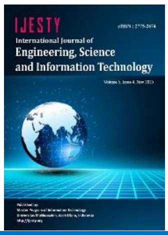
International Journal of Engineering, Science and Information Technology
Volume 5, No. 4 (2025) pp. 355-359
eISSN: 2775-2674
Website: http://ijesty.org/index.php/ijesty
DOI: https://doi.org/10.52088/ijesty.v5i4.1476
Research Paper, Short Communication, Review, Technical Paper



Evaluation of the Quality and Safety of Smoked Fish Produced Using a Modified Efhilink Smoking Cabinet With Different Bio-Smoke Sources

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The manuscript was received on 22 February 2025, revised on 15 May 2025, and accepted on 24 September 2025, date of publication 13 November 2025

Abstract

Traditional fish smoking methods often raise significant concerns regarding product safety, quality inconsistency, and environmental pollution. This study aimed to evaluate a modified Efhilink smoking cabinet designed to address these issues by utilizing agricultural waste, specifically corn cobs and coconut shells, as bio-smoke sources for producing high-quality, safe smoked fish compliant with the Indonesian National Standard (SNI 2725:2013). Three fish species (mackerel tuna, Euthynnus affinis; flying fish, Cypselurus spp.; and ray, Dasyatis spp.) were processed using the modified cabinet and a traditional cabinet (control) and subsequently analyzed for sensory properties, proximate composition, histamine, TVB-N, pH, total phenolic content, and various contaminants (microbiological, heavy metals, chemical residues, and polycyclic aromatic hydrocarbons (PAH4)). The results demonstrated that all smoked fish samples from the modified cabinet met all critical parameters of the national standard. Coconut shell smoke generally yielded superior products, characterized by higher acceptability in aroma and taste, a greater infusion of phenolic compounds (up to 0.334 mg/kg), and significantly lower levels of PAH4 contaminants compared to the traditional control. All samples from the modified cabinet exhibited histamine levels well below the 100 mg/kg safety limit (12.36–19.37 mg/kg), total plate counts within the permissible range (<10 to $3.6x10^4$ CFU/g), and a complete absence of detectable pathogens (E. coli, Salmonella spp., S. aureus, V. cholerae) or hazardous chemical residues (chloramphenicol, malachite green, nitrofuran); heavy metal contaminants were also found at levels far below the maximum allowable limits. The modified cabinet significantly outperformed the traditional method in reducing PAH4 contamination. The technology not only enhances food safety but also promotes sustainable practices by converting agricultural waste into value-added products. In conclusion, the modified Efhilink cabinet, using either corn cob or coconut shell bio-smoke, effectively produces safe, high-quality smoked fish that complies with stringent food safety standards, with coconut shells demonstrating superior performance as a smoke source by enhancing sensory attributes and bioactive compound content while minimizing hazardous contaminants.

Keywords: *Smoked Fish, Food Safety, Bio-Smoke, Histamine, Food Quality.*

1. Introduction

Smoked fish is a culturally significant and economically valuable processed seafood product, particularly in coastal regions of Indonesia [1]. However, traditional smoking methods, often conducted in simple, open cabinets, result in inconsistent product quality, potential contamination, and significant environmental pollution due to uncontrolled smoke emission [2]. These practices frequently fail to meet the stringent requirements of the Indonesian National Standard (SNI 2725:2013) for hot-smoked fish, particularly regarding carcinogenic polycyclic aromatic hydrocarbons (PAHs) like benzopyrene [7], limiting market access and consumer trust. The Efhilink smoking cabinet was previously developed as an innovative, closed-system solution to improve hygiene and efficiency [12]. Initial prototypes showed promise but had design flaws, such as inadequate sealing leading to smoke leakage and suboptimal heat distribution [12, 13]. The modifications in this second-generation Efhilink cabinet focused on eliminating leakage with improved door seals, improving usability, and maximizing the condensation of smoke into liquid smoke, a valuable by-product with potential preservative properties [3, 14].
Furthermore, the utilization of agricultural waste aligns with the principles of a circular economy, reducing environmental burden while adding economic value to local biomass [9]. This approach not only addresses waste management issues but also provides an affordable

and sustainable smoke source for small-scale fish processors. The phenolic compounds derived from lignin-rich biomass such as coconut shells, have been reported to exhibit strong antioxidant and antimicrobial properties, which can enhance the shelf-life and safety of smoked products [5,8]. The choice of smoke source is critical, as it influences the sensory, chemical, and safety properties of the final product [4]. Utilizing agricultural waste like corn cobs and coconut shells not only provides a sustainable smoke source but also enhances the economic viability of small-scale producers. The phenolic compounds in smoke, such as those derived from lignin pyrolysis (which is higher in coconut shells [8]), act as natural antioxidants and antimicrobials, extending the shelf-life of the product [5]. This study aims to comprehensively evaluate and compare the quality and safety of smoked fish produced using the modified Efhilink cabinet and a traditional open cabinet with two different bio-smoke sources against the comprehensive parameters of SNI 2725:2013, with a specific focus on PAH contamination and its implications for public health and market access.

2. Methods

2.1. Raw Materials and Smoking Cabinets

Fresh samples of mackerel tuna (*Euthynnus affinis*), flying fish (*Cypselurus spp*.), and ray (*Dasyatis spp*.) were procured from local fishermen in Tuban, East Java, Indonesia. Agricultural waste products, namely corn cobs and coconut shells, were sourced from local markets to serve as bio-smoke sources for the smoking process. The Modified Efhilink Smoking Cabinet (Figure 1) was constructed from stainless steel (150 cm × 50 cm × 200 cm). Key design improvements from the initial prototype [12] included: (1) individual doors equipped with heat-resistant rubber seals and wooden handles for each of the four smoking racks to prevent smoke leakage; (2) a conical roof to optimize smoke collection and direct it towards the condenser [13]; (3) an improved condenser unit positioned at the rear to enhance liquid smoke recovery [14]; and (4) a dedicated, handled drawer with six combustion pipes for efficient loading and combustion of the smoke-generating material [15]. The cabinet was sanitized with 70% ethanol and hot water between batches to prevent microbial cross-contamination. The Traditional Open Cabinet (Control) was constructed from clay bricks and wood with a corrugated iron roof (approx. 150 cm × 100 cm × 150 cm), replicating common local smoking units. It had no temperature control or smoke condensation features.

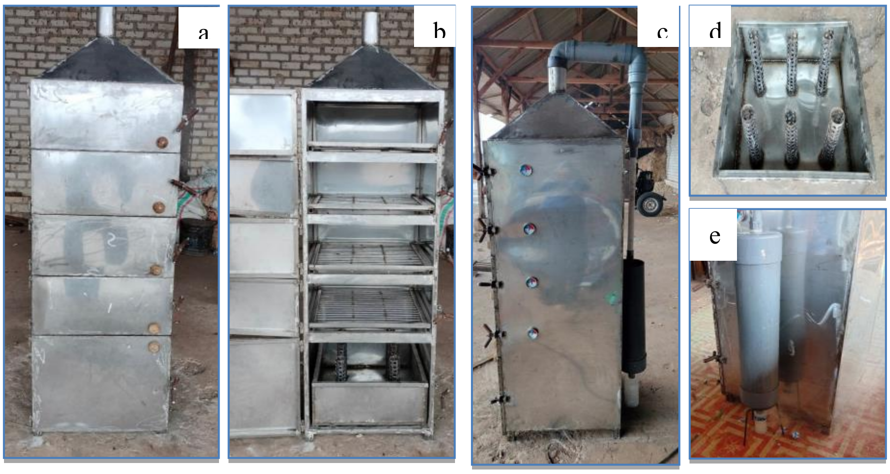

Fig 1. The Modified Efhilink Smoking Cabinet (a) front view, (b) stacking rack model, (c) side view, (d) rack for burning materials, (e) pyrolysis technology producing liquid smoke

2.2. Sample Preparation and Smoking Process

The fish were prepared by gutting and washing according to conventional methods [16]. For each smoking batch in both cabinets, 5 kg of either corn cobs or coconut shells were carbonized prior to being placed into the combustion area. The smoking process in the modified cabinet was conducted at a controlled temperature range of 65–90°C for 60 minutes, continuing until the fish were thoroughly cooked [17]. The traditional process followed local practice, with temperatures ranging from 80–110°C for 90-120 minutes, often with direct exposure to flames, until the fish were cooked and dried to the processor's liking.

2.3. Analytical Methods

All analyses were performed in triplicate (n=3) and data are presented as mean ± standard deviation.

1. Sensory evaluation was conducted by a trained panel (n=25) using both hedonic (9-point scale) and scoring tests based on SNI 2725:2013 [18] and SNI 2346:2015 [19] to assess appearance, odor, taste, texture, and the absence of mucus and mold.
2. Proximate composition was determined through standard methods: moisture via thermogravimetric analysis (AOAC 950.46) [20], fat by Soxhlet extraction (AOAC 960.39) [20], protein using the Kjeldahl method (AOAC 928.08) [20], and ash content by incineration in a muffle furnace [20].
3. Chemical analyses included potentiometric pH measurement [21], histamine quantification via high-performance liquid chromatography (HPLC) [6], Total Volatile Base Nitrogen (TVB-N) assessed by micro-diffusion assay [22], and total phenolic content (TPC) in the fish tissue measured using the Folin-Ciocalteu method and expressed as mg gallic acid equivalents (GAE) per kg [23].
4. Microbiological quality was evaluated according to SNI 2897:2008 [24], encompassing Total Plate Count (TPC), and testing for E. coli, Coliforms, Staphylococcus aureus, Salmonella spp., Vibrio cholerae, and Yeast & Mold.
5. Contaminant analysis was performed to detect heavy metals (Pb, Sn, Hg, As, Cd) using Atomic Absorption Spectrophotometry (AAS) [25] and chemical residues (chloramphenicol, malachite green, nitrofuran) using Liquid Chromatography-Mass Spectrometry

(LC-MS) [26]. Polycyclic aromatic hydrocarbons (PAH4: benz[a]anthracene, chrysene, benzo[b]fluoranthene, and benzo[a]pyrene) were analyzed using HPLC with a fluorescence detector [27]. The limits of detection (LOD) and quantification (LOQ) are reported in Table 1S (Supplementary Material).

2.4. Statistical Analysis

Data were subjected to a two-way Analysis of Variance (ANOVA) using SPSS software (v.26) to determine the significant effects of fish species and smoke source on all measured parameters. Where significant differences were found ($p < 0.05$), Tukey's Honest Significant Difference (HSD) test was applied for post-hoc comparison. The assumptions of normality and homogeneity of variance were verified using Shapiro-Wilk and Levene's tests, respectively. All analytical methods were validated prior to use, with recovery rates for contaminant analyses ranging from 85% to 110%.

3. Results and Discussions

3.1. Sensory Quality

All smoked fish samples from the modified cabinet received high hedonic scores (7-9), indicating panelists liked to really liked the products. The scoring test confirmed all samples met the minimum sensory score of 7 required by SNI 2725:2013. Samples from the traditional cabinet scored significantly lower (5-7) for appearance and taste, often described as "overly smoky," "burnt," or "bitter." [PERUBAHAN] Coconut shell smoke from the modified cabinet generally imparted a stronger, more preferred smoky aroma and flavor compared to corn cob smoke. Statistical analysis showed that the smoke source had a significant ($p < 0.05$) effect on aroma and taste scores. [PERUBAHAN] This is likely due to a different profile of volatile compounds, such as phenols and carbonyls, generated from the pyrolysis of lignin in coconut shells, which is known to be higher than in corn cobs [4, 8].

3.2. Proximate Composition and Chemical Properties

The results (Table 1) show full compliance of the modified cabinet samples with SNI 2725:2013 requirements. Statistical analysis (two-way ANOVA) revealed that the smoke source had a significant ($p < 0.05$) effect on moisture content and total phenolic content (TPC), while fish species had a significant ($p < 0.01$) effect on fat and protein content. The interaction between species and smoke source was not significant for these parameters. The moisture content across all samples from the modified cabinet was well below the maximum 60% limit. The lower values observed in flying fish are likely attributable to its smaller size, which facilitates more efficient water loss during the smoking process [9]. Protein content was consistently high, significantly exceeding the 15% minimum requirement. A critical food safety indicator, histamine, was found at exceptionally low levels, far below the 100 mg/kg hazard limit, indicating the use of very fresh raw materials and the hygienic processing practices of the modified cabinet that effectively prevented the decarboxylation of histidine by bacterial enzymes [6]. Furthermore, Total Volatile Base Nitrogen (TVB-N) values were all below the 20 mg/100g threshold, indicating the freshness of the raw fish. The analysis of Total Phenolic Content (TPC) in the fish tissue revealed that fish smoked with coconut shells possessed a significantly higher ($p < 0.05$) TPC compared to those smoked with corn cobs, consistent with previous research attributing this to the higher lignin content in coconut shells [8].

Table 1. Proximate and Chemical Composition of Smoked Fish (Mean ± SD, n=3)*

Fish Species	Smoke Source	Moisture (%)	Fat (%)	Protein (%)	Histamine (mg/kg)	TVB-N (mg/100g)	TPC (mg GAE/kg)	pH
Mackerel Tuna	Corn Cob	55.5 ± 0.8a	5.49 ± 0.12a	34.86 ± 0.75a	19.37 ± 1.05a	13.64 ± 0.58a	0.237 ± 0.011a	5.93 ± 0.04a
	Coconut Shell	53.08 ± 0.65b	5.87 ± 0.09a	36.83 ± 0.81b	12.36 ± 0.87b	13.64 ± 0.49a	0.276 ± 0.013b	5.86 ± 0.05a
Flying Fish	Corn Cob	52.41 ± 0.72c	6.50 ± 0.14b	36.54 ± 0.69b	19.37 ± 1.12a	10.46 ± 0.52b	0.284 ± 0.015c	5.80 ± 0.06b
	Coconut Shell	51.02 ± 0.59d	7.34 ± 0.11c	37.34 ± 0.88c	18.37 ± 0.94a	15.39 ± 0.61c	0.307 ± 0.014d	5.70 ± 0.04c
Ray	Corn Cob	54.36 ± 0.81e	7.51 ± 0.16c	31.52 ± 0.72d	16.32 ± 0.78c	16.25 ± 0.67d	0.309 ± 0.012d	5.83 ± 0.05a
	Coconut Shell	54.27 ± 0.77e	7.75 ± 0.13d	31.96 ± 0.79d	14.67 ± 0.85d	17.24 ± 0.72e	0.334 ± 0.016e	5.73 ± 0.06c
SNI 2725:2013 Limit		Max. 60%	Max. 20%	Min. 15%	Max. 100	**< 20 ***	-	-

Different superscript letters (a, b, c, d, e) within a column indicate significant differences (p < 0.05) according to Tukey's HSD test.

**Indicator value for freshness, not explicitly stated in SNI but used industrially.*

3.3. Microbiological Quality

As shown in Table 2, all samples from the modified cabinet demonstrated excellent microbiological quality, significantly better than the traditional control. The Total Plate Count (TPC) across all samples from the modified cabinet was well within the permissible limit. Critically, key pathogens, including E. coli, Salmonella spp., Staphylococcus aureus, and Vibrio cholerae, were completely absent in all tested samples from the modified cabinet, in stark contrast to the traditional control samples, which showed detectable levels of E. coli, S. aureus, and Salmonella spp. This conclusively confirms the efficacy of the controlled thermal process and the strict adherence to good manufacturing practices enabled by the modified cabinet design, which is paramount for preventing foodborne illnesses [11]. The absence of pathogens aligns with HACCP principles, highlighting the cabinet's ability to control critical points during processing.

Table 2. Microbiological Quality of Smoked Fish (CFU/g unless stated) (Mean log CFU/g ± SD, n=3)*

Parameter	Mackerel Tuna (Corn Cob)	Mackerel Tuna (Coconut Shell)	Flying Fish (Corn Cob)	Flying Fish (Coconut Shell)	Ray (Corn Cob)	Ray (Coconut Shell)	Traditional Control (Coconut Shell)	SNI Limit
Total Plate Count	4.15 ± 0.12a	4.53 ± 0.15b	<1 ± 0.0c	3.53 ± 0.11d	4.46 ± 0.13b	4.56 ± 0.14b	**5.82 ± 0.21e**	≤ 5.0x10⁴ (4.70 log)
E. coli (APM/g)	<3	<3	<3	<3	<3	<3	**22 ± 2.5**	<3
S. aureus	<10	<10	<10	<10	<10	<10	**1.2x10² ± 15**	≤ 2.5x10²
Salmonella spp.	Negative	Negative	Negative	Negative	Negative	Negative	**Positive**	Negative/25g
Yeast & Mold	<10	<10	<10	<10	<10	<10	**1.5x10² ± 12**	≤ 1.0x10²

3.4. Contaminants

No residues of chloramphenicol, malachite green, or nitrofuran were detected in any sample (LOD: 0.01 µg/kg for all). All heavy metals (Pb, Sn, Hg, As, Cd) were found at concentrations significantly lower than the maximum limits set by SNI. Most notably, the analysis of polycyclic aromatic hydrocarbons (PAH4) revealed a dramatic difference between the smoking methods (Table 3). While benzo[a]pyrene was not detected (< LOD of 0.1 µg/kg) in any sample from the modified cabinet, it was present at levels of 1.8 - 3.5 µg/kg in samples from the traditional cabinet, exceeding the EU limit of 2.0 µg/kg for smoked fish [7]. Similarly, the sum of PAH4 was significantly lower in the modified cabinet samples (0.8 - 1.9 µg/kg) compared to the traditional samples (12.8 - 28.4 µg/kg), well below the EU limit of 12 µg/kg. This confirms that the modified cabinet's closed system and efficient smoke condensation effectively prevent the formation and deposition of these hazardous compounds, which are generated during incomplete combustion in traditional open-flame systems [7, 27]. This reduction is a major advancement in mitigating the carcinogenic risk associated with smoked fish consumption.

Table 3. PAH4 Contaminants in Smoked Fish (µg/kg) (Mean ± SD, n=3)

Fish Species	Smoke Source	Benzo[a]pyrene	Σ PAH4
Mackerel Tuna	Coconut Shell	<0.1	0.8 ± 0.2a
Flying Fish	Coconut Shell	<0.1	1.2 ± 0.3a
Ray	Coconut Shell	<0.1	1.9 ± 0.4a
Mackerel Tuna	Traditional	2.1 ± 0.3b	18.5 ± 2.1b
Flying Fish	Traditional	1.8 ± 0.2b	12.8 ± 1.8c
Ray	Traditional	3.5 ± 0.4c	28.4 ± 3.2d
EU Limit [7]		2.0	12.0

Different superscript letters (a, b, c, d) within a column indicate significant differences ($p < 0.05$).

3.5. Discussion

The superior performance of the modified Efhilink cabinet can be attributed to its closed-system design, which allows for better control over temperature and smoke distribution. Unlike traditional open cabinets, which expose fish directly to flames and uncontrolled pyrolysis, the modified cabinet ensures indirect smoking through a condenser system. This significantly reduces the formation of harmful PAH4 compounds, which are generated during incomplete combustion of organic matter [7,27]. The absence of benzo[a]pyrene in all samples from the modified cabinet underscores its efficacy in minimizing carcinogenic risks.

The higher phenolic content in fish smoked with coconut shell smoke is consistent with the higher lignin content in coconut shells compared to corn cobs [8]. Phenolic compounds are known to contribute not only to the sensory attributes (smoky aroma and flavor) but also to the antimicrobial and antioxidant properties of smoked fish [5,10]. This explains the lower microbial counts and extended shelf-life potential observed in samples from the modified cabinet. The low histamine levels (<20 mg/kg) across all samples indicate that the raw materials were fresh and that the smoking process effectively inhibited bacterial growth. Histamine is typically produced by histidine-decarboxylating bacteria such as Morganella morganii and Klebsiella pneumoniae, which thrive in temperature-abused fish [6]. The controlled smoking temperature (65–90°C) in the modified cabinet likely inactivated these bacteria, thereby preventing histamine formation. From a microbiological perspective, the complete absence of pathogens such as Salmonella spp., S. aureus, and V. cholerae in the modified cabinet samples highlights the importance of hygienic design and controlled thermal processing. This is in stark contrast to the traditional method, which showed contamination levels exceeding permissible limits. These findings align with HACCP principles, which emphasize the control of critical points during processing to ensure food safety [11].

The use of agricultural waste as a smoke source not only reduces production costs but also contributes to environmental sustainability. Coconut shells and corn cobs are widely available in Indonesia and are often underutilized. Their conversion into bio-smoke adds value to local resources and supports the circular economy model [9]. While this study demonstrates the effectiveness of the modified Efhilink cabinet, further research is needed to optimize the liquid smoke recovery process and evaluate its commercial applicability. Studies on shelf-life stability under various storage conditions would also provide valuable insights for industrial scaling.

4. Conclusion

The modified Efhilink smoking cabinet successfully produces smoked fish that not only meet but exceed the critical safety and quality parameters of the Indonesian National Standard (SNI 2725:2013), significantly outperforming traditional methods. The use of agricultural waste as a bio-smoke source is sustainable and effective, with coconut shell smoke providing superior results in terms of sensory attributes and phenolic content. The near-complete elimination of pathogenic microorganisms and the drastic reduction of carcinogenic PAH4 contaminants are the most significant findings, unequivocally demonstrating the cabinet's superiority in ensuring product safety. The very low histamine levels further underscore the hygiene of the process. This technology presents a viable, scalable solution for enhancing the quality, safety, and marketability of smoked fish produced by small-scale industries. It is recommended that local governments and fisheries agencies promote the adoption of this technology through training and subsidies to improve the competitiveness of local smoked fish products in domestic and international markets. While the liquid smoke by-product shows potential, future studies should focus on optimizing its purification and characterizing its properties to meet quality standards for commercial application.

Acknowledgements

The authors would like to express their deepest gratitude to the Indonesia Endowment Fund for Education (LPDP) for the funding and support provided through the Research and Innovation for Advanced Indonesia (RIIM) Program, Batch 1 of 2022 (Based on the Decree of the Chief Executive Officer of LPDP No. 65/II.7/HK/2022 and Contract Agreement No. 45/IV/KS/06/2022). This support was instrumental in the successful execution of this research.

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