

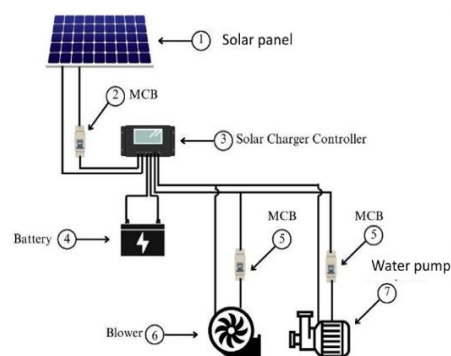
Innovative integration of solar energy and pyrolysis technology in fish smoking for improved liquid smoke yield and quality

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Highlights:

- Solar-powered fish smoking system with pyrolysis–condenser design.
- Converts smoke emissions into antimicrobial liquid smoke product.
- Liquid smoke shows suitable acidity, phenol, and no Pb/Cd detected.
- Reduces pollution while supporting sustainable fish processing systems.

Abstract

Traditional fish smoking still causes environmental pollution and health issues due to uncontrolled smoke emissions. Field data indicate that 54.0% of workers in fish smoking centers are exposed to heavy smoke, and 66.7% experience severe respiratory symptoms, underscoring the need for cleaner technologies. This study developed an integrated solar-powered fish smoking system combining pyrolysis and a naturally cooled spiral condenser to convert combustion smoke into liquid smoke as a natural preservative. The prototype was designed and tested using corn cob biomass as the pyrolysis feedstock. Evaluated parameters included solar panel efficiency, smoking chamber performance, and liquid smoke quality. Characterization covered specific gravity, pH, acetic acid, phenol content, and heavy metals (Pb, Cd). Results showed that pure corn cob liquid smoke had a specific gravity of 0.99965 g/cm³, pH 3.55, acetic acid 1.747%, and phenol 7.8859%, while smoke applied to fish yielded 1.008572 g/cm³, 3.70, 3.950%, and 12.4242%, respectively. Both Pb and Cd were not detected (< LOD), confirming safety from contamination. Although acetic acid and phenol contents correspond to SNI 8985:2021 grade 2, further purification is needed to meet food-grade standards. The system effectively produces functional, antimicrobial liquid smoke while reducing emissions, supporting sustainable fish smoking and the circular economy.

Keywords: Liquid smoke; Pyrolysis; Smoked fish; Solar energy; Spiral condenser

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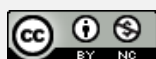
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1. Introduction

The fish smoking industry is one of the key sectors in fish processing in Indonesia, particularly in coastal regions. However, this activity continues to generate environmental challenges, as uncontrolled smoke emissions can pollute the air and cause health problems for workers, visitors, and surrounding communities. Previous studies have reported that residual smoke from fish smoking can trigger respiratory illnesses such as asthma, chronic obstructive pulmonary disease (COPD), and acute respiratory infections, with 54.0% of workers exposed to heavy smoke and 66.7% experiencing severe respiratory symptoms [1], [2], [3]. According to data from the Geographical Industry Information System of the East Java Provincial Department of Industry and Trade, there are 39 fish smoking industries distributed across the coastal areas of East Java [4]. Most of these industries still rely on open systems, where smoke is released directly into the

environment [5], [6]. Furthermore, recent research has emphasized that traditional approaches generate pollutants such as PM_{2.5} and PAHs at levels exceeding permissible thresholds, thus necessitating technological improvements to mitigate environmental impacts [6].

Pollutant exposure from fish smoking industries has been found to surpass quality standards. For instance, studies reported that CO gas concentrations at fish smoking sites reached 10,511 $\mu\text{g}/\text{m}^3$, exceeding the regulatory threshold of 10,000 $\mu\text{g}/\text{m}^3$ set by Government Regulation No. 22 of 2021. This situation highlights the urgency of adopting environmentally friendly fish smoking technologies. Several initiatives have been undertaken, including hygiene and sanitation improvements, installation of smoke chimneys, and the development of APIRALING (Environmentally Friendly Fish Smoking Device) in Tanjungsari Village, Central Java, which converts smoke waste into liquid effluents [7]. Other studies have tested hot smoking and cold smoking methods to reduce pollution. Nevertheless, these technologies have not fully addressed the issue, as smoke is merely converted into liquid waste without further utilization [8].

Several previous studies have stressed the importance of transforming smoke into value-added products. For example, Simanjuntak *et al.* [9] demonstrated that liquid smoke derived from coconut shell pyrolysis exhibits significant antimicrobial activity, making it a promising natural preservative [10]. Similarly, Shariff *et al.* [11] reported that utilizing corn biomass waste as pyrolysis feedstock not only improves energy efficiency but also reduces exhaust gas emissions. The pyrolysis process of biomass such as coconut shells or agricultural waste can produce value-added products such as liquid smoke and biochar [12]. In addition, Latuconsina *et al.* [13] highlighted that the integration of solar energy in food processing systems contributes to operational cost reduction while supporting renewable energy principles. Recent advancements also include the application of liquid smoke enriched with natural additives to improve food shelf life and safety, which has been well received by consumers [2]. Automated smoking machines equipped with microcontrollers and rotary systems with cyclone filtration have also been introduced to improve efficiency, safety, and product quality [14], [15].

Therefore, an innovative approach is required that not only reduces pollution but also generates value-added by-products. This study proposes the integration of a pyrolysis system with a naturally cooled spiral condenser in a solar-powered fish smoking device. The spiral condenser, supported by a water circulation pump, is designed to improve cooling efficiency and thereby increase the volume of liquid smoke produced. The system is further reinforced with multilayer smoke filters composed of coconut fiber, activated carbon, and cotton to reduce pollutant emissions. Additionally, the use of solar panels to power the blower during combustion enhances energy efficiency, shortens processing time, and improves final product quality.

Although several fish smoking technologies have been introduced, most still focus on emission reduction without producing value-added by-products. Solutions such as closed smokehouses, chimney modifications, and filtration can mitigate emissions but typically convert smoke into liquid waste without subsequent utilization. Previous studies also noted that both conventional and improved smoking systems generally do not integrate smoke into value-added products and have yet to fully adopt circular and sustainable concepts [16], [17]. Similarly, pyrolysis-based liquid smoke studies remain limited to conventional condensers with relatively low yields and rarely involve renewable energy integration [16]. Moreover, the adoption of renewable energy in fish processing, particularly in fish smoking, remains rare and mostly limited to aquaculture systems rather than post-harvest processing [17], [18], [19]. This highlights a research gap in developing fish smoking technologies that are not only environmentally friendly but also capable of generating value-added products.

This study introduces novelty through the integration of a pyrolysis system, a naturally cooled spiral condenser, and multilayer filtration using coconut fiber, activated carbon, and cotton to minimize pollutant emissions. In addition, the use of solar panels as an energy source for operating the blower represents an energy-saving strategy while promoting renewable energy utilization. This interdisciplinary integration aligns with global trends toward more efficient, low-emission, and renewable-energy-based food production systems [17], [18], [19], [20]. The process is expected to reduce environmental impacts, improve the yield and quality of liquid smoke, and support innovations that enhance food safety, sustainability, and circular economy principles in the fish processing industry [16], [17], [18].

Therefore, the main objective of this study is to design, develop, and evaluate an integrated pyrolysis-based liquid smoke production system equipped with a naturally cooled spiral condenser, multilayer filtration, and solar-powered blower to enhance production efficiency, reduce emissions, and improve the quality of liquid smoke for sustainable fish processing applications.

2. Methods

This study employed an applied experimental research design with a research and development (R&D) approach to design, construct, and test a prototype of a hybrid fish smoking machine powered by solar energy and equipped with pyrolysis technology and a naturally cooled spiral condenser. The R&D approach has been widely applied in the development of modern fish smoking equipment, both at the industrial and household scales [10], [14], [15], [21].

The research process began with the system design stage, which integrated the technical specifications of solar panels, smoking chamber, pyrolysis unit, spiral condenser, and natural cooling system. This design was based on power and thermal flow analysis, ensuring that each component could operate efficiently in a unified system [15], [22]. Subsequently, a prototype was developed according to this design, utilizing corn cob waste as the primary feedstock for pyrolysis. The selection of corn cobs aligns with current trends in the use of local biomass for energy efficiency and sustainability [1], [15].

The equipment developed in this study represents an innovative fish smoking system that integrates pyrolysis technology, a naturally cooled spiral condenser, and solar energy utilization. The system was specifically designed to improve the quality of smoked fish products while minimizing adverse environmental impacts. The schematic design of the system is presented as follows (Figure 1).

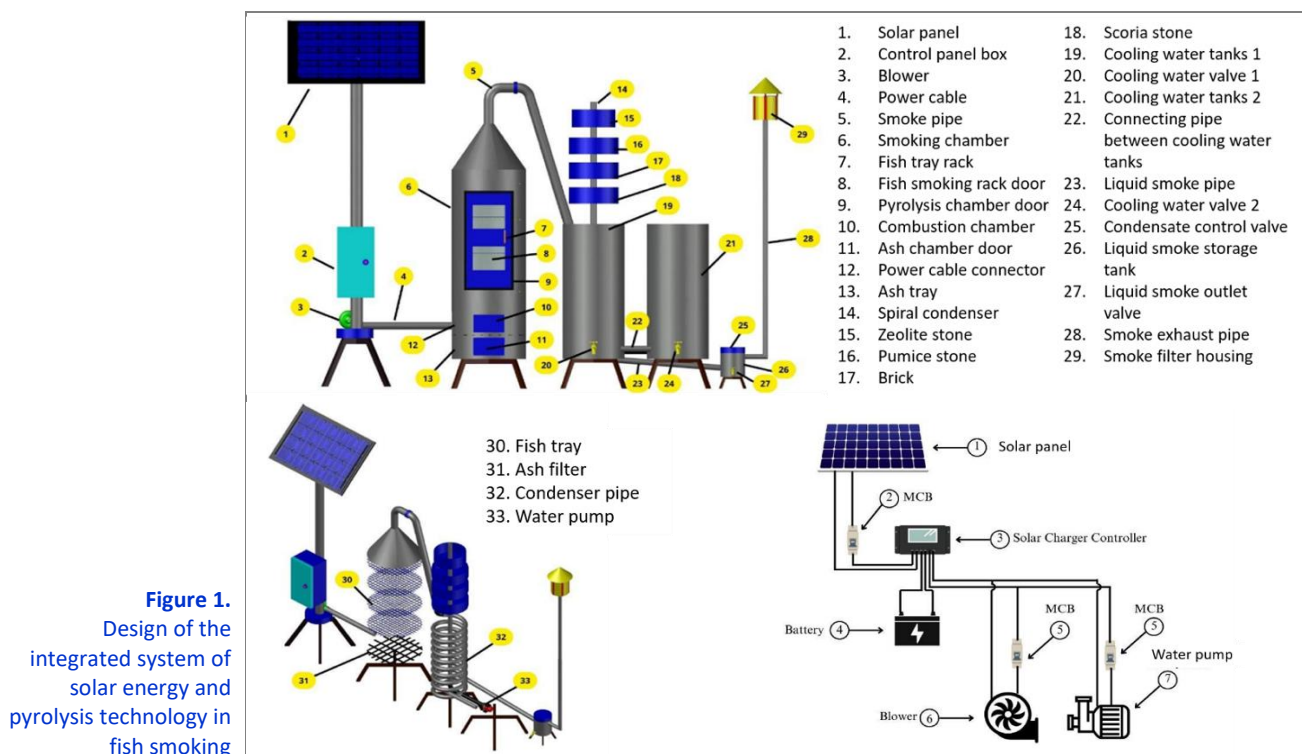


Figure 1.
Design of the
integrated system of
solar energy and
pyrolysis technology in
fish smoking

The primary energy source in this system is a solar panel (1), which functions to capture sunlight and convert it into electrical energy. The electricity is then directed through a control panel (2) equipped with a miniature circuit breaker (MCB) and a solar charge controller, before being stored in a battery. The stored electricity is used to operate the blower (3), which regulates smoke flow, and the water pump (33), which circulates coolant to maintain the temperature of the spiral condenser.

The pyrolysis process takes place inside the combustion chamber (12), where corn cob biomass is used as fuel. During operation, the average pyrolysis temperature recorded in the reactor was 82.80 °C, representing the thermal conditions for slow pyrolysis and smoke generation. Corn cobs have been extensively studied as a promising feedstock for pyrolysis due to their high volatile matter content, low sulfur and ash levels, and desirable calorific value. Previous studies have shown that corn cobs can yield bio-oil, biochar, and syngas with competitive quality and efficiency compared to other biomass sources [11], [23], [24], [25], [26], [27], [28]. Rich in hemicellulose and cellulose, corn cobs are highly suitable for both fast and slow pyrolysis [11], [25].

Moreover, their utilization contributes to energy efficiency and facilitates the principles of circular economy in agricultural waste management [23], [28].

The combustion process generates smoke that flows into the smoking chamber (6), where fish are arranged on racks (30). Residual ash is collected in the ash chamber (13) and can be removed through the ash door (11), with an ash filter (31) installed to prevent solid particles from entering the smoking chamber. Excess smoke is then channeled through a connecting pipe (5) into the spiral condenser (32).

Within the condenser, hot smoke undergoes cooling through a combination of natural and water-assisted cooling media. The average operating temperature inside the spiral condenser was recorded at 60.10 °C, while the average cooling water temperature was maintained at 30.45 °C through continuous circulation from the cooling reservoir (19, 21) using the water pump (33). Cooling media inside the condenser include zeolite (15), pumice (16), and scoria stones (17), which function as heat absorbers and thermal stabilizers. Although previous studies emphasize catalysts and adsorbents such as activated carbon and zeolite in pyrolysis systems [29], [30], the key criteria for cooling media selection are high specific heat capacity and thermal stability. Locally available mineral stones may therefore serve as practical and economical thermal absorbers, although this aspect remains underexplored in pyrolysis research.

As the smoke temperature decreases within the condenser, condensate in the form of liquid smoke is produced. The condensate flows through a liquid smoke pipe (23) into a storage tank (26), with flow regulated by valves (20, 24, 27). The average production of liquid smoke obtained from the system was approximately 300 mL per 6-hour operation, equivalent to an average production rate of about 50 mL per hour under stable operating conditions. The liquid smoke produced exhibits antimicrobial properties and can be utilized as a natural preservative for smoked fish.

The fish used in this study was *Sardinella lemuru* (locally known as lemuru fish), a small pelagic marine species commonly processed in traditional smoking industries in Indonesia. Each individual fish had an average body weight of approximately 32 ± 2 g. For each smoking batch, a total of 18 kg of fresh lemuru fish was loaded into the smoking chamber, representing a typical small-scale production capacity.

The smoking process for one complete batch was conducted for 1 hour and 10 minutes under controlled airflow conditions generated by the solar-powered blower. During this period, fish were arranged uniformly on stainless-steel racks to ensure homogeneous exposure to smoke circulation. The smoking duration was determined based on preliminary trials to achieve adequate dehydration, color development, and smoke penetration without causing excessive surface charring.

Meanwhile, uncondensed smoke is passed through a multi-layer smoke filter (29) containing coconut fiber, activated carbon, and cotton. This stage reduces pollutant emissions before smoke is released into the environment, making the system more environmentally friendly compared to traditional smoking methods. A solar charge controller located in the control panel (2) manages the entire process, ensuring optimal energy distribution between the blower (3) and water pump (33).

With these integrations, the hybrid fish smoking system has three primary functions: (1) reducing pollution through multi-stage cooling and filtration, (2) producing high-quality liquid smoke as a natural preservative, and (3) conserving energy through solar power utilization for both the blower and cooling pump. Once the prototype was constructed, functional tests were performed to ensure all components operated safely and effectively [10], [21].

Subsequently, performance tests were conducted, which included: (a) measuring the efficiency of solar panels under actual solar radiation; (b) assessing the smoking chamber performance in terms of temperature, humidity, and smoking time; (c) evaluating the yield and quality of liquid smoke from the pyrolysis and spiral condenser system; and (d) determining the effectiveness of the natural cooling system in reducing smoke temperature and improving liquid smoke quality [10], [15], [22]. Performance evaluation, system efficiency, and thermal analysis are critical steps in the design of modern smoking equipment [14], [15], [22].

The characterization of liquid smoke involved both quantitative and qualitative analyses, including organoleptic tests (color, aroma, taste) of smoked fish samples, as well as measurements of pH, total acidity, specific gravity, total phenolic content, and heavy metals (Pb and Cd). These physicochemical assessments are now considered standard practice to ensure the quality and safety of smoked fish products [10], [31], [32]. Data collected were analyzed using descriptive statistics and compared with applicable quality standards using appropriate statistical tests [31], [32].

This research was conducted over six months at the Bioenergy Laboratory and UPA Biosains Politeknik Negeri Jember, covering the stages of system design, prototype fabrication, functional and performance testing, and liquid smoke quality analysis. It is expected that this innovation will lead to a more sustainable fish smoking process that efficiently utilizes solar energy, produces high-quality liquid smoke for food applications, and adheres to circular economy principles [10], [14], [15], [21].

The physicochemical and heavy metal analyses of liquid smoke were conducted at UPA Biosains, Politeknik Negeri Jember, using calibrated analytical instruments under controlled laboratory conditions. All measurements were performed in triplicate ($n = 3$), and the results are reported as mean $\pm$ standard deviation. Specific gravity was determined using a 25 mL calibrated glass pycnometer at a controlled temperature of 25 ± 1 °C. The empty pycnometer was weighed using an analytical balance with a precision of ± 0.0001 g, followed by calibration with distilled water to verify volume accuracy. The pycnometer was subsequently filled with liquid smoke samples, and specific gravity was calculated based on the mass-to-volume ratio with temperature correction applied according to the density of distilled water at 25 °C.

Total acidity, expressed as acetic acid (CH_3COOH), was determined using an acid–base titration method with standardized 0.1 N NaOH solution. The NaOH solution was standardized prior to analysis to ensure accuracy. Ten milliliters of liquid smoke were diluted to 100 mL with distilled water, and a 10 mL aliquot was titrated using phenolphthalein as an indicator until a stable pale pink endpoint persisted for 30 seconds. The acetic acid content was calculated based on titrant volume, NaOH normality, dilution factor, and the molecular weight of acetic acid (60.05 g/mol). All titration data were recorded and verified according to the laboratory dataset.

Total phenolic content was analyzed using a UV–Vis spectrophotometer operated with UVProbe software version 2.70. Absorbance measurements were performed at a wavelength of 740 nm using a multi-point calibration curve prepared from gallic acid standard solutions ranging from 0 to 100 mg/L. The calibration equation obtained was $y = 0.0102454x + 1.58210 \times 10^{-4}$ with a coefficient of determination (R^2) of 0.99856, indicating excellent linearity.

The Folin–Ciocalteu method was applied by mixing diluted liquid smoke samples with 10% Folin–Ciocalteu reagent, followed by the addition of 7.5% sodium carbonate solution. After incubation for 30 minutes at room temperature in dark conditions, absorbance was measured at 740 nm. Samples were diluted 10 $\times$ or 20 $\times$ depending on concentration level to ensure absorbance values fell within the linear calibration range. Phenolic content was calculated from the calibration curve and expressed as percentage after conversion considering dilution factors.

Heavy metal analysis for lead (Pb) and cadmium (Cd) was conducted using Flame Atomic Absorption Spectrophotometry (AAS) with a Shimadzu AA-7000 system equipped with an ASC-7000 autosampler. Prior to measurement, liquid smoke samples were subjected to wet acid digestion using concentrated nitric acid (HNO_3) at approximately 120 °C until a clear solution was obtained, then diluted to a final volume of 50 mL with deionized water. For Pb determination, measurements were performed at a wavelength of 283.3 nm with a lamp current of 10 mA, slit width of 0.7 nm, and deuterium background correction (BGC-D2). The calibration curve was established in the concentration range of 0–2.5 ppm, yielding the equation $\text{Abs} = 0.023320\text{Conc} - 0.0064667$ with a correlation coefficient (r) of 0.9997.

For Cd analysis, measurements were conducted at 228.8 nm with a lamp current of 8 mA and slit width of 0.7 nm under similar background correction conditions. The calibration curve covered the range of 0–0.8 ppm and showed excellent correlation ($r = 1.0000$), with polynomial regression as reported in the instrument output.

Instrumental parameters included a pre-spray time of 3 seconds, integration time of 5 seconds, and duplicate to triplicate readings per sample. Blank samples and calibration standards were measured prior to unknown samples to ensure analytical stability. All measured Pb and Cd concentrations in the liquid smoke samples were below the instrument detection limits and were therefore reported as $< \text{LOD}$ in accordance with the analytical reports.

Quality control procedures included verification of calibration curves with acceptance criteria of $R^2 \geq 0.995$, monitoring of relative standard deviation (RSD) within instrument limits ($\leq 5\%$ for standards), and calculation of limits of detection (LOD) and limits of quantification (LOQ) based on blank signal variability using 3σ and 10σ criteria. These procedures ensured the reliability, repeatability, and validity of the analytical results.

To strengthen the safety assessment of the produced liquid smoke, polycyclic aromatic hydrocarbons (PAHs) were analyzed using Gas Chromatography–Mass Spectrometry (GC–MS). The analysis was conducted at UPA Biosains, Politeknik Negeri Jember, using a Shimadzu GCMS-QP

system equipped with an AOC™-6000 Plus autosampler. The analytical approach followed recent validated methodologies for PAH determination in smoked food products and liquid smoke matrices using GC–MS [6], [33], [34].

Prior to analysis, liquid smoke samples were filtered through a 0.22 µm PTFE syringe filter to remove particulate matter. A 1 µL aliquot of filtered sample was injected in split mode. Chromatographic separation was performed using an SH-I-5 Sil MS capillary column (30 m × 0.25 mm I.D., 0.25 µm film thickness), suitable for aromatic hydrocarbon separation. Helium (99.999%) was used as the carrier gas under constant pressure mode. The oven temperature program was set at 80 °C (held for 5 min), ramped at 23 °C/min to 270 °C, and held for 50 min, resulting in a total runtime of 63.26 min. The injector temperature was maintained at 280 °C, while the MS interface and ion source temperatures were both set at 250 °C. The mass spectrometer operated in electron ionization (EI) mode at 70 eV with a scan range of m/z 40–600.

Identification of PAHs was performed by comparing retention times and mass spectra with certified PAH standards and the NIST spectral library. The targeted analytes included the 16 priority PAHs commonly regulated in food safety monitoring, particularly benzo[a]pyrene (BaP), benzo[a]anthracene (BaA), chrysene (Chr), and benzo[b]fluoranthene (BbF), which are widely recognized as carcinogenic indicators in smoked food products [6], [35].

3. Results and Discussion

3.1. Specific Gravity

The specific gravity test (Table 1) revealed a difference between pure corn cob liquid smoke and corn cob liquid smoke applied to fish. The specific gravity of pure corn cob liquid smoke was $0.99965 \pm 0.00003 \text{ g/cm}^3$ ($n = 3$), while corn cob liquid smoke applied to fish showed a higher value of $1.00857 \pm 0.00004 \text{ g/cm}^3$ ($n = 3$). The low standard deviation values indicate good measurement consistency among replicates. The initial value of pure liquid smoke remained below the SNI 8985:2021 standard range of 1.0050–1.0500 g/cm^3 for both grade 1 and grade 2 quality. This indicates that corn cob liquid smoke requires further optimization processes, such as purification through distillation or activated carbon filtration, to comply with the standard criteria. Conversely, corn cob liquid smoke applied to fish met the grade 1 standard with a value of 1.008572 g/cm^3 . This increase may be attributed to the interaction of active compounds in liquid smoke (organic acids, phenols, and carbonyls) with the protein and lipid components of fish, thereby increasing the solution density. This phenomenon is consistent with the findings of [36], who reported that the specific gravity of nyamplung shell liquid smoke ranged between 1.005–1.013 g/mL , depending on pyrolysis temperature. Similarly, Amrullah and Octaviananda [37] demonstrated that the specific gravity of liquid smoke produced from a mixture of corn cobs and sugarcane bagasse reached 1.0225 g/mL , which complies with grade 1 standards. Meanwhile, Amrullah and Adriantini [38] emphasized that purification through distillation and activated carbon filtration can enhance liquid smoke quality, including specific gravity parameters. Therefore, corn cobs show potential as a raw material for liquid smoke, although the relatively low initial specific gravity needs to be optimized. The increase observed after application on fish indicates the functional potential of liquid smoke not only as a preservative but also as a contributor to positive interactions with food

Table 1.
Specific gravity test
results

No	Variation	Specific Gravity
1	Corn Cob Liquid Smoke	$0.99965 \text{ g/cm}^3 \pm 0.00003$
2	Corn Cob Liquid Smoke with Fish	$1.00857 \text{ g/cm}^3 \pm 0.00004$

substrates, thus supporting its application as a natural preservative alternative.

3.2. Acetic Acid Content

The acetic acid (CH_3COOH) content test (Table 2) was carried out on two samples, namely pure corn cob liquid smoke and corn cob liquid smoke applied to fish. The results showed a significant difference in acetic acid concentrations between the two treatments. The acetic acid content of pure corn cob liquid smoke ranged from 1.699 to 1.818% w/w, with a mean value of $1.747 \pm 0.061\%$ w/w ($n = 3$). Although relatively low, this value still falls within Quality Grade 2 according to SNI 8985:2021, which requires an acetic acid content of 1.10–7.99% for grade 2, while grade 1 is defined as 8.00–15.00%. This indicates that corn cob liquid smoke, despite its relatively low acetic acid content, still meets the minimum standard for use as a natural preservative in food and other products.

In contrast, corn cob liquid smoke applied to fish showed significantly higher acetic acid levels, with a mean value of $3.950 \pm 0.027\%$ w/w ($n = 3$). This value also falls within Quality Grade 2 based

on SNI 8985:2021, but its concentration was more than double that of pure corn cob liquid smoke. This phenomenon can be explained by the interaction of active compounds in liquid smoke with fish biochemical components, particularly proteins and lipids. Such interactions may increase the concentration of dissolved organic acids detected during analysis, resulting in higher measured acetic acid levels after application on fish [36].

Chemically, acetic acid is the main component of liquid smoke, formed during the pyrolysis of lignocellulosic compounds, particularly from the decomposition of hemicellulose and cellulose [39], [40]. This compound plays a critical role in antimicrobial activity, as it can reduce the pH of the substrate to levels that inhibit the growth of spoilage microorganisms [41]. Thus, the differences in acetic acid content between pure liquid smoke and that applied to fish reinforce the dual function of liquid smoke—both as a preservative and as a flavor-enhancing agent in food products.

These findings are consistent with those of [37] who reported that liquid smoke derived from a mixture of corn cobs and sugarcane bagasse contained 49.76% acetic acid. Although much higher than the values obtained in this study, such concentrations can still be adjusted to standards through dilution. Meanwhile, Wibowo [36] found that liquid smoke from nyamplung shells contained approximately 9.47% acetic acid, which meets Quality Grade 1 standards. These comparisons demonstrate that both raw materials and pyrolysis conditions significantly influence the acetic acid concentration of liquid smoke.

Table 2.
Calculation of acetic acid
content (CH₃COOH)

Sample	Replication	NaOH Volume	NaOH Normality	fp	W (mg)	CH ₃ COOH content (% w/w)	Average CH ₃ COOH Content (% w/w)	Quality Grade (%) Based on SNI 8985:2021			
								1	2		
Corn cob liquid smoke	1	1.42	0.1	10	5057	1.699	1.747 ± 0.061	8.00 – 15.00	1.10 – 7.99		
	2	1.52	0.1	10	5057	1.818					
	3	1.44	0.1	10	5057	1.723					
Corn cob liquid smoke with fish	1	3.30	0.1	10	5034	3.966	3.950 ± 0.027				
	2	3.30	0.1	10	5034	3.966					
	3	3.26	0.1	10	5034	3.918					

3.3. Phenol Content

The phenol content test (Table 3) was conducted on two samples, namely pure corn cob liquid smoke and corn cob liquid smoke applied to fish. Phenol content values are reported as mean ± standard deviation based on three independent measurements (n = 3). The phenol content of pure corn cob liquid smoke was 7.89 ± 0.02%, whereas liquid smoke applied to fish showed a significantly higher value of 12.42 ± 0.04%. In pure corn cob liquid smoke, the average phenol content was 7.8859% with an absorbance value of 0.808. In contrast, the phenol content of corn cob liquid smoke applied to fish reached 12.4242%, with an average absorbance of 0.637. The results indicated a significant difference between the two treatments. This shows that phenol levels nearly doubled after the liquid smoke was applied to fish.

According to SNI 8985:2021, the phenol content in lignocellulosic liquid smoke should not exceed 2% for both grade 1 and grade 2 quality. Thus, the phenol content in both samples tested in this study was substantially higher than the standard. This phenomenon may be explained by several factors, including the lignocellulosic composition of corn cobs, which contains a high proportion of lignin, leading to abundant lignin degradation. Lignin is the primary precursor of phenolic compounds formed during pyrolysis [39]. The increase in phenol content observed in the sample applied to fish may also be attributed to the interaction of phenolic compounds with proteins and lipids in fish tissue, which can enrich the dissolved aromatic compounds. Additionally, the difference in dilution methods (a dilution factor of 20 for the fish-applied sample compared to 10 for the pure liquid smoke) may also have influenced the final measured concentrations.

Phenolic compounds are important components of liquid smoke, as they contribute antibacterial and antioxidant properties. At certain concentrations, phenols are beneficial in inhibiting the growth of spoilage microorganisms in food products [41]. However, excessive phenol levels can present toxicity risks and fail to comply with food safety standards. Therefore, additional purification steps such as redistillation or activated carbon filtration are required to reduce phenol levels to meet quality standards [38], [40].

These results are consistent with Wibowo [36], who reported that the phenol content of liquid smoke derived from nyamplung shells ranged from 0.66–4.19%, depending on pyrolysis

conditions. These values were lower than those obtained in the present study, indicating that the type of raw material plays a crucial role in determining phenol levels. Similarly, Amrullah and Octaviananda [37] found that phenol content in liquid smoke produced from a mixture of corn cobs and sugarcane bagasse could reach relatively high levels but could still be managed through purification.

Table 3.
Phenol content

No	Sample	Sample Weight (g)	Dilution Factor	Absorbance	Average Absorbance	Phenol Content (mg/kg)	Phenol Content (%)
1	Corn cob liquid smoke	1.000	10	0.807 0.809	0.808	7885.886	7.8859 ± 0.02
2	Corn cob liquid smoke with fish	1.000	20	0.635 0.638	0.637	6212.087	12.4242 ± 0.04

3.4. pH

The pH test results (Figure 2) showed that pure corn cob liquid smoke exhibited a pH of 3.55 ± 0.03 , while liquid smoke applied to fish showed a slightly higher pH of 3.70 ± 0.02 ($n = 3$). Both values fall within the range of 2.76–4.50 required by SNI 8985:2021 for quality grade 2 but do not meet the criteria for quality grade 1, which requires a lower pH of 1.50–2.75. The relatively higher pH of corn cob liquid smoke compared to the quality grade 1 standard indicates that the composition of organic acids, particularly acetic acid, formed during the pyrolysis process remains limited. This condition may be influenced by several factors, including pyrolysis temperature, processing time, raw material moisture content, and the degree of purification.

According to Maga [39], the decomposition of hemicellulose generates organic acids such as acetic acid, which contribute to lowering the pH of liquid smoke. Therefore, the more optimal the hemicellulose decomposition, the lower the resulting pH of liquid smoke. The increase in pH observed in the liquid smoke applied to fish (3.70) compared to pure liquid smoke (3.55) can be explained by the interaction of acidic compounds with fish components such as proteins and minerals, which act as buffering agents. This mechanism reduces the concentration of free H^+ ions, thereby raising the pH of the solution.

This finding is consistent with Darmadji [40], who reported that the presence of proteins and lipids can influence the stability of liquid smoke pH during its application to food products. The results of this study also align with Amrullah and Adriantini [38], who found that liquid smoke derived from coconut shells, corn cobs, and candlenut shells, purified through distillation and activated carbon filtration, exhibited pH values ranging from 3.2 to 3.8, thereby classified as quality grade 2. Similarly, Amrullah and Octaviananda [37] reported that liquid smoke obtained from the pyrolysis of a corn cob and sugarcane bagasse mixture had a pH of 2.5, which meets quality grade 1 standards. These differences highlight that raw material type and pyrolysis conditions play a critical role in determining the pH of liquid smoke products.

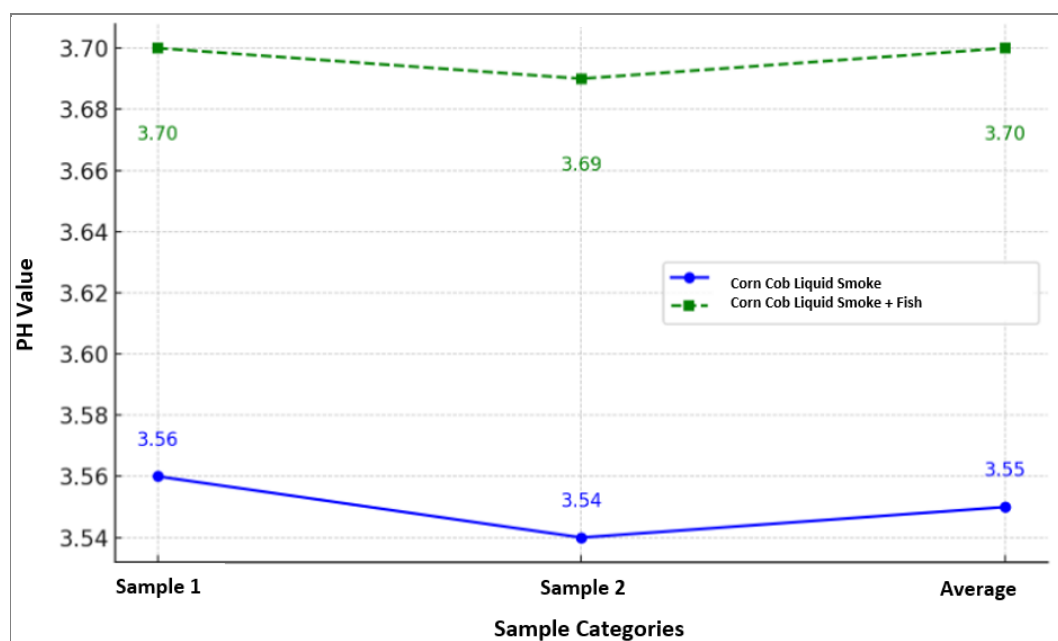


Figure 2.
pH test results

From a functional perspective, pH values in the range of 3.5–3.7 still provide significant antimicrobial effects by creating an environment unfavorable for the growth of pathogenic and spoilage microorganisms [41]. Thus, although corn cob liquid smoke only meets quality grade 2, it can still be applied as a natural preservative. However, to improve quality and achieve grade 1 standards, further optimization of the pyrolysis process (e.g., operating at higher temperatures of 400–500 °C) and repeated purification are required to increase acetic acid concentration and lower pH values.

3.5. Heavy Metal Content (Pb)

The (Figure 3) shows the calibration curve of lead (Pb), illustrating the relationship between Pb concentration (ppm) and absorbance. The curve exhibits a clear linear trend, indicating a reliable analytical response of the instrument across the studied concentration range. The limit of detection (LOD) and limit of quantification (LOQ) for Pb are indicated at 0.01 absorbance and 0.03 absorbance, respectively, as marked by the dashed lines and the shaded region. This zone represents the range in which Pb signals cannot be quantified with acceptable accuracy and precision. The liquid smoke sample derived from corn cob and fish, indicated by a cross (x), is located below the LOD line, demonstrating that the Pb signal of the sample is lower than the minimum detectable limit of the analytical method. Consequently, the Pb concentration in the liquid smoke sample cannot be quantified and is appropriately reported as below the limit of detection (< LOD). These findings indicate that lead contamination was not detected at quantifiable levels in the liquid smoke produced from corn cob and fish, confirming that the product meets safety criteria for heavy metal content based on the detection limits of the analytical method. In atomic absorption spectrophotometry (AAS) analysis, negative concentration results may occur due to several factors, including baseline correction, instrument noise, or blank samples exhibiting higher absorbance than the test samples [42].

Accordingly, it can be confirmed that corn cob liquid smoke, both before and after application to fish, is free from significant Pb contamination. The presence of heavy metals, particularly Pb, is an important parameter in assessing the quality of liquid smoke, as Pb is toxic and accumulative in the human body. Long-term exposure to Pb may cause kidney dysfunction, neurological disorders, and hematological problems [43]. Therefore, Pb levels in liquid smoke must remain below the permissible limit. Based on international food safety standards, Pb content in food additives should not exceed 1 ppm [44].

The findings of this study are consistent with those of [38], who reported that liquid smoke purified by distillation and activated carbon from various lignocellulosic materials (coconut shells, corn cobs, and candlenut shells) also exhibited very low or undetectable Pb levels. This confirms that the pyrolysis of biomass generally does not generate hazardous heavy metals, except when

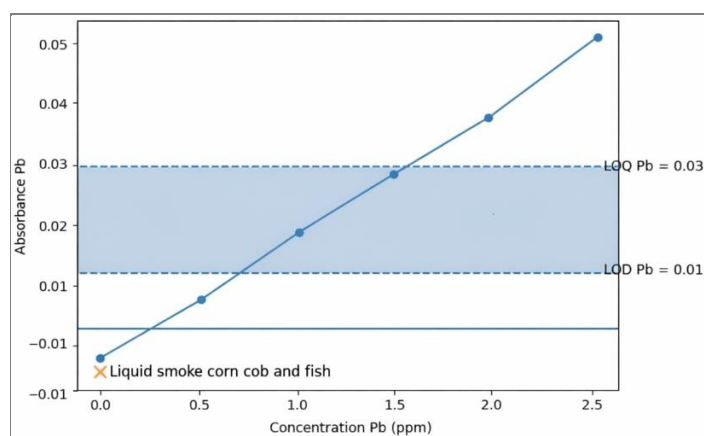


Figure 3.
Calibration curve of Pb
with LOD-LOQ zone

raw materials are already contaminated. The absence of detectable Pb in corn cob liquid smoke, both in pure form and after application to fish, indicates that the product is relatively safe in terms of heavy metal contamination. This supports its potential application as a natural food preservative in accordance with food safety principles and the quality standards of lignocellulosic liquid smoke.

3.6. Cd

The (Figure 4) presents the calibration curve of cadmium (Cd), showing the linear relationship between Cd concentration (ppm) and absorbance. The linear trend indicates a good instrumental response within the tested concentration range, confirming the suitability of the analytical method for Cd determination. The limit of detection (LOD) and limit of quantification (LOQ) are indicated at 0.02 absorbance and 0.06 absorbance, respectively, represented by the shaded region in the graph. This region defines the concentration range in which Cd signals cannot be reliably

quantified. The liquid smoke sample derived from corn cob and fish is marked by a cross (x) and is positioned below the LOD line, indicating that the Cd signal of the sample is lower than the instrument's detection capability. Therefore, the Cd concentration in the liquid smoke sample cannot be quantified and is appropriately reported as below the limit of detection (< LOD). These results suggest that cadmium was not detected at quantifiable levels in the liquid smoke produced from corn cob and fish, indicating compliance with safety requirements for heavy metal contamination based on the detection limits of the analytical method. Such results are commonly caused by instrument baseline offsets, blanks producing higher readings than samples, or imperfect zero-intercept corrections [42].

The absence of Cd in these samples is a highly positive outcome, considering that Cd is a toxic heavy metal that accumulates in human tissues. Long-term exposure to cadmium can lead to kidney damage, reproductive disorders, and an increased risk of cancer [45]. According to the Codex Alimentarius, the maximum permissible limit of Cd in food products is generally 0.1–0.2 ppm, depending on the food type [44]. Therefore, the results of this study indicate that corn cob liquid smoke, both before and after application to fish, is well below the safe threshold.

These findings are consistent with [38], who reported that liquid smoke derived from coconut shells, corn cobs, and candlenut shells after purification contained insignificant or undetectable levels of Pb and Cd, making it suitable for development as a natural preservative. Furthermore, these results reinforce earlier findings that pyrolysis of lignocellulosic biomass generally does not produce heavy metal compounds, unless the raw materials are already contaminated [37].

Table 4 presents a comprehensive summary of the physicochemical and safety parameters of corn cob liquid smoke compared with the SNI 8985:2021 standards and Codex/WHO guidelines. The results indicate that the specific gravity of pure corn cob liquid smoke was 0.99965 g/cm³, slightly below the standard range (1.0050–1.0500), while the sample applied to fish showed an increase to 1.008572 g/cm³, meeting the SNI grade 1 requirement. The pH values of both samples (3.55–3.70) were within the grade 2 range (2.76–4.50), confirming moderate acidity suitable for antimicrobial activity, although not low enough to qualify for grade 1 (1.50–2.75). The acetic acid content was 1.747% for the pure sample and 3.950% for the fish-applied sample, both within the grade 2 range (1.10–7.99%), suggesting sufficient preservative potential. Conversely, the phenol content was relatively high—7.8859% for pure liquid smoke and 12.4242% for the fish-applied sample—exceeding the SNI limit of 2.0%. This indicates the need for further purification, such as redistillation or activated carbon filtration, to meet food-grade safety standards. Importantly, the heavy metals Pb and Cd were not detected (< LOD) in either sample, remaining well below Codex/WHO safety limits (≤1 ppm for Pb and ≤0.1–0.2 ppm for Cd). This confirms that both liquid

smoke products are safe from toxic metal contamination. Overall, the table demonstrates that while corn cob liquid smoke meets several SNI parameters (specific gravity, pH, acetic acid) and is free from heavy metals, its phenol content remains above permissible levels, necessitating post-production purification for commercial or food applications.

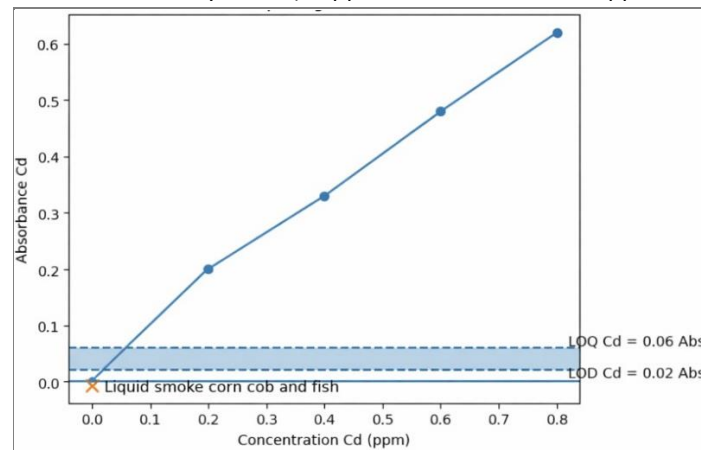


Figure 4.
Calibration curve of Cd
with LOD-LOQ zone

Table 4.
Comprehensive
recapitulation of quality
parameters of corn cob
liquid smoke compared
with SNI 8985:2021 and
Codex/WHO standards

Parameter	Corn Cob Liquid Smoke	Corn Cob Liquid Smoke + Fish	Standard (SNI 8985:2021 / Codex)
Specific Gravity (g/cm ³)	0.99965	1.008572	1.0050–1.0500
pH	3.55	3.70	Grade 1: 1.50–2.75; Grade 2: 2.76–4.50
Acetic Acid (%)	1.747	3.950	Grade 1: 8–15; Grade 2: 1.10–7.99
Phenol (%)	7.8859	12.4242	≤ 2.0
Pb (ppm)	Not detected (< LOD)	Not detected (< LOD)	≤ 1 ppm (Codex/WHO)
Cd (ppm)	Not detected (< LOD)	Not detected (< LOD)	≤ 0.1–0.2 ppm (Codex/WHO)

3.7. PAHs Analysis

The GC–MS chromatograms of corn cob liquid smoke did not show detectable peaks corresponding to the monitored priority PAHs above the instrument detection limits. In particular, benzo[a]pyrene was not detected in the analyzed sample. Likewise, other high molecular weight PAHs, including benzo[b]fluoranthene, benzo[k]fluoranthene, chrysene, and indeno[1,2,3-cd]pyrene, were not detected.

According to current European Union regulations (Regulation EC No. 1881/2006, amended by EU No. 835/2011), the maximum permitted level of benzo[a]pyrene in smoked food products is 2 µg/kg, while the maximum level for the sum of four PAHs (BaP, BaA, BbF, and Chr) is 12 µg/kg [35]. The absence of detectable PAHs in this study indicates that the produced liquid smoke complies with internationally accepted food safety standards.

The absence of PAHs may be attributed to several technical factors. PAH formation is strongly associated with high-temperature pyrolysis and incomplete combustion above 400 °C, which favors the formation of high-molecular-weight aromatic structures [33], [34]. In the present system, the controlled thermal conditions, combined with the spiral condenser and multilayer filtration (coconut fiber, activated carbon, and cotton), likely reduced tar fractions and polyaromatic compounds prior to condensation. Activated carbon in particular has been reported to effectively adsorb PAHs from smoke streams and reduce carcinogenic residues in smoked products [6].

Overall, the PAHs analysis confirms that the integrated solar–pyrolysis smoking system not only improves emission control but also maintains safety with respect to carcinogenic polycyclic aromatic hydrocarbons.

4. Conclusion

This study successfully developed and tested an innovative hybrid fish smoking system integrating solar energy, pyrolysis technology, and a natural spiral condenser for the production of liquid smoke from corn cobs. The system not only reduced environmental pollution but also produced liquid smoke with measurable physicochemical characteristics relevant to food preservation. The results showed that the specific gravity of liquid smoke increased from 0.99965 g/cm³ (raw sample) to 1.008572 g/cm³ after application on fish, meeting the requirements of SNI 8985:2021 for quality grade 1. The acetic acid content ranged from 1.747% in raw liquid smoke to 3.950% after fish application, which falls within SNI quality grade 2, confirming its preservative potential. In contrast, the phenolic content was relatively high (7.89% in raw and 12.42% after fish application), exceeding the maximum 2% set by SNI, indicating the need for further purification processes such as redistillation or activated carbon filtration. The pH values (3.55–3.70) were within the acceptable range for quality grade 2, while ensuring antimicrobial activity suitable for food preservation. Importantly, heavy metals (Pb and Cd) were not detected, remaining below the detection limits and well under Codex/WHO safety thresholds, confirming the product's safety regarding toxic contaminants. Overall, this research demonstrates that corn cobs are a promising biomass feedstock for producing functional liquid smoke with antimicrobial and preservative properties. However, optimization in the purification stage is still required to reduce phenolic levels to meet the SNI 8985:2021 safety standards. The integration of solar energy and pyrolysis in fish smoking provides a sustainable, environmentally friendly solution that aligns with circular economy principles by valorizing agricultural residues into value-added products. This system can contribute significantly to improving the safety, quality, and sustainability of traditional smoked fish industries.

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Authors' Declaration

Authors' contributions and responsibilities - Conceived and designed the experiments (R.E.R, M.A.S, E.D.L); Performed the experiments (R.E.R, H.H, R.F, M.A.S, E.D.L, I); Analyzed and interpreted the data (R.E.R, H.H, R.F, M.A.S); Wrote the original paper (R.E.R, H.H, R.F M.A.S, BR); and Wrote the revised manuscript (R.E.R, H.H, R.F, M.A.S, E.D.L, I, BR).

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Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

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