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Mandailing smoked fish cuisine: cultural, nutritional, and local wisdom insights

Esi Emilia[1], Nila Reswari Haryana[1], Risti Rosmiati[1], Erli Mutiara[2], Laili Fitria[3], Rachmat Mulyana[4], Wisnu Prayogo[4]
[1]Department of Nutrition, Faculty of Engineering, Universitas Negeri Medan, Medan, Indonesia
[2]Department of Culinary, Faculty of Engineering, Universitas Negeri Medan, Medan, Indonesia
[3]Department of Environmental Engineering, Faculty of Engineering, Universitas Tanjungpura, Pontianak, Indonesia
[4]Department of Building Engineering Education, Faculty of Engineering, Universitas Negeri Medan, Medan, Indonesia

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ABSTRACT

This study explores the uniqueness of Mandailing traditional cuisine, focusing on the cultural and nutritional significance of its iconic smoked fish dishes, such as smoked fish rendang, smoked fish curry, smoked fish with chili sauce, and smoked fish with vegetables. These dishes showcase the traditional fish smoking practices developed as a preservation method, allowing the Mandailing community to adapt to the abundance of rivers and natural resources in their highland environment. Smoking fish not only extended its shelf life but also became a cornerstone of Mandailing culinary identity, reflecting the community's ingenuity and resourcefulness. Mandailing cuisine is deeply influenced by neighboring culinary traditions from West Sumatra and North Tapanuli, resulting in a rich fusion of bold flavors, often characterized using coconut milk and fresh spices. The preparation of smoked fish combines traditional high-heat cooking techniques with unique flavor profiles that distinguish Mandailing dishes from other Indonesian cuisines. This research highlights the importance of Mandailing smoked fish practices in sustaining local food systems and preserving cultural heritage. By emphasizing both cultural and nutritional aspects, it underlines the relevance of these traditional practices in promoting food diversity, environmental sustainability, and the recognition of Indonesia's rich culinary landscape.

Corresponding Author:

Esi Emilia
Department of Nutrition, Faculty of Engineering, Universitas Negeri Medan
Willem Iskandar Street, Pasar V, Medan, 20221, Indonesia
Email: esiemilia@unimed.ac.id

1. INTRODUCTION

Food heritage embodies the intersection of cultural identity, ecological adaptation, and community resilience, functioning as a living record of human creativity and survival [1], [2]. In Indonesia, the world's largest archipelagic state, culinary diversity reflects a vast ecological and ethnic mosaic. Each region has cultivated distinctive cooking traditions that mirror local environments and social structures, from the rendang of the Minangkabau to the arsik of the Batak and the salai of the Dayak. These regional cuisines illustrate how food simultaneously serves as nourishment, ritual, and heritage, linking taste to territorial belonging and cultural memory [3]. Increasingly, traditional cuisines are recognized as instruments for safeguarding intangible cultural heritage while supporting food security, rural livelihoods, and environmental sustainability [4]. Among Indonesia's many preservation practices, fish smoking stands out for its antiquity,

adaptability, and symbolic meaning. Smoking combines dehydration and antimicrobial protection through natural compounds, phenols, aldehydes, and organic acids, which enhance both shelf life and sensory character [5]. Regional variations in smoking fuel, temperature, and duration have yielded distinct culinary identities. For example, in Central Java, Gunawan *et al*. [6] reported that barracuda (*Sphyraena sp*.) smoked traditionally at 80-100 °C for 15 minutes achieved superior sensory scores compared to liquid-smoke methods. Later work on lizardfish (*Saurida tumbil*) at 160 °C for 5 hours produced unique flavoring powders [7]. In East Java, milkfish (*Chanos chanos*) treated with mangrove-leaf liquid smoke at 130 °C showed microbial safety compliance with SNI 2725:2013 [8]. South Sumatra studies combined smoking and canning of *Pangasius hypophthalmus*, producing long-life products sterilized at 121 °C for 15 minutes [9]. Elsewhere, selais (*Kryptopterus lais*) smoked 4-5 hours in Riau emphasized sensory acceptability [10], while skipjack tuna (*Katsuwonus pelamis*) smoked 3-4 hours in Papua highlighted socio-economic benefits [11]. Collectively, these findings reveal that Indonesian smoked fish systems form a geographically diverse matrix shaped by climate, resource availability, and social adaptation. Despite this progress, most studies concentrate on coastal and marine-based systems, overlooking inland food traditions rooted in freshwater ecology. The available evidence in Table 1 confirms this imbalance: Central Java, South Sumatra, and coastal islands dominate research outputs on safety, quality, and nutrition, while inland highland regions like Mandailing remain under-documented. Parallel ethnographic studies in Table 1 reveal strong representation of Javanese, Balinese, Minangkabau, and Batak cuisines, yet Mandailing heritage receives minimal scholarly attention despite its distinct socio-ecological identity. This gap motivates the present study, which situates Mandailing smoked fish cuisine as both a culinary and environmental knowledge system.

Mandailing, located along the Bukit Barisan highlands of North Sumatra, offers a unique intersection of geography, ecology, and culture. The region's rivers, notably the Batang Gadis, sustain abundant freshwater biodiversity, including carp fish (*Cyprinus carpio*), snakehead fish (*Parachanna obscura*), catfish (*Clarias gariepinus*), and river catfish (*Pangasius hypophthalmus*), that form the basis of smoked fish production. Smoking is more than a preservation method; it encodes communal values of cooperation and stewardship. The customary institution of *Lubuk Larangan*, which designates river sanctuaries closed to fishing during certain periods, demonstrates the integration of ecological conservation and food ethics [12]. The traditional process employs bamboo racks and coconut-shell or hardwood fuels to produce *ikan salai*, later used as the main ingredient in dishes such as *rendang ikan salai, gulai ikan salai, and balado ikan salai* [13]. These dishes combine smoking's aromatic depth with coconut-milk richness, reflecting both inland agricultural abundance and coastal culinary influence. Benchmarking Mandailing against other ethnic cuisines clarifies its uniqueness. The Minangkabau's *rendang* employs prolonged coconut-milk reduction, symbolizing endurance and moral wisdom, yet seldom integrates smoked fish. The Batak Toba's arsik emphasizes andaliman spice and sour broth without smoke processing [14]. The Dayak salai method focuses on drying river fish through mild smoking but typically excludes complex sauces or coconut components [15]. In contrast, Mandailing cuisine merges smoke preservation with coconut-based gastronomy, creating a hybrid inland-maritime culinary identity. This synthesis highlights cultural acculturation within Sumatra's interior and reveals how local communities reinterpret preservation techniques to sustain both flavor and meaning.

From a nutritional and biochemical perspective, smoked fish provides valuable protein (19-78%), moderate fat (2-17%), and essential minerals such as calcium and phosphorus, while remaining shelf-stable [16]–[18]. Temperature and duration, from 40-160 °C and 15 minutes to 5 hours, directly influence moisture retention, lipid oxidation, and sensory attributes [19]. These parameters also determine visual appearance, texture firmness, and aroma intensity, critical indicators of consumer preference and market acceptability. Recent innovations such as liquid-smoke application and hybrid thermal treatments aim to reduce carcinogenic polycyclic aromatic hydrocarbons (PAHs) while preserving traditional flavor profiles [20]. However, these advancements have rarely been examined through a cultural lens, and none have explicitly connected biochemical data with ethnographic documentation. Consequently, the novelty of this study lies in its dual cultural-nutritional approach, uniting laboratory analysis of nutrient composition with anthropological interpretation of culinary practice.

This interdisciplinary framework addresses a triple research gap: i) the spatial gap is the absence of inland smoked fish studies, particularly in Mandailing highlands; ii) the epistemic gap is the limited integration between food-science data and ethnographic understanding; and iii) the comparative gap is the lack of cross-ethnic benchmarking within Indonesia's culinary landscape. By documenting Mandailing smoked fish techniques, analyzing nutritional and physicochemical attributes, and interpreting cultural significance, this study reframes traditional cuisine as adaptive technology and intangible heritage. Such integration responds to global calls to link heritage preservation with sustainable diets and community resilience. Ultimately, understanding Mandailing smoked fish systems reveals how indigenous foodways, rooted in ecological ethics and culinary innovation, can inspire modern approaches to nutrition, cultural continuity, and sustainability.

Table 1. Overview of fish-based cuisines and primary research focuses across Indonesian ethnic regions

Research focus			Region/ethnic group	Reference
Fish-based overview				
Barracuda	*Sphyraena sp.*	Safety, quality, and nutritional	Central Java	[6]
– Shark	– *Chiloscyllium punctatum*	Safety, quality, and nutritional	Central Java	[21]
– Stingrays	– *Carcharhinus limbatus*			
	– *Carcharhinus brevipinna*			
	– *Rhizoprionodon taylori*			
	– *Rhizoprionodon oligolinx*			
	– *Rhynchobatus australiae*			
	– *Hemigaleus microstoma*			
	– *Neotrygon kuhlii*			
	– *Maculabatis gerrardi*			
	– *Pastinachus ater*			
	– *Himantura fai*			
	– *Himantura uarnacoides*			
	– *Aetomylaeus nichofii*			
Lizardfish	*Saurida tumbiil*	Acceptability and nutritional	Central Java	[7]
Milkfish	*Chanos chanos*	Sustainability	Central Java	[22]
Milkfish	*Chanos chanos*	Microbial and nutritional	East Java	[8]
Selais	*Kryptopterus lais*	Quality	Riau	[10]
Catfish	*Clarias gariepinus*	Quality and nutritional	South Sumatra	[23]
Catfish	*Pangasius hypophthalmus*	Nutritional	South Sumatra	[24]
Yellowfin tuna	*Thunnus albacares*	Microbial	Ambon	[25]
Skipjack tuna	*Katsuwonus Pelamis*	Costs and income	Southwest Papua	[26]
Skipjack tuna	*Katsuwonus Pelamis*	Microbial and nutritional	Southwest Papua	[27]
Skipjack tuna	*Euthynnus affinis*	Microbial and nutritional	Bali	[28]
Skipjack tuna	*Katsuwonus Pelamis*	Safety and acceptability	East Nusa Tenggara	[29]
Ethnic group-based overview				
Ethnic culinary		*Dodol*	Mandailing	[30]
Ethnic culinary		Cultural cuisine	Mandailing	[31]
Ethnic culinary		Vegetable cuisine	Mandailing	[13]
Ethnic culinary		Cultural cuisine	Madura	[32]
Ethnic culinary		Cultural cuisine	Batak	[33]
Ethnic culinary		Lemang	Batak	[34]
Ethnic culinary and philosophy		Cultural cuisine	Java	[35]
Ethnic culinary and philosophy		*Ketupat and Opor*	Java	[36]
Ethnic culinary		*Tuak*	Dayak	[15]
Ethnic culinary		*Lontong*	Banjar	[37]
Ethnic culinary		Cultural cuisine	Bali	[38]
Ethnic culinary		Cultural cuisine	Minangkabau	[39]
Ethnic culinary		Cassava rice	Sunda	[40]
Ethnic culinary		Cultural cuisine	Melayu	[41]
Ethnic culinary and philosophy		*Pempek*	Palembang	[42]
Ethnic culinary and philosophy		Cultural cuisine	Bugis	[43]

2. METHOD

2.1. Research design

This research employed a mixed-method design integrating ethnographic qualitative inquiry with biochemical laboratory analysis to capture both the cultural meaning and nutritional properties of Mandailing smoked fish traditions. The study adopted the convergent-parallel model proposed by Creswell and Poth [44], in which qualitative and quantitative data were collected concurrently, analyzed independently, and then merged for holistic interpretation. The qualitative component explored social values, traditional knowledge, and symbolic meanings embedded in local fish-smoking practices. Ethnographic observations were conducted directly at production sites to document each processing stage: fish selection, dressing, brining, drying, and smoking; using field notes, photographs, and sketches. As illustrated in Figure 1, the sequential steps of Mandailing smoked fish production begin with raw fish cleaning, dressing, and marinating in traditional spice mixtures, followed by drying and smoking with coconut-shell fuel until the product achieves its distinctive color and aroma. Semi-structured interviews were held with experienced fish smokers, culinary practitioners, and community elders to understand intergenerational knowledge transfer and the socio-economic functions of smoked fish cuisine within village life. The quantitative component scientifically validated these practices through proximate biochemical analysis of representative smoked fish samples. Laboratory examinations determined moisture, crude-protein, fat, and ash contents according to Association of Official Analytical Chemists (AOAC) standards [45]. Four dominant freshwater species were analyzed in triplicate to ensure precision and comparability with international food-science data. Integrating both cultural and biochemical perspectives enabled a comprehensive and empirically grounded understanding

of Mandailing smoked fish heritage. Methodological integration was guided by three principles: i) contextual triangulation among observations, interviews, and biochemical results; ii) cross-disciplinary validation linking local food wisdom with nutritional evidence; and iii) ethical collaboration emphasizing informed consent, confidentiality, and respect for cultural property. Through this design, the study demonstrated how traditional preservation technology embodies environmental adaptation and cultural resilience while contributing to sustainable diets and food security in Indonesia's inland communities.

Figure 1. Sequential steps of smoked fish production in the Mandailing Natal tradition

2.2. Data collection procedures

Data collection consisted of ethnographic observation, semi-structured interviews, and review of secondary data. Direct observation was carried out at smoked fish production sites to document every stage of processing, from raw fish selection, cleaning, marinating, and smoking temperature control to the choice of wood fuel and duration of exposure. Detailed field notes, photographs, and short video recordings were used to capture both the physical process and its socio-cultural context. Semi-structured interviews lasting 30-60 minutes were conducted with the selected informants to gather in-depth insights regarding traditional knowledge, cultural symbolism, and socio-economic implications of fish smoking. Interview transcripts were transcribed verbatim and translated into English for analysis. In addition, secondary data such as scientific papers, ethnographic records, and cultural archives related to Indonesian smoked fish traditions were collected to provide contextual depth and support triangulation. This combination of methods ensured that both tangible and intangible aspects of Mandailing smoked fish practices were accurately represented, offering a holistic understanding of their cultural significance, environmental sustainability dimensions, community resilience, intergenerational knowledge transfer, and evolving adaptation to modern livelihood challenges.

2.3. Biochemical and nutritional analysis

To complement the ethnographic findings with scientific validation, a comprehensive biochemical analysis was carried out on representative smoked fish samples collected from the three selected study sites. Laboratory examinations were conducted at the food chemistry laboratory of Universitas Negeri Medan using standardized and internationally recognized analytical protocols. The samples consisted of four dominant freshwater species representing typical Mandailing smoked fish varieties commonly processed by local artisans using coconut-shell fuel. Each species was analyzed in triplicate to maintain data consistency and ensure the reliability of results. Standard procedures based on the AOAC (2019) guidelines were applied to determine the proximate composition, including moisture, crude protein, crude fat, and ash contents, as summarized in Table 2. All fish samples were collected immediately after the smoking process, allowed to cool to ambient temperature, and then stored in sterile containers to prevent contamination prior to analysis. The resulting biochemical data were carefully processed and compared with previous international studies on smoked fish quality and nutritional characteristics to confirm analytical accuracy, methodological precision, consistency, and cross-study comparability [16], [18], [20].

Table 2. Biochemical and nutritional analysis

Parameter	Analytical method	Standard method
Moisture	Oven drying at 105 °C	AOAC 950.46
Protein	Kjeldahl method	AOAC 981.10
Fat	Soxhlet extraction	AOAC 960.39
Ash	Muffle furnace at 550 °C	AOAC 920.153

3. RESULTS AND DISCUSSION

3.1. Local wisdom in ecosystem conservation through the *Lubuk Larangan* tradition

Mandailing Natal Regency, located in the southernmost part of North Sumatra, Indonesia, is a region of exceptional ecological and cultural wealth. Covering about 6,620 km², it is traversed by six major river systems sustaining agriculture, inland fisheries, and highland valleys. These rivers host freshwater species such as carp (*Cyprinus carpio*), snakehead (*Parachanna obscura*), catfish (*Clarias gariepinus*), and river catfish (*Pangasius hypophthalmus*), vital protein sources that support rural livelihoods. Fishing and fish processing have long shaped Mandailing's economy and culture. Among these, smoked fish (*ikan salai*) production stands out as an indigenous innovation combining practical preservation and ancestral symbolism. In Mandailing markets, smoked fish wrapped in banana leaves or bamboo weavings embody ecological awareness and aesthetic skill. As shown in Figure 1, the process begins with selecting, cleaning, and brining fresh fish, followed by air-drying and smoking over coconut-shell charcoal at 45-180 °C for 30-120 minutes. The result is a golden-brown product with firm texture and a unique aroma. This practice reflects how local knowledge fuses ecological sustainability, culinary creativity, and spiritual value. One emblematic expression of Mandailing wisdom is the *Lubuk Larangan* system in Gunung Tua Julu Village, Panyabungan sub-district. The community, blessed with a fertile landscape, depends heavily on the Batang Gadis River for irrigation, fisheries, and daily needs. *Lubuk Larangan*, literally "forbidden pool," represents a customary river-management system rooted in ancestral ecological insight, Islamic ethics, and collective social agreement. According to Putra and Saleh [12], certain river sections are periodically closed to allow fish regeneration. Elders, religious figures, and village councils decide through communal deliberation. Once declared protected, the river is guarded until reopening day, when abundant fish are harvested collectively as a symbol of gratitude and prosperity. The system predates modern environmental policy, embodying moderation (*wasathiyah*) and moral reciprocity (*timbal balik*), where humans act as guardians of nature's order. Its longevity shows how spiritual and social values ensure ecological stability. Fishing during closure is both illegal and immoral; violators face customary sanctions such as public apology, fines, or the Biko Kawi oath, swearing abstention under spiritual penalty. This moral-based control fosters long-term adherence to ecological ethics.

The annual river reopening, usually after Eid al-Fitr or during Shawwal, is celebrated as a communal festival. Hundreds gather to fish in joy and thanksgiving as shown in Figure 2. Men, women, and children wade through clear waters beneath a steel bridge amid lush vegetation, transforming the river into a symbol of identity and ecological awareness. Funds from entry tickets support mosque repairs, roads, orphans, and public health, showing how natural resources are reinvested in communal welfare. Despite the festivity, ecological rules remain strict: destructive methods such as electrofishing or chemical baits are banned; fine-mesh nets allow juveniles to escape and reproduce. Violations incur moral penalties, reminding people to protect biodiversity. Thus, customary law operates as a socio-ecological contract linking individuals, community, and environment. Although similar traditions exist in West Sumatra, Bengkulu, and South Kalimantan, the Mandailing version shows distinct features. The Minangkabau's *Lubuk Larangan* emphasizes economic redistribution, while Mandailing integrates Islamic ethics linking environmental obedience with spiritual accountability. The participation of *ulama desa* in council decisions is unique, as the river is viewed not merely as a livelihood but as a sacred trust (*amanah Allah*). This spiritualized conservation contrasts with secular models among Batak or Dayak groups. Mandailing culture also connects *Lubuk Larangan* with its culinary and ritual life. As Rahmawati and Mulyadi [31] and Rao *et al.* [30] note, Mandailing food heritage, *ikan sale, dodol* Mandailing, and *lemang bambu*, embody harmony between nature, labor, and faith. Fish from reopened rivers serve in communal feasts, linking ecological renewal to gastronomic celebration. In contrast, Batak water rituals focus on ancestral offerings rather than sustainable fishery management [33]. Hence, Mandailing tradition merges spirituality with pragmatic resource ethics rarely found elsewhere. The Mandailing model is inclusive and educational. Children and youth join the festival, learning from elders about river ethics, biodiversity, and cooperation. This intergenerational learning sustains local wisdom. In Kalimantan, similar handil larangan systems are limited to clan control, while Mandailing's open participation fosters social cohesion and moral equity. It represents a democratic and religiously infused approach to environmental management grounded in justice and ecological balance. From a cultural-ecological perspective, *Lubuk Larangan* serves as a living curriculum of sustainability; teaching moderation in resource use, gratitude through rituals, and redistribution through social projects and community empowerment initiatives.

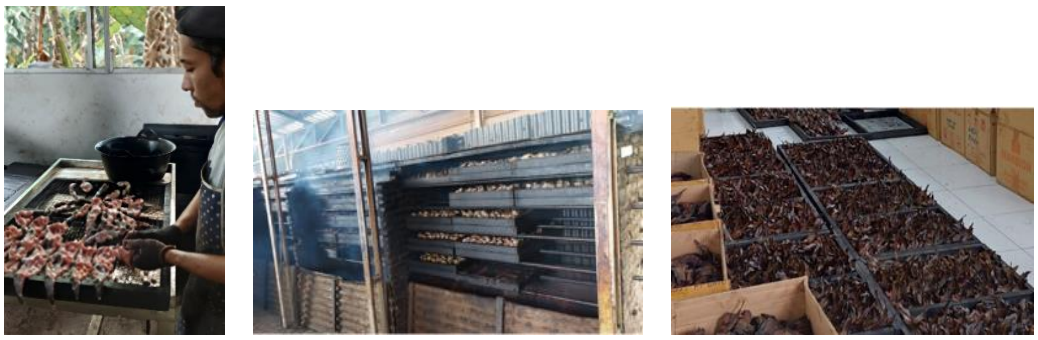
3.2. History and tradition of smoked fish in Mandailing society

Fish is a perishable food prone to spoilage due to microbial growth [46]–[48]. Hence, preservation techniques are crucial to extend its shelf life and ensure long-term availability. Various methods, including drying, salting, seasoning, cooking, and smoking, have been used since ancient times. Among the Mandailing

people, smoking fish has long been a traditional practice and an integral part of their social and cultural life. This method not only preserves fish but also enhances its flavor and aroma, making it more delicious and durable. Smoked fish is a distinctive processed product in Mandailing. This technique enables the preservation of abundant freshwater species such as carp, tilapia, catfish, and garing fish, commonly found in the rivers and rice paddies of Mandailing Natal Regency. Smoking is particularly vital in the highlands, where limited storage technology necessitates traditional preservation methods. Figure 3 illustrates the methods of fish smoking practiced in the Mandailing community, initial grilling of fresh fish over a charcoal-fired rack as shown in Figure 3(a), multi-tier bamboo or metal racks inside the smoking chamber using firewood and coconut husks as fuel as shown in Figure 3(b), and cooling and packaging of fully smoked fish ready for distribution as shown in Figure 3(c). Assogba *et al.* [49] described the process, as illustrated in Figure 3, as both simple and effective. It involves cleaning and preparing the fish, which are then smoked over a wood fire. The smoke not only preserves the fish by reducing its water content and inhibiting microbial growth but also imparts a distinctive aroma and savory flavor [50]. A key feature of this technique is the use of traditional tools such as para-para or parasapan ni gulaen, tiered racks that ensure even smoke penetration. Bamboo chimneys are also used to channel smoke thoroughly, enhancing the preservation process and extending shelf life. Specific local woods improve the fish's unique flavor, ensuring durability without compromising quality. This indigenous knowledge reflects a deep ecological understanding of resource use and thermal control, shaped by generations of adaptation to local environments and evolving culinary traditions. The technique remains central to Mandailing cuisine, where smoked fish serves as a staple ingredient in dishes such as smoked fish rendang (*rendang ikan salai*), smoked fish curry (*gulai ikan salai*), smoked fish balado (*balado ikan salai*), and spiced smoked fish (*arsik ikan salai*). These dishes are enriched with local spices like andaliman, asam cakala, candlenut, and shallots, producing a unique blend of spicy, tangy, and savory flavors [13], [30]–[34].

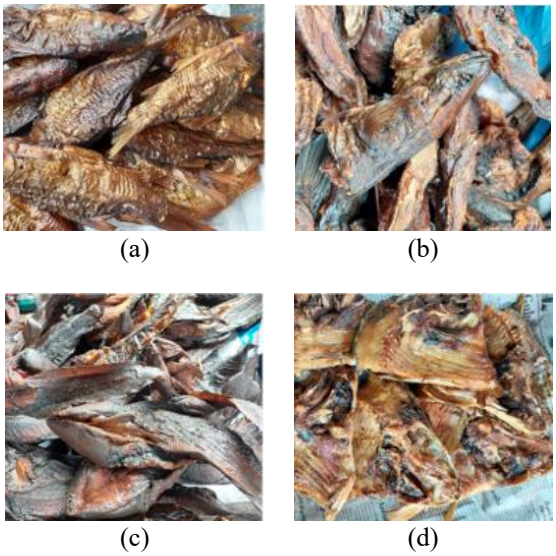
Almost all freshwater fish from rivers, rice fields, and ponds in Mandailing can be smoked as shown in Figure 4, such as smoked carp fish as shown in Figure 4(a), smoked snakehead fish as shown in Figure 4(b), smoked catfish as shown in Figure 4(c), and smoked river catfish as shown in Figure 4(d). Fish smoking reflects deep local wisdom integrating practical, economic, and cultural values. This technique not only preserves food but also symbolizes the community's connection with nature. It extends fish shelf life without chemical preservatives and creates distinctive flavors and aromas unattainable by modern methods. This unique taste makes smoked fish an essential element of Mandailing cuisine, often complemented by indigenous spices in Figure 5, such as andaliman as shown in Figure 5(a) and asam cikala as shown in Figure 5(b). These endemic ingredients, *Zanthoxylum acanthopodium* and *Etlingera elatior*, impart citrus-spicy and mildly acidic notes that harmonize with the smoky aroma, forming the sensory signature of Mandailing dishes. Despite its importance, modern technologies like gas stoves and foreign cuisines are gradually replacing traditional smoking [51], especially among younger generations. This transition offers efficiency but risks diminishing the cultural essence and flavor quality shaped by wood-fired methods. As seen in Figure 5(c), traditional markets such as poken in Mandailing Natal remain vital for preserving these skills, where smoked fish producers depend on natural materials and intergenerational knowledge transfer. Preserving this heritage requires balancing tradition and modernization. Integrating traditional methods with innovation, promoting smoked fish through digital media, and emphasizing its cultural value via culinary tourism can sustain its relevance and identity. Such initiatives protect authenticity and marketability while positioning smoked fish as a cultural and gastronomic symbol of Mandailing, presenting the region's heritage to broader audiences locally, nationally, and internationally. Moreover, academic collaborations, culinary documentation, and heritage festivals strengthen youth awareness, ensuring intergenerational transmission of artisanal expertise and reinforcing Mandailing smoked fish as a living cultural legacy bridging environmental wisdom, craftsmanship, and the modern economy [51].

Figure 2. The activities at *Lubuk Larangan* on Tua Julu Mountain



(a) (b) (c)

Figure 3. Traditional fish-smoking process in Mandailing Natal of (a) initial grilling of fresh fish over a charcoal-fired rack, (b) multi-tier bamboo or metal racks inside the smoking chamber using firewood and coconut husks as fuel, and (c) cooling and packaging of fully smoked fish ready for distribution



(a) (b) (c) (d)

Figure 4. Mandailing smoked fishes of (a) smoked carp fish, (b) smoked snakehead fish, (c) smoked catfish, and (d) smoked river catfish

(a) (b)

Figure 5. Indigenous spices of (a) andaliman and (b) asam cikala

3.3. Nutritional contents in smoked fish

The nutritional evaluation of Mandailing smoked fish revealed clear variations in proximate composition among the four dominant freshwater species, as summarized in Table 3. Moisture ranged from 28.89-70.10%, protein from 19.35-78.03%, fat from 2.92-11.69%, and ash from 1.50-10.76%. These results show how species type, muscle density, lipid profile, and smoking parameters influence biochemical quality. The broad moisture range reflects variable dehydration efficiency of traditional smoking, typically performed

at 45-180 °C for about two hours using coconut-shell fuel. The moisture level of Mandailing smoked carp (70.1%) aligns with Syam and Patang [52] (71.07%) and Ljubojević *et al.* [53] (63.46%), suggesting comparable dehydration despite differences in fuel and temperature, yet remains higher than Shehata *et al.* [54] (48.22%) where longer smoking (5-6 hours, 50-90 °C) reduced residual moisture. Moderate moisture in Mandailing carp enhances texture, prevents hardness, and limits microbial growth, achieving a balance between safety and sensory quality. Protein composition reflects intrinsic muscle structure and denaturation by heat. Mandailing smoked snakehead recorded the highest protein (78.03%), markedly higher than Akinwumi *et al.* [55] (54.11%) and Omoruyi *et al.* [56] (55.10%). This difference arises from rapid dehydration and shorter exposure, minimizing protein solubilization and degradation.

Table 3. Nutritional content of smoked fish 1

Fish	Scientific name	Brining condition	Smoking method	Smoking material	Temperature (°C)	Duration (h)	Reference
Carp fish	*Cyprinus carpio*	10% NaCl, 2 h	Traditional hot smoking	Coconut shells	45-180	2	This study
	Ctenopharyngodon idella	10% NaCl, 2 h	Hot smoking	Beech sawdust	50-90	5-6	[54]
	Hypophthalmichthys molitrix	15% brine	Hot smoking	Mixed hardwood	>70	4	[59]
	Cyprinus carpio	10% brine, 2 h	Hot smoking	Hardwood sawdust	85	4-6	[53]
	Cyprinus carpio	20% brine, 48 h	Hot smoking	Coconut shells+sawdust	65	4	[52]
	Cyprinus carpio	N.A.	Smoke-drying	Psidium guajava, Mangifera indica, and Rhizophora mangle	80	7	[60]
Snakehead fish	*Parachanna obscura*	10% NaCl, 2 h	Traditional hot smoking	Coconut shells	45-180	2	This study
	Parachanna obscura	10% NaCl, 2 min	Smoke-drying	Sawdust	60	4	[55]
	Parachanna obscura	N.A.	Smoke-drying	Magbon-Alade	N.A.	16	[56]
	Channa punctatus	20% NaCl, 10 min	Hot smoking	Sawdust	N.A.	1.5	[64]
Catfish	*Clarias gariepinus*	10% NaCl, 2 h	Traditional hot smoking	Coconut shells	45-180	2	This study
	Clarias gariepinus	N.A.	Hot smoking	Sawdust	60-70	15	[57]
	Clarias gariepinus	N.A.	Smoke-drying	*Psidium guajava, Mangifera indica, dan Rhizophora mangle*	80	7	[60]
	Clarias gariepinus	N.A.	Smoke-drying	Wood	85	24	[65]
	Clarias gariepinus	10% NaCl, 1 h	Hot smoking	Charcoal	140	6-8	[66]
	Clarias gariepinus	N.A.	Hot smoking	N.A.	52-80	2	[67]
River catfish	*Pangasius hypophthalmus*	10% NaCl, 2 h	Traditional hot smoking	Coconut shells	45–180	2	This study
	Hemibagrus nemurus	N.A.	Hot smoking	*Hevea brasiliensis*	50-60	1	[68]
	Hemibagrus nemurus	N.A.	Hot smoking	Mangrove Rambutan wood	80-90	6-8	[69]
	Hemibagrus nemurus	N.A.	Hot smoking	Smoke wood	80-100	4	[58]
	Mystus gulio	2.5% NaCl, 5 min	Liquid-smoke-assisted hot smoking	Coconut shell	50-60	12	[68]
	Hemibagrus nemurus	N.A.	Hot smoking	Hardwood smoke	50-70	7	[62]
	Mystus nemurus	7% NaCl, 60 min	Liquid-smoke-assisted drying	Coconut shell	50-60	6	[68]

The local high-temperature, short-time regime thus preserves amino acids more effectively than prolonged low-temperature drying. Catfish and river catfish showed moderate protein (34.82 and 36.57%), within tropical freshwater norms but under the 68-72% reported by Foline *et al.* [57] and Maskilin *et al.* [58], variations attributed to species genetics and lipid-water interactions. Fat content remained moderate (2.92-11.69%), supporting low-fat, high-protein consumption. Carp with 2.92% fat was lean, comparable to El-Lahamy *et al.* [59] (3.09%), while catfish contained 11.69%, consistent with its lipid richness. Higher fat in Tiwo *et al.* [60] (14-18%) often results from longer exposure or higher heat, causing lipid concentration. The controlled two-hour Mandailing process limits oxidation, maintaining aroma without rancidity. Coconut-shell smoke enhances oxidative stability through phenolic antioxidants, a property supported by studies on tropical biomass fuels. Ash content (1.50-10.76%) indicates mineral contribution from bones and connective tissue. Snakehead fish showed the highest ash, consistent with its dense skeletal structure. This corresponds to Foline *et al.* [57] (10.23%) and exceeds Tiwo *et al.* [60] (4-6%), implying that Mandailing's short-duration heating favors mineral retention by preventing volatilization of inorganic compounds such as calcium phosphate. Cross-species comparison highlights that Mandailing smoked snakehead offers the most nutrient-dense profile; high protein and ash but low fat, representing an optimal dietary and economic balance. Traditional Mandailing hot-smoking rivals industrial methods while maintaining authenticity and minimal nutrient loss. The use of coconut-shell fuel differentiates it from hardwood or sawdust processes [61], [62]; coconut shells produce steady heat and light phenolic compounds that enhance aroma without bitterness, promoting flavor and nutrient preservation. Environmental adaptation also shapes outcomes: coastal smoked tuna from Ambon or Papua shows higher fat and lower protein due to marine lipids [63], while Mandailing freshwater species display leaner profiles typical of highland hydrology. This ecological contrast underscores inland cuisines' nutritional diversity within Indonesia's broader food system.

3.4. Processing smoked fish dishes

Coconut is a fundamental agricultural product that profoundly shapes the uniqueness of Mandailing cuisine. It is utilized in various forms, such as coconut milk, grated coconut, or coconut oil, across nearly all Mandailing dishes, ranging from main courses and soups to desserts. Coconut milk plays a pivotal role in enhancing flavor, imparting a creamy texture, and adding a distinctive aroma to traditional dishes [36]. Its generous use creates the rich, savory taste that defines Mandailing cuisine, making it an indispensable ingredient in the region's culinary tradition. Beyond its culinary role, coconut also reflects the agricultural self-sufficiency of Mandailing communities, where every part of the fruit, from shell to sap, is valued and utilized for food, fuel, crafts, and essential cultural purposes. It also symbolizes economic resilience and intergenerational knowledge, as coconut cultivation and processing techniques are traditionally passed down within local households as part of community-based food systems and cultural identity, deeply embedded in daily rituals, seasonal festivities, and household culinary practices, reinforcing communal bonds and intergenerational cultural continuity. This reliance on coconut as a culinary staple aligns with findings by Yunindanova *et al.* [69], who emphasize coconut's role in traditional Indonesian cooking for its ability to intensify flavors and improve nutritional value through medium-chain fatty acids, antioxidant properties, and long-term metabolic health benefits. The diversity of local spices further enriches the complexity and distinction of Mandailing cuisine. The fertile land of Mandailing supports the growth of a wide range of spices, including chili peppers, turmeric, candlenuts, ginger, and onions. These spices not only contribute to the intricate balance of taste in Mandailing dishes but also offer health benefits due to their bioactive compounds [70]. Informants from the Mandailing community frequently note that the abundant use of such spices, particularly red chilies, shallots, garlic, turmeric, and andaliman (Sichuan pepper), is considered essential to achieving the signature "bold yet balanced" flavor that defines Mandailing food culture.

Mandailing cuisine reflects the region's agricultural richness and cultural heritage, characterized by its reliance on locally sourced ingredients from rivers and fertile highlands. River and freshwater fish serve as the principal protein sources, most notably processed into smoked products using traditional hot-smoking methods. Among these, four dominant species: smoked carp fish (*Cyprinus carpio*), smoked snakehead fish (*Channa striata*), smoked catfish (*Clarias batrachus*), and smoked river catfish (*Hemibagrus nemurus*), are regarded as the culinary cornerstones of Mandailing smoked fish dishes as shown in Table 4. These species are highly valued for their distinctive textures, nutritional profiles, and adaptability to local cooking traditions. Smoked carp offers a mild sweetness and firm flakes; smoked snakehead contributes lean, dense flesh rich in protein; smoked catfish and river catfish, with higher lipid content, impart deeper smokiness and richer mouthfeel. The cuisine's overall flavor profile, savory, spicy, slightly sour, and subtly smoky, is achieved through the interplay of coconut milk, fresh herbs, and traditional spices such as asam cikala (local sour fruit), lime, lemongrass, turmeric leaves, and candlenuts. This balance exemplifies the Mandailing people's mastery in harmonizing local resources to produce dishes that are both sensorially satisfying and nutritionally balanced. Smoked fish, in particular, functions as both a preservation technique and a cultural

expression, embodying the community's sustainable relationship with its surrounding natural environment and resources, ensuring continued harmony between humans and nature while promoting cultural resilience and ecological awareness. Figure 6 shows four smoked fish varieties transformed into several emblematic dishes that represent Mandailing culinary identity; most notably smoked fish curry as shown in Figure 6(a), smoked fish with chili sauce as shown in Figure 6(b), smoked fish rending as shown in Figure 6(c), and smoked fish with vegetables as shown in Figure 6(d). The smoking process imparts the fish with a distinctive aroma and flavor, while subsequent combination with coconut milk, chilies, and aromatic spices elevates the dishes into cultural symbols of endurance and creativity. Passed down through generations, the art of smoking and processing these fish reflects the Mandailing community's dedication to preserving its culinary heritage, sustaining local knowledge, and showcasing Indonesia's inland gastronomic diversity [13].

Table 4. Nutritional content of smoked fish 2

Smoked fish		Best nutritional composition				
Fish	Scientific name	Moisture (%)	Protein (%)	Fat (%)	Ash (%)	Reference
Carp fish	*Cyprinus carpio*	70.1	19.35	2.92	9.47	This study
	Ctenopharyngodon idella	48.22	23.38	13.88	6.38	[54]
	Hypophthalmichthys molitrix	59.44	29.46	3.09	7.64	[59]
	Cyprinus carpio	63.46	35.20	28.10	4.55	[53]
	Cyprinus carpio	71.07	19.35	2.92	6.63	[52]
	Cyprinus carpio	N.A.	85.46	7.99	4.52	[60]
Snakehead fish	*Parachanna obscura*	28.89	78.03	3.04	10.76	This study
	Parachanna obscura	5.84	54.11	22.09	10.23	[55]
	Parachanna obscura	6.47	64.67	8.87	13.20	[56]
	Channa punctatus	63.81	26.55	4.81	4.80	[64]
Catfish	*Clarias gariepinus*	50.09	34.82	11.69	1.5	This study
	Clarias gariepinus	7.30	68.40	12.50	6.40	[57]
	Clarias gariepinus	N.A.	81.28	14.17	6.06	[60]
	Clarias gariepinus	23.94	61.42	3.19	10.73	[65]
	Clarias gariepinus	19.87	59.03	12.06	7.55	[66]
	Clarias gariepinus	4.05	67.84	8.96	7.88	[67]
River catfish	*Hemibagrus nemurus*	48.8	36.57	9.85	2.04	This study
	Hemibagrus nemurus	10.83	49.50	17.36	N.A.	[68]
	Hemibagrus nemurus	11.73	48.07	18.72	N.A.	[68]
	Hemibagrus nemurus	11.89	71.00	7.01	4.84	[58]
	Mystus gulio	41.32	72.01	16.05	5.17	[68]
	Hemibagrus nemurus	34.01	2.47	50.59	11.45	[62]
	Mystus nemurus	10.29	29.55	24.38	N.A.	[68]

(a) (b) (c) (d)

Figure 6. Smoked fish processing of (a) smoked fish curry, (c) smoked fish with chili sauce, (c) smoked fish rendang, (d) smoked fish with vegetables

4. CONCLUSION

This study demonstrates that Mandailing smoked fish traditions represent a sophisticated integration of ecological stewardship, cultural identity, and nutritional functionality. The community-governed *Lubuk Larangan* system reflects an indigenous conservation model that regulates resource access through spiritual norms, collective responsibility, and ecological restraint ensuring not only fish population continuity but also the social durability of customary governance. Nutritional evidence confirms that Mandailing hot-smoking techniques yield protein-rich products with moderate lipid levels and safe mineral profiles, demonstrating competitiveness with modern industrial standards while maintaining artisanal authenticity. The use of coconut-shell fuel further signifies adaptive ecological intelligence, producing thermally stable combustion and phenolic antioxidants that enhance flavor stability without compromising health value. More importantly, the ethnographic findings reveal that smoked fish in Mandailing is not merely a preserved protein commodity but a cultural medium that encodes memory, identity, and intergenerational knowledge transfer. As such, Mandailing smoked fish systems can be interpreted as a living technology, evolving yet deeply rooted in local wisdom, where culinary practice operates as both a food security strategy and cultural resistance to homogenization. This study affirms the urgency of reframing traditional foodways not as relics of the past, but as resilient knowledge infrastructures capable of informing sustainable diets, heritage preservation, and future-oriented gastronomy models for diverse local and global contexts, including climate-vulnerable rural communities worldwide.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Esi Emilia	✓		✓	✓	✓	✓		✓		✓		✓	✓	✓
Nila Reswari Haryana		✓			✓	✓		✓	✓	✓	✓	✓		✓
Risti Rosmiati	✓		✓	✓			✓			✓	✓		✓	✓
Erli Mutiara		✓			✓	✓		✓		✓		✓		
Laili Fitria	✓			✓	✓				✓			✓		
Rachmat Mulyana		✓	✓			✓	✓			✓				
Wisnu Prayogo	✓	✓			✓					✓		✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
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I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [EE], upon reasonable request.

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BIOGRAPHIES OF AUTHORS

Esi Emilia is an experienced academic with expertise in the field of Nutrition Science. She is currently a faculty member in the Department of Nutrition at Universitas Negeri Medan. Her academic journey includes earning a Doctorate in Nutrition Science and Family Resource Management from Institut Pertanian Bogor. Passionate about community nutrition and resource management, she is dedicated to advancing the field through research and education. She can be contacted at email: esiemilia@unimed.ac.id.

Nila Reswari Haryana is an academic with a specialization in Nutrition Science. She is affiliated with the Department of Nutrition at Universitas Negeri Medan. She holds a Master's degree in Nutrition Science from Institut Pertanian Bogor. With a strong focus on nutrition education and research, she is committed to contributing to the development of the field. She can be contacted at email: nilareswariharyana@unimed.ac.id.

Risti Rosmiati is an academic specializing in Nutrition Science, currently serving as a faculty member in the Department of Nutrition at Universitas Negeri Medan. She holds a Master's degree in Nutrition Science from Institut Pertanian Bogor. With a dedication to advancing nutrition education and research, Risti Rosmiati actively contributes to the development of the field. She can be contacted at email: ristirosmiati@unimed.ac.id.

Erli Mutiara is an experienced academic specializing in Culinary Science. She currently serves as a faculty member in the Department of Culinary at Universitas Negeri Medan. Her academic journey includes earning a Doctorate in Nutrition Science and Family Resource Management from Institut Pertanian Bogor, with research focused on community-based food systems and dietary health. She can be contacted at email: erli@unimed.ac.id.

Laili Fitria is a faculty member in the Department of Environmental Engineering at Universitas Tanjungpura. She holds a Master's degree in Environmental Engineering from Institut Teknologi Bandung and is currently pursuing her doctoral studies in Environmental Engineering at Chung Yuan Christian University, Taiwan. With a strong academic foundation and ongoing research interests, Laili Fitria is committed to advancing knowledge and practice in environmental engineering. She can be contacted at email: fitria.laili@gmail.com.

Rachmat Mulyana is a faculty member in the Department of Building Engineering Education at Universitas Negeri Medan. He holds a Doctorate in Environmental Science from Institut Pertanian Bogor. With expertise in environmental science and its integration into building engineering education, He is dedicated to advancing research and education in his field. He can be contacted at email: rachmatmulyana@unimed.ac.id.

Wisnu Prayogo is a faculty member in the Department of Civil Engineering at Universitas Negeri Medan. He is currently pursuing his Doctoral degree in Environmental Engineering at Chung Yuan Christian University. His undergraduate to doctoral studies has focused on the same field: water quality engineering and aquatic system restoration, particularly in developing sustainable engineering approaches to improve and rehabilitate degraded water bodies. With a strong academic foundation and active engagement in research, He is dedicated to advancing scientific understanding and practical innovations in the field of environmental engineering. He also serves as an editor and reviewer for more than twenty national and international journals related to environmental engineering and its applications. He can be contacted at email: wisnuprayogo@unimed.ac.id.