with species, diet, season, fishing site, and reproductive condition and while these methods provide significant advantages, they are also associated with risks such as microbial contamination, lipid oxidation, pesticide residues and heavy metal accumulation when processing and handling are inadequate. Recent innovations such as vacuum packaging, automated smoking systems, and electrostatic smoking offer solutions to minimize hazards and improve quality, but additional challenges must be considered. Climate change, with its rising temperatures, unpredictable rainfall and humidity, threatens traditional sun drying and smoking practices, while consumer preferences are shifting towards safer, hygienically processed, and culturally significant products like shutki in Bengal and bacalhau in Portugal. Ensuring compliance with international regulations such as Codex Alimentarius, EU directives, and FSSAI standards is critical to safeguard health and support trade. Moreover, dried and smoked fish have growing nutraceutical potential, with fish powders and fortified products serving as affordable sources of protein, omega-3 fatty acids, selenium, and vitamins to combat malnutrition and promote public health. The future of this sector lies in embracing emerging technologies such as intelligent packaging with oxygen scavengers and antimicrobial films, vacuum and liquid smoking that reduce toxicants, and AI- or IoT-enabled dryers that ensure real-time monitoring of safety and quality. By integrating traditional practices with modern innovations and sustainable technologies, dried and smoked fish can continue to play a vital role in reducing post-harvest losses, ensuring consumer safety, and contributing significantly to global food and nutritional security.

CONFLICT OF INTEREST

The author declares no conflict of interest.

AUTHORS' CONTRIBUTION

NS Sengar - Writing the original draft, Sample collection, Sample Analysis and Data curation; V Sahu - Conceptualization, Investigation, Supervision, Writing - Review & Editing; JK Jakhar - Advisor, Conceptualization, Data curation; D Dhruve - Investigation, Draft correction, Supervision; Soibam Ngasotter - Advisor and Supervision; Tameshwar - Investigation and Supervision; MK Gendley - Investigation and Supervision; S Jakhar - Investigation and Supervision.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on a reasonable request from the corresponding author.

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