PERFORMANCE EVALUATION OF MOBILE AND STATIONARY FISH SMOKING TECHNOLOGIES

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ABSTRACT

A study was carried out to evaluate the performance of mobile and stationary fish smoking technologies. The experiment was conducted using a randomized block factorial design, with smoking temperature as a blocking factor. According to the investigation findings, at a smoking temperature of 90 ℃ and a smoking time of 4 hours, the maximum moisture content reduction of 81.4% was noted. In contrast, at a smoking temperature of 70 ℃ and a smoking time of 2 hours, the minimum moisture content reduction of 57.6% was noted for the electric fish smoker. Based on the test results of the electric fish smoker, at 90 ℃ of smoking temperature and 4 h of smoking time, the maximum drying rate of 0.69 kg h^{-1} was obtained. The findings verified that the maximum thermal efficiency of 69.8% was recorded at a smoking temperature of 90 ℃, and a smoking time of 2 h for the electric fish smoker. Based on comparative evaluation results, the moisture content reduction, drying rate, fuel consumption and thermal efficiency for the fuelwood fish smoker were found to be 66.17%, 0.38 kg h^{-1}, 4.8 kg kg^{-1} fish, and 37.9%, respectively. The study demonstrated that electric fish smoking technology significantly outperformed fuelwood smoking technology across all evaluated parameters. This study revealed that the electric fish smoking technology is strongly recommended for demonstration and scaling up to end users, particularly in areas where traditional fish smoking methods remain dominant.

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በሞባይል እና በቋሚ የዓሣ ማጨስ ቴክኖሎጂዎች የአፈጻጸም ግምገማ ለማድረግ ጥናት ተካሂዷል። ሙከራው የተከናወነው የተደራጀ የቡድን ፋክቶሪያል ዲዛይን በመጠቀም ሲሆን የማጨስ ሙቀት እንደ ቡድን መከፋፈያ ተወስዷል። እንደ ምርመራው ውጤቶች መሠረት፣ በ90 ℃ የማጨስ ሙቀት እና በ4 ሰዓት የማጨስ ጊዜ ከፍተኛው 81.4% የእርጥበት መቀነስ ተመዝግቧል፤ በ70 ℃ የማጨስ ሙቀት እና በ2 ሰዓት የማጨስ ጊዜ ግን ዝቅተኛው 57.6% የእርጥበት መቀነስ ለኤሌክትሪክ የዓሣ ማጨሻ ተመዝግቧል። የኤሌክትሪክ የዓሣ ማጨሻ የፈተና ውጤቶች መሠረት፣ በ90 ℃ የማጨስ ሙቀት እና በ4 ሰዓት የማጨስ ጊዜ ከፍተኛው 0.69 kg h^{-1} የማድረቅ ፍጥነት ተገኝቷል፤ በ70 ℃ እና በ2 ሰዓት የማጨስ ጊዜ ግን ዝቅተኛው 0.47 kg h^{-1} ተመዝግቧል። ውጤቶቹ በ90 ℃ የማጨስ ሙቀት እና በ2 ሰዓት የማጨስ ጊዜ ከፍተኛው 69.8% የሙቀት ብቃት መመዝገቡን አሳይተዋል፤ በ70 ℃ የማጨስ ሙቀት እና በ4 ሰዓት የማጨስ ጊዜ ግን ዝቅተኛው 45.6% የሙቀት ብቃት ለኤሌክትሪክ የዓሣ ማጨሻ ተመዝግቧል። የንጽጽር ግምገማ ውጤቶች መሠረት፣ ለየእንጨት ነዳጅ የዓሣ ማጨሻ ግን 66.17%፣ 0.38 kg h^{-1}፣ 4.8 kg kg^{-1} ዓሣ እና 37.9% ተመዝግበዋል። ጥናቱ ኤሌክትሪክ የዓሣ ማጨስ ቴክኖሎጂ ከእንጨት ነዳጅ ማጨስ ቴክኖሎጂ ጋር ሲነጻጸር በሁሉም የተገመገሙ መለኪያዎች ላይ ከፍተኛ አፈጻጸም እንዳሳየ አረጋግጧል።በተለይም በባህላዊ የዓሣ ማጨስ ቴክኖሎጂ በሚበዛባቸው አካባቢዎች ለመስራት እና ለማስፋፋት ኤሌክትሪክ የዓሣ ማጨስ ቴክኖሎጂ በጥብቅ ይመከራል።

INTRODUCTION

Fish is one of the most important sources of high-quality animal protein, essential fatty acids, vitamins, and minerals for billions of people worldwide. It contributes approximately 17% of the global population's intake of animal protein and provides essential nutrients, including omega-3 fatty acids, vitamins A and D, calcium, phosphorus, iron, and iodine (*Badoni et al., 2021*). Fish is generally ranked as the third largest source of animal protein in the world (*Tacon et al., 2025*). It is one of the most essential renewable natural resources and a key component of global food security. Over three billion people rely on fish as their primary source of protein (*Boyd et al., 2022*).

In addition to nutrition, fish play an important role in income generation, employment, industrial production (fish oil, fish meal, and animal feed), recreation, and ecological balance (*Bakhsh et al., 2023*).

According to *Bhujel (2024)*, global total fish production was approximately 193.7 million tons, of which 92.3 million tons came from capture fisheries and 101.4 million tons from aquaculture. In developing countries, fish contribute more than 50% of animal protein intake among coastal and rural populations (*Akpalu & Okyere, 2023)*. Ethiopia's annual fish production was estimated at 29,000 metric tons, mainly from lakes, rivers, reservoirs, and emerging aquaculture systems. However, the country has a much higher production potential under improved management and commercial aquaculture expansion (*Lakew, 2025*).

Despite its importance, fish is highly perishable due to its high moisture content (70–80%), which accelerates microbial growth and enzymatic spoilage (*Ali et al., 2022*). Under tropical conditions, fresh fish may spoil within 8–12 hours if not properly preserved. This rapid deterioration leads to significant post-harvest losses, especially in regions with limited cold storage facilities (*Abbas et al., 2024*). Globally, it is estimated that 20–35% of harvested fish is lost annually due to inadequate preservation, poor handling, and limited processing technologies (*Abelti & Teka, 2024*). These losses reduce food availability, lower market value, and negatively affect income generation for fish processors and traders.

To reduce these losses, various preservation methods such as drying, salting, fermentation, and smoking are widely used. Among these, smoking is one of the most important methods because it combines drying, heating, and chemical preservation effects, reducing moisture content from about 75–80% to 10–20%, thereby extending shelf life from hours to weeks or months (*Adeyeye, 2019*). Smoking also improves sensory qualities such as flavor, aroma, and texture, increasing consumer acceptability (*Puke & Galoburda, 2020*).

Traditional fish smoking systems, commonly made from mud, clay, metal drums, or open-fire structures using firewood, are widely used due to low cost and simplicity *(Idris et al., 2025*). However, they suffer from low thermal efficiency (10–20%), high fuel consumption (2.5–4.0 kg of wood per kg of fish), and uneven temperature distribution, which leads to inconsistent product quality and high operational costs (*Bujas et al., 2022*).

These limitations have encouraged the development of improved fish smoking technologies such as chorkor kilns, cabinet smokers, solar-assisted systems, and hybrid dryers (*Abiodun et al., 2021*). These technologies aim to improve heat transfer, airflow, fuel efficiency, and product quality. For example, solar integration can reduce fuelwood consumption by 35–60% (*Manaye et al., 2022*). One of the improved technologies is the electric fish smoking system, which reduces fuel consumption, processing time, and smoke contamination while enhancing drying rate, moisture reduction, thermal efficiency, and final product safety (*Tahir et al., 2020*). It is suitable for both small-scale and commercial processing due to better control of smoking conditions and improved product quality *(Akande & Adeyemi, 2016*).

As a research gap, there is still limited comparative evidence on the performance of mobile and stationary fish smoking technologies under similar operating conditions in Ethiopia. Most existing studies have focused either on traditional smoking methods or on single improved technologies, without adequately evaluating key performance indicators such as fuel efficiency, drying rate, thermal efficiency, processing time, product quality, and moisture reduction in a comparative framework (*Oyewole et al., 2025*). In addition, context-specific data on how these technologies perform under local fish processing conditions remains insufficient, particularly in developing regions where adoption decisions depend on cost, accessibility, and operational efficiency (*Shittu et al., 2021*). This lack of comprehensive, quantitative comparison creates a knowledge gap that limits informed selection and scaling of the most efficient and sustainable fish smoking system.

Continuous research is necessary to develop and evaluate efficient, low-cost, and environmentally sustainable fish smoking systems. The quantitative evaluation of moisture reduction, thermal efficiency, fuel utilization, drying characteristics, and product quality provides scientific evidence for selecting appropriate technologies and improving processing performance. Technology is critically important in fish processing because it drives improvements in productivity, processing, efficiency, and sustainability.

The main objective of this study is to investigate the key performance parameters of fish smoking technologies in terms of thermal efficiency, fuel consumption, moisture content reduction, product quality, and drying rate in order to improve fish preservation efficiency and reduce post-harvest losses. Therefore, this study aimed to evaluate the performance of mobile (electric) and stationary (fuelwood) tilapia fish species smoking technologies to generate performance metrics information for fish producers in Ethiopia.

MATERIALS AND METHODS

Study area

The study was conducted in Sebeta and Melkassa, two major agricultural research-oriented areas in central Ethiopia, which were selected for their contrasting agro-climatic conditions and suitability for evaluating fish smoking technologies. Sebeta, located approximately 25 km southwest of Addis Ababa at an altitude of about 2,200 m above sea level, experiences a subtropical highland climate with mean annual temperatures ranging from 10°C to 25°C and annual rainfall between 900 and 1,200 mm. Melkassa, situated in the East Shewa Zone of the Oromiya Region about 107 km southeast of Addis Ababa along the main road to Adama, lies at an altitude of approximately 1,550 m above sea level and has a semi-arid climate with mean annual temperatures ranging from 14°C to 32°C and annual rainfall of about 700–850 mm. Therefore, the selection of Sebeta and Melkassa enabled the study to evaluate fish smoking technologies under diverse environmental and operational conditions, thereby improving the reliability and applicability of the research findings.

Description of fish smoking technologies

The fish smoking technologies are widely used for fish preservation through moisture reduction and smoke treatment. Electric smoking technology uses electrically generated heat with controlled temperature and uniform drying conditions, resulting in higher thermal efficiency, faster processing time, improved product quality, and reduced environmental pollution. In contrast, fuelwood smoking relies on burning wood to produce heat and smoke, making it less efficient due to uneven heating, higher fuel consumption, longer drying time, and increased smoke emissions. Overall, electric fish smoking technology provides a cleaner, more efficient, and environmentally sustainable alternative to fuelwood smoking systems.

Mobile or electric fish smoking technology

The mobile or electric fish smoking technology shown in Figure 1 uses electrical energy as the primary heat source to smoke fish under controlled temperature and airflow conditions. The main components of the electric fish smoking technology include an electric heating element, which converts electrical energy into thermal energy for smoking fish; a smoking chamber, which is an insulated enclosure where fish are placed to ensure uniform heat and smoke distribution; and fish trays made of stainless steel to properly arrange fish for effective drying and smoking. A temperature control system, consisting of thermostats, controllers, or sensors, is used to regulate and maintain the desired smoking temperature, while a fan or air circulation system ensures even distribution of heat and smoke throughout the chamber. In addition, insulation materials surround the chamber to minimize heat loss and enhance thermal efficiency. The power supply system, including electrical wiring, switches, plugs, and control panels, provides and regulates electric power to the smoker. An exhaust outlet removes excess smoke, moisture and hot air while maintaining proper airflow, and an oil collector gathers fish oil, water droplets, and residues for improved hygiene and easier cleaning.

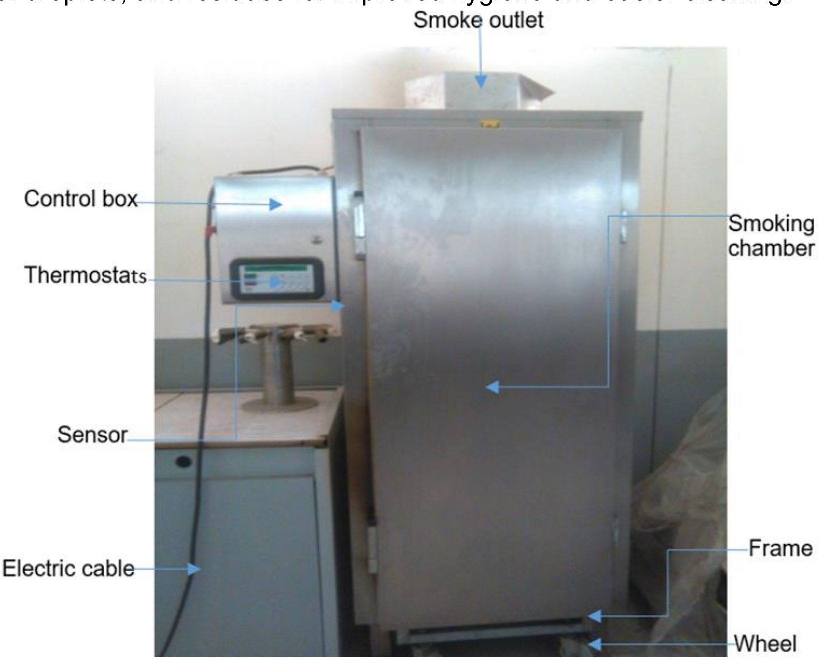

Fig. 1 - Mobile or electric fish smoking technology

This smoking chamber, as shown in Figure 1, has an overall length of 600 mm, height of 1400 mm, and width of 500 mm and is made from aluminum with a thickness of 3 mm to enhance fish quality, marketability, and acceptability. The outer part of the cabinet is made from mild steel with a length of 650 mm, height of 1500 mm, width of 550 mm, and a thickness of 1.5 mm, which covers the inner part of the chamber, and between them, there is an aluminum foil that minimizes heat loss. The developed smoker was portable; it moved from place to place, and the chamber was supported by a flexible frame.

Fig. 2 - Fish tray

Fig. 3 - Stove

Stationary or fuelwood fish smoking technology

The stationary or fuelwood fish smoking technology, as shown in Figure 4, uses firewood as the primary source of heat for smoking fish. In this system, fish are placed on trays inside a smoking chamber, where heat generated from burning wood removes moisture while smoke imparts desirable flavor, color, and preservative compounds. The main components of the fuelwood fish smoking technology include: the combustion chamber, where firewood is burned to produce heat and smoke; the smoking chamber, where fish are dried and smoked under controlled conditions; fish trays made of wire mesh, perforated metal, or wood for uniform arrangement and proper smoke circulation; a smoke outlet to regulate smoke flow and ventilation; firewood as the heat source; and insulated brick walls that retain heat and improve smoking efficiency.

Fig. 4 - Stationary or fuelwood fish smoking technology

The fish smoking mechanism in this system is hanged type and a laying type of fish smoking mechanism on a fish tray. The fish tray can hold smoking fish; it is constructed from wire mesh with a length of 950 mm, a width of 850 mm and a height of 300 mm. There are four trays; each tray contains 25 tilapia fish species, so that one hundred fish can be smoked at once a time. In the case of vertically smoking fish hung by a hook made from a rod. The fish are hung on the hanger with a crossed arrangement to optimize the smoke heat air contact. The heat transfers from the combustion chamber to the smoking chamber by convention with concrete pipe. This heat transfer occurs within the smoking cabinet, like a fish tray and a fish smoking chamber. The wood used for smoking fish in this case was Acacia (Girar). This smoking chamber uses wood as a source of energy. No burning of the smoker due to combustion from oil drops on the heat source because smoking & combustion chambers are developed separately.

Materials

The materials used in this study were selected to support the investigation of smoking technologies, ensure accurate performance evaluation, and maintain product safety and quality. The materials generally used in this research work were fish samples, controlled fuel sources, and precise measuring instruments, which enabled a comprehensive assessment of fish smoking performance under different operational conditions. The selection of materials was based on availability, durability, heat resistance, cost-effectiveness, and suitability for fish smoking operations under local conditions in Sebeta and Melkassa.

Fish material

The fresh tilapia fish species was the primary raw material used for the smoking experiments. The fish samples of uniform size and species were selected to minimize variability in processing outcomes. Typically, freshwater species commonly available in local waters were used. The fish were obtained immediately after harvesting to ensure freshness, with initial moisture content estimated at approximately 70–80% *(Sabu & Sasidharan, 2020*). Before smoking, the fish were washed thoroughly with clean water to remove dirt, slime, and blood residues, and then allowed to drain under hygienic conditions.

Fig. 5 - Experimental material; a) before adding salt, b) after adding salt

Fuel materials

The electrical energy and fuelwood were the main fuel sources used for generating heat and smoke in the mobile and stationary smoking technologies. The hardwood species were selected due to their higher calorific value and slower burning characteristics compared with softwoods in the case of a stationary smoker. The fuelwood was cut into uniform sizes to ensure consistent combustion rates.

Measurement device

The range of instruments was used to evaluate the performance of the fish smoking technologies quantitatively. These included a digital weighing balance for measuring fish weight before and after smoking. Moisture meter or oven-drying apparatus for determining moisture content reduction. Thermocouples and digital thermometers for monitoring temperature distribution inside smoking chambers. Stopwatch for recording processing time. A hygrometer for measuring relative humidity in the smoking environment. Calorimeter for estimating fuel energy value. These instruments were essential for ensuring accurate measurement of thermal efficiency, drying rate, and process consistency (*Nwakuba, 2016*).

Cleaning and hygiene materials

During experimentation, to ensure food safety and hygienic processing conditions, several cleaning materials were used during the preparation and handling of fish samples and equipment. These included clean water, food-grade detergents, disinfectants, and clean cloths. The proper sanitation practices were applied to reduce contamination risks during smoking (*Geraldo et al., 2024*).

Packaging and storage materials

After smoking, fish products were stored and evaluated using appropriate packaging materials. These included polyethylene bags, plastic containers, and aluminum foil packs to prevent moisture reabsorption and contamination. Storage materials were selected based on their ability to preserve product quality during short-term evaluation periods (*Nizio et al., 2023*).

Methods

The study employed an experimental and comparative approach to evaluate fish smoking technologies under controlled conditions. The key performance indicators, including thermal efficiency, fuel consumption, moisture content reduction, processing time, and sensory quality, were systematically measured. The methodology ensured reliable, quantitative, and reproducible assessment of smoking technologies suitable for improving fish preservation systems in rural and peri-urban processing environments.

Sample collection and preparation

Sample allocation to mobile smokers: A total of 270 Nile tilapia were used in the experiment. The fish were randomly assigned to mobile smoking technology. Each temperature treatment consisted of three replications, with 15 fish per replication, resulting in 45 fish per treatment. Therefore, the mobile smoker processed a total of 270 fish for the experiment.

Sample allocation to mobile and stationary smokers for comparative evaluation: A total of 90 Nile tilapia were used in the experiment. The fish were randomly allocated to two smoking treatments: a mobile electric smoker and a stationary fuelwood smoker. Each treatment was replicated three times, with 15 fish per replication, resulting in 45 fish per treatment. Thus, 45 fish were assigned to the mobile electric smoker and 45 fish to the stationary fuelwood smoker. Random allocation of fish to treatments and replications was used to minimize experimental bias.

Test conditions: Both the mobile electric smoker and the stationary fuelwood smoker were evaluated using the same sample load of 15 Nile tilapia per replication under identical experimental conditions. Fish of similar size and weight were used, and the smoking trials were conducted under the same ambient environmental conditions. The same smoking temperatures and processing durations were maintained for both technologies to ensure that any observed differences in performance were attributable to the smoking technology rather than variations in sample load or environmental conditions.

The fresh fish samples were collected immediately after harvest from the Sebeta research center. The tilapia fish species commonly available in the study areas were selected to reflect typical processing conditions. The fish were sorted based on uniform size and weight to minimize variability in smoking performance. Before smoking, the fish were washed thoroughly using clean water to remove slime, blood, and surface impurities. The fish were then drained for approximately 15–30 minutes under hygienic conditions (*Bedane et al., 2022*). The initial weight and moisture content were recorded before loading into the smoking chambers. The experimental fish were healthy Nile tilapia with an average initial body weight of 250 ± 20 g and an average total length of 26.0 ± 1.5 cm (mean ± standard deviation).

Fig. 6 - Dimension and weight measurement of the tilapia fish species

Smoking procedure

The smoking process was conducted separately for each smoking technology under similar environmental conditions. A predetermined quantity of fish was loaded into each smoking chamber for both technologies. The power supply system contained electrical wiring, switches, plugs, and control panels that provide and regulate electric power to the smoker. The fuelwood was ignited in the combustion chamber, and fire intensity was controlled to maintain a temperature range between 70°C and 90°C, which is optimal for fish smoking (*Alakali et al., 2017*). The temperature inside the smoking chamber was monitored using thermocouples placed at different locations to assess heat distribution. The smoking process continued until the fish reached the desired dryness level.

Measurement of performance parameters

Key performance parameters commonly evaluated include thermal efficiency, fuel consumption, drying rate, smoking time, moisture reduction, processing capacity, and sensory acceptability. Several quantitative parameters were measured to evaluate the performance of each smoking technology. After smoking, fish samples were removed and allowed to cool at ambient temperature before post-processing measurements were taken. The total smoking duration was recorded for each treatment.

Moisture content reduction

The moisture content was determined using the oven-drying method. Final moisture content was used to assess product stability and shelf life potential. The fish samples were weighed before and after drying to calculate moisture loss using Equation (1), the formula by *Ojotu et al. (2024)*.

$$\text{Moisture loss (\%)} = \frac{W_1 - W_2}{W_1} \times 100 \tag{1}$$

Drying rate

The drying rate was calculated using Equation (2), based on the reduction in moisture content over the smoking period (*Ojotu et al., 2024*).

$$\text{Drying rate (kg h}^{-1}\text{)} = \frac{\text{Moisture removed (kg)}}{\text{Time(h)}} \tag{2}$$

Fuel Consumption

The fuelwood consumption was measured by weighing the amount of wood used before and after each smoking session. The fuel consumption of an electric fish smoking technology is commonly expressed as the amount of electrical energy used during smoking relative to the quantity of fish processed or moisture removed. The total fuel consumed per kilogram of smoked fish was calculated using Equations (3) and (4) by *Sintali et al. (2023)*.

$$\text{Fuel consumption } (F_{cw}) = \frac{\text{Total fuel used (kg)}}{\text{Mass of smoked fish (kg)}} \tag{3}$$

$$\text{Fuel consumption } (F_{ce}) = \frac{E \times t}{Wf} \tag{4}$$

Electrical energy equivalent conversion

To enable comparison between the electric and fuelwood smoking technologies, the electrical energy consumed by the mobile electric smoker was converted to an equivalent fuelwood mass based on the energy content of the fuelwood. Electrical energy consumption was first recorded in kilowatt-hours (kWh) using an energy meter. This conversion was used solely to provide an energy-equivalent comparison between the mobile electric smoker and the stationary fuelwood smoker. The equivalent fuelwood consumption was then calculated using the lower heating value (LHV) of fuelwood according to the following Equations (5) and (6) by *Sintali et al. (2023)*.

$$\text{Equivalent fuelwood (kg)} = \frac{\text{Electrical energy (kWh)}}{\text{LHV of fuelwood (MJ kg}-1)} \text{x}3.6 \tag{5}$$

$$\text{Equivalent fuelwood consumption (kg kg}^{-1}\text{fish)} = \frac{\text{Equivalent fuelwood}}{\text{Mass of fish processed}} \tag{6}$$

where 3.6 is the conversion factor from 1 kWh to 3.6 MJ, and the LHV of air-dried fuelwood was assumed to be 16 MJ kg^{-1}, equivalent fuelwood in (kg), and mass of fish processed in (kg).

Determination of fuelwood calorific value: The calorific value of the fuelwood was not measured experimentally. Instead, the lower heating value (LHV) of air-dried fuelwood was obtained from literature. An LHV of 16 MJ kg^{-1} was used for the calculations, which is within the typical range reported for air-dried hardwood fuelwood. This value was used to estimate the energy equivalent of the fuelwood consumed during the smoking process.

Thermal efficiency

The thermal efficiency of each smoking technology was estimated using Equations (7) and (8) by comparing the useful energy utilized for moisture removal to the total energy content of the fuelwood and electricity. The thermal efficiency of an electric fish smoking technology is generally expressed as the ratio of the useful heat utilized for moisture evaporation from the fish to the total electrical energy supplied to the smoker formula by *Sintali et al. (2023)*.

$$\text{Thermal efficiency for fuelwood (\%)} = \frac{\text{Energy usd for drying}}{\text{Total fuel energy input}} \text{x}100 \tag{7}$$

$$\text{Thermal efficiency for electric (\%)} = \frac{\text{Mw x Lv}}{\text{Ein}} \tag{8}$$

where, W_1 = initial weight of fresh fish, W_2 = final weight after smoking, F_c = fuel consumption (kWh kg^{-1} fish), E = electrical power rating of the smoker (kW), t = smoking time (hours), W_f = weight of fish processed (kg), ηth = thermal efficiency (%), Mw = mass of water evaporated from fish (kg), Lv = latent heat of vaporization of water (Kj kg^{-1}) (commonly 2257 Kj kg^{-1}), and Ein = total electrical energy supplied to the smoker (kJ).

Sensory evaluation

The sensory quality of smoked fish was evaluated using a semi-trained panel of 10–15 individuals familiar with fish products. The evaluation was conducted under controlled conditions to minimize bias. The attributes assessed included: color, aroma, texture, taste and overall acceptability. Panelists evaluated coded samples using a 9-point hedonic scale to ensure blind assessment. Mean sensory scores were calculated for each smoking technology (*Rossetto et al., 2024*).

Selection and training of sensory panelists: Sensory evaluation was conducted by semi-trained panelists selected from staff and food science experts familiar with fish and fish products. Panelists were selected based on their willingness to participate, good health, normal sensory perception (including taste, smell, and vision), and prior experience in food sensory evaluation. Before the evaluation, the panelists received a 30-minute training session on the evaluation procedure and the quality attributes to be assessed. During training, reference smoked fish samples were used to familiarize panelists with the evaluation criteria and to improve consistency among assessors. Drinking water was provided for palate cleansing between samples, and samples were presented in a randomized order using coded identifiers to minimize bias.

Ethical considerations: Before the sensory evaluation, all panelists were informed about the study's objectives and procedures. Written informed consent was obtained from each participant before participation. Participation was voluntary, and panelists were free to withdraw from the evaluation at any time without consequence. The sensory evaluation involved the consumption of smoked fish prepared under hygienic conditions and posed minimal risk to participants. All personal information and evaluation responses were kept confidential and used solely for research purposes. The study was conducted in accordance with institutional ethical guidelines for research involving human participants.

Fig. 7 - Sensory evaluation of smoked fish by the panelists

Experimental design

The experiment was carried out by randomized block factorial design with smoking temperature as a blocking factor and the levels of smoking temperature with smoking time taken as a treatment combination. Each experiment is to be replicated three times to ensure reliability and reduce experimental error, to have 18 experimental units (3×2×3 = 18). Quantitative data, including moisture content reduction, drying rate, fuel consumption, thermal efficiency, and sensory evaluation scores, were considered as experimental treatments. Each treatment consisted of 45 fish, with 15 fish allocated to each of three replications, resulting in a total of 270 fish for the six treatments. Random allocation of fish to treatments and replications was used to minimize experimental bias and ensure the reliability of the results.

Statistical data analysis

The collected data were analyzed using Statistix 8 software and Statistical Package for Social Sciences software (SPSS version 25.0). Confidence intervals of 95% was used to show the significant effect of the independent variable on the dependent variable. The mean separation between treatment means was conducted by least significance difference (LSD) at a 5% level. Comparative analysis between stationary and mobile smoking technologies was conducted. Descriptive statistics such as mean and standard deviation were computed for all measured parameters. The data were subjected to two-way analysis of variance (ANOVA) by following the appropriate procedure.

RESULTS AND DISCUSSION

Effects of smoking temperature and time on performance indicators

The results indicate that smoking temperature and smoking time have a significant influence on moisture content reduction, drying rate, energy consumption, and thermal efficiency of the electric or mobile fish smoking technology. The findings suggest that maintaining an optimal combination of smoking temperature and time is critical for achieving efficient drying performance, leading to a marked reduction in moisture content, lower fuel consumption, and higher thermal efficiency in electric fish smoking technology. The optimum operating conditions were generally observed within a smoking temperature range of 70–90°C and a smoking time of 2–4 hours. A similar trend was reported by *Adepoju et al. (2018)*. The electric or mobile fish smoking technology was evaluated at three smoking temperature levels (70, 80, and 90°C) and two smoking time levels (2 and 4 h) to assess its performance. The test results indicated that the electric smoker performed efficiently in fish smoking under controlled temperature and time conditions.

Effects of smoking temperature and time on moisture content reduction

Analysis of variance for the effects of smoking temperature, smoking time, and the interaction effect on the moisture content reduction of the mobile or electric fish smoking technology was presented in Table 1. The analysis of variance indicated that the main effects of smoking temperature, smoking time, and the interaction effect were significant at the 5% level (Table 1), as the P-values were less than 5%. The results revealed that the moisture content reduction of a fish smoking technology was influenced by smoking temperature, smoking time, and the interaction effect.

Table 1

Analysis of variance (ANOVA) for moisture content reduction

Sources	DF	SS	MS	F	P	
Replication	2	23.11	11.554			
Smoking temperature	2	1120.70	560.351	600.0	0.0000	*
Smoking time	1	80.22	80.222	85.90	0.0000	*
ST ×St	2	26.85	13.427	14.38	0.0011	*
Error	10	9.34	0.934			
Total	17	1260.22				

* = significant, ** = non-significant, P < 0.05, significant at 5 % level, P>0.05, non-significant at 5% level.

In accordance with the investigation findings, the moisture content reduction ranged from 57.6 % to 81.4 %, as illustrated in Figure 8.

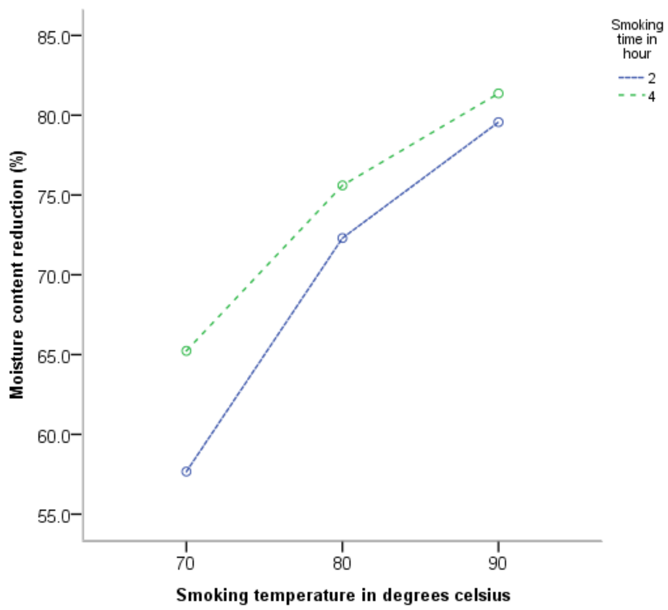

Fig. 8 - Effects of smoking temperature and time on moisture content reduction

The smoking technology moisture content reduction increased from 57.6 % to 81.4% when the smoking temperature increased from 70 to 90 ℃, whereas the smoking temperature increased, the moisture content reduction tended to rise; on the other hand, smoking time began to increase. Based on the result, the moisture content reduction was directly associated with the smoking time and also directly associated with the smoking temperature of the technology. From the investigation results, at 90 ℃ of smoking temperature and 4 h smoking time, the maximum moisture content reduction of 81.4% was noted; also, at 70 ℃ smoking temperature and 2 h smoking time, the minimum moisture content reduction was noted, as it was verified. It was observed that an increase in smoking temperature and time led to a marked reduction in moisture content, as higher thermal energy enhanced the evaporation and diffusion of water from fish tissues. This study's finding is related to the previous research findings conducted by *Toworfe et al. (2023).*

Effects of smoking temperature and time on drying rate

The analysis of variance for the main effects of smoking temperature, smoking time, and the interaction effect on the drying rate of the mobile fish smoking technology. Analysis of variance showed that the effect of smoking temperature and smoking time was significant at a 5% level because the value for P found in Table 2 was lower than 0.05, based on the result, and their interaction effect was also significant at a 5% level. As a result, the main effect of smoking temperature and smoking time could influence the drying rate of a smoking technology; also, the interaction effect did influence the drying rate.

Table 2

Analysis of variance (ANOVA) for drying rate

Sources	DF	SS	MS	F	P	
Replication	2	0.00163	0.00082			
Smoking temperature	2	0.10093	0.05047	5046.67	0.0000	*
Smoking time	1	0.00681	0.00681	680.56	0.0000	*
ST ×St	2	0.00018	0.00009	8.89	0.0060	*
Error	10	0.00010	0.00001			
Total	17	0.10965				

* = significant, ** = non-significant, P < 0.05, significant at 5 % level, P>0.05, non-significant at 5% level.

From the investigation outcomes, it was revealed that the smoking technology drying rate ranged from 0.47 to 0.69 kg h^{-1}, as demonstrated in Figure 9.

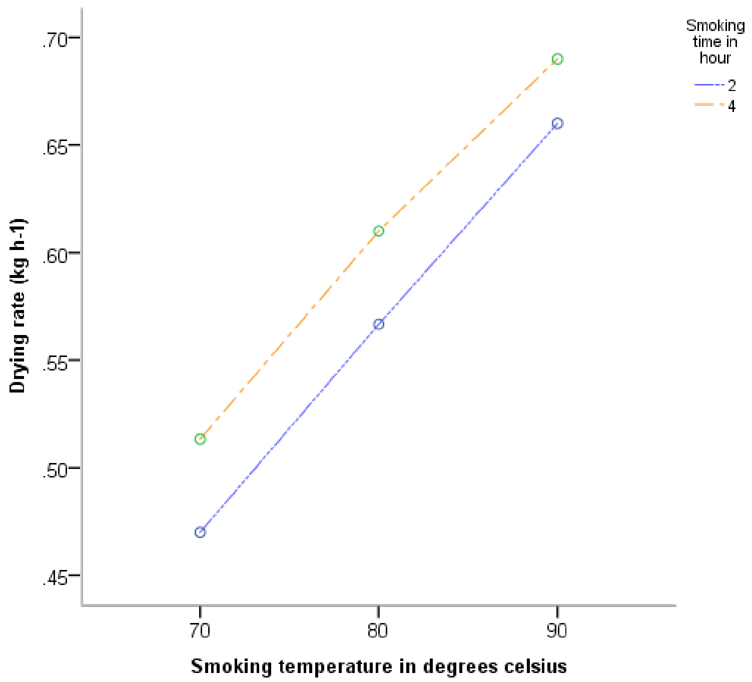

Fig. 9 - Effects of smoking temperature and time on drying rate

So, the drying rate increased from 0.47 to 0.69 kg h^{-1} as the smoking temperature increased from 70 to 90 ℃. The drying rate tends to increase as the smoking temperature and smoking time increase. It demonstrated that a direct association exists between the smoking temperature and smoking time of the drying rate. Generally, at 90 ℃ of smoking temperature and 4 h of smoking time, the maximum drying rate of 0.69 kg h^{-1} was obtained, whereas at 70 ℃ and 2 h smoking time, the minimum drying rate of 0.47 kg h^{-1} was obtained. The drying rate increased with rising temperature due to enhanced heat transfer and moisture migration; however, the rate gradually decreased over time as the moisture gradient between the fish surface and interior diminished. The previous studies in the literature relating results were reported by *Sintali et al. (2023a)*.

Effects of smoking temperature and time on fuel consumption

Analysis of variance for the effects of smoking temperature, smoking time, and the interaction effect on the fuel consumption of the mobile fish smoking technology was presented in Table 3. The analysis of variance indicated that (Table 3) the main effect of smoking temperature and smoking time was significant at a 5% level, depending on the result obtained, because the value for P found was less than 0.05, as well as the interaction effect was significant due to the value obtained for P was lower than 5% (P<5%). Depending on the findings, fuel consumption was impacted by the main effects, whereas it was also affected by the interaction effect.

Table 3

Analysis of variance (ANOVA) for fuel consumption

Sources	DF	SS	MS	F	P	
Replication	2	0.10858	0.05429			
Smoking temperature	2	8.82194	4.41097	754.16	0.0000	*
Smoking time	1	0.37267	0.37267	63.72	0.0000	*
ST ×St	2	0.19034	0.09517	16.27	0.0007	*
Error	10	0.05849	0.00585			
Total	17	9.55203				

* = significant, ** = non-significant, P < 0.05, significant at 5 % level, P>0.05, non-significant at 5% level.

Based on the investigation results, it was found that the fuel consumption ranged from 0.5 to 2.49 kg of fuel kg^{-1} smoked fish, as shown in Figure 10.

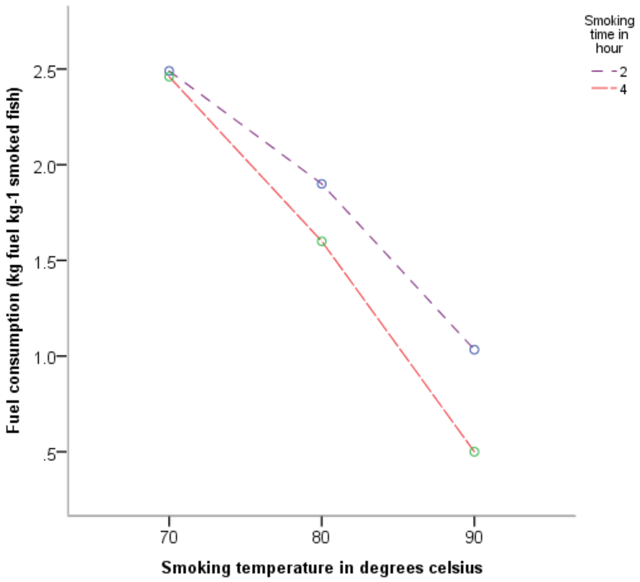

Fig. 10 - Effects of smoking temperature and time on fuel consumption

The fuel consumption reduced from 2.49 to 0.5 kg fuel kg^{-1} smoked fish as the smoking temperature rose from 70 to 90 ℃. By adjusting the smoking temperature and smoking time, fuel consumption was expected to decline as well. It demonstrated that the smoking temperature and smoking time had a reverse association with fuel consumption. According to the findings, at a smoking temperature of 90 ℃ and a smoking time of 4h, the smallest fuel consumption was observed at 0.5, whereas at a smoking temperature of 70℃ and a smoking time of 2 h, the highest fuel consumption was observed at 2.49 for the smoking technology.

Regarding fuel consumption, the results showed that higher temperatures and longer smoking durations increased total electrical energy use due to continuous heater operation and elevated power demand. A similar funding pattern for the smoker was reported by *Taherzadeh-Shalmaei et al. (2021)*.

Effects of smoking temperature and time on thermal efficiency

Analysis of variance for the effect of smoking temperature, smoking time, and interaction on the thermal efficiency of mobile fish smoking technology is presented (Table 4). Based on the findings, the analysis of variance revealed that the effect of smoking temperature and smoking time was significant at the level of five per cent due to the values for P obtained were lower than 0.05; however, the interaction effect was non-significant. According to the outcomes, the thermal efficiency was affected by smoking temperature and smoking time without their interaction effect.

Table 4

Analysis of variance (ANOVA) for thermal efficiency

Sources	DF	SS	MS	F	P	
Replication	2	9.45	4.727			
Smoking temperature	2	1361.56	680.780	1160.2	0.0000	*
Smoking time	1	58.32	58.320	99.41	0.0000	*
ST ×St	2	3.64	1.820	3.10	0.0895	**
Error	10	5.87	0.587			
Total	17	1438.84				

* = significant, ** = non-significant, P < 0.05, significant at 5 % level, P>0.05, non-significant at 5% level.

Based on the investigation results, the mean thermal efficiency of the mobile fish smoking technology varied from 45.6% to 69.8% with increasing smoking temperature from 70 to 90 ℃, whereas thermal efficiency increased from 45.6% to 69.8%. Figure 11 illustrates that the thermal efficiency of the technology tended to increase with the increase of smoking temperature and decreased with smoking time, which means thermal efficiency had a direct relationship to the smoking temperature and was inversely associated with smoking time.

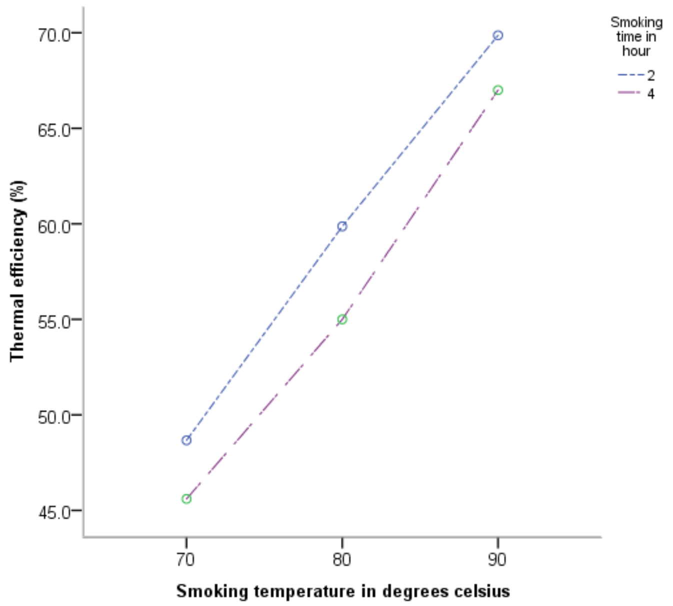

Fig. 11 - Effects of smoking temperature and time on thermal efficiency

The maximum thermal efficiency of 69.8% was recorded at a smoking temperature of 90 ℃, and a smoking time of 2 h, whereas the minimum thermal efficiency was 45.6 recorded at a smoking temperature of 70 ℃, and a smoking time of 4 h. It was found that thermal efficiency improved with controlled increases in temperature and proper smoking duration, as more input energy was effectively converted into useful heat for moisture removal. This study's finding result is similar to the previous research conducted by *Nwakuba et al. (2025)*.

Mean separations of treatment means

The least significance difference all pairwise comparisons test of moisture content reduction, drying rate, fuel consumption and thermal efficiency for mobile fish smoking technology were carried out for each treatment was given below in Table 5 then this analysis was subjected to the least significance difference all pairwise comparisons test of dependent variables for three levels of smoking temperature and two levels of smoking time to know significant differences among treatment means, So, the least significance difference all pairwise comparisons test showed (Table 5) that there were 6 groups (a, b, c, d, e and f) for test of moisture content reduction, drying rate and thermal efficiency for treatment, all 6 means are significantly different from one another but for test of fuel consumption for treatment, there are 4 groups (a, b, c, and d) in which the treatment means were not significantly different from one another at 5% level based on least significance difference all pairwise comparisons test.

Table 5

Comparisons between treatment means for the mobile fish smoking technology

No.	Treatment combination	Smoking temperature (℃)	Smoking time (h^{-1})	Moisture content reduction (%)	Drying rate (kg h^{-1})	Fuel consumption (kg kg^{-1})	Thermal efficiency (%)
1	S_T1S_t1	70	2	57.66^f	0.470^f	2.490^a	48.66^e
2	S_T1S_t2	70	4	65.23^e	0.513^e	2.460^a	45.60^f
3	S_T2S_t1	80	2	72.3^d	0.566^d	1.90^b	59.86^c
4	S_T2S_t2	80	4	75.6^c	0.610^c	1.60^c	55.0^d
5	S_T3S_t1	90	2	79.56^b	0.660^b	1.033^d	69.86^a
6	S_T3S_t2	90	4	81.37^a	0.690^a	0.50^b	67.0^b

S_T = Smoking temperature, S_t = Smoking time

Comparative evaluation of fish smoking technologies

This study demonstrated that electric fish smoking technology significantly outperformed fuelwood smoking systems across all evaluated parameters. The technology achieved an 81.4% improvement in moisture content reduction, reduced drying time by 0.69 kg h^{-1}, lowered fuel consumption by 2.49 kg kg^{-1} of fish smoked, increased thermal efficiency by 69.8%, and enhanced sensory acceptability by 48%. These findings confirm that electric fish smoking technology provides a more efficient, energy-saving, and high-quality fish processing method compared to fuelwood systems. The findings of this study demonstrate that both fish smoking technologies can significantly enhance fish preservation efficiency, improve product quality and safety, and reduce post-harvest losses.

Moisture content reduction

The moisture content of fish before and after smoking showed a clear difference between fuelwood and electric smoking technologies. Both systems reduced moisture significantly; however, the electric system achieved a greater reduction, resulting in safer storage conditions.

Table 6

Moisture content reduction in fish smoking technologies

Smoking technologies	Initial moisture (%)	Final moisture (%)	Moisture content reduction (%)
Stationary technology	78.05 ± 0.38	26.4 ± 0.2	66.17 ± 0.05
Mobile technology	78.1 ± 0.15	14.5 ± 0.22	81.4 ± 0.51

The electric smoking technology achieved a final moisture content of 14.5%, which is below the critical safe storage threshold of 15%. This level is ideal for long-term preservation and significantly reduces microbial growth risk. In contrast, the stationary smoker retained 26.4% moisture, which is insufficient for long-term storage and increases susceptibility to spoilage.

Drying rate

The drying rate varied significantly between smoking technologies as indicated in Table 7. The electric smoking technology increases drying rate by approximately 0.69 kg h^{-1}, which significantly increases the shelf life of fish. This faster drying is due to higher and more stable internal temperature (70–90°C), improved smoke circulation system, reduced moisture boundary layer resistance and enhanced energy transfer efficiency.

Table 7

Drying rate

Smoking technologies	Drying rate ($kg\ h^{-1}$)	Total smoking time (h)	Smoking temperature (℃)
Stationary technology	0.38 ± 0.01	4	90
Mobile technology	0.69 ± 0.015	4	90

Thermal efficiency and fuel consumption

As indicated in Table 8, the thermal efficiency of electric fish smoking technology was higher, but the fuel usage was considerably lower in the electric smoking system.

Table 8

Thermal efficiency and fuel consumption

Smoking technologies	Thermal efficiency (%)	Fuel consumption ($kg\ kg^{-1}$ fish)	Fuel saving
Stationary technology	37.9 ± 0.1	4.8 ± 0.05	low
Mobile technology	69.8 ± 0.78	2.49 ± 0.1	high

The electric fish smoking technology achieved approximately 69.8% of the maximizing of thermal efficiency due to an enclosed combustion chamber design, reduced heat leakage, efficient smoke recycling within the system and improved insulation materials. Fuelwood systems suffer from heat losses, leading to inefficient fuel use and higher operating costs. The electric smoker thus offers both environmental and economic benefits by reducing deforestation pressure and energy waste.

Based on the comparative evaluation of both electric and fuelwood fish smoking technologies, the results obtained for evaluation parameters in Figure 12 were higher in the case of electric fish smoking but lower in the fuelwood smoker, except for fuel consumption. The findings strongly support the adoption of electric fish smoking technologies in regions such as Sebeta and Melkassa, where traditional processing systems remain dominant.

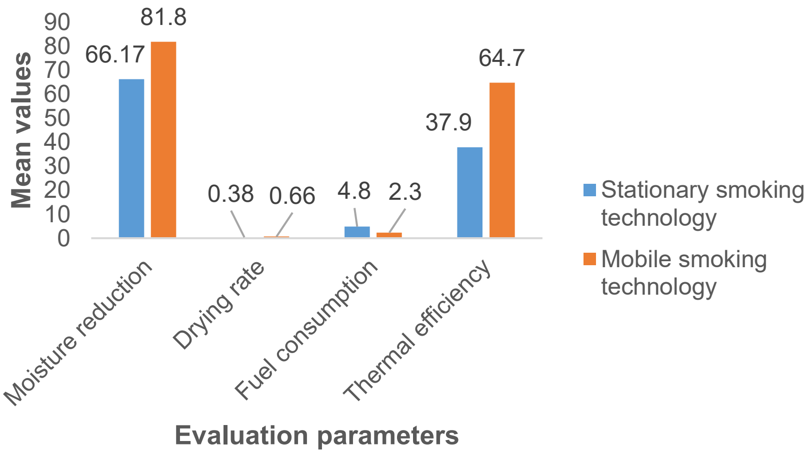

Fig. 12 - Comparative evaluation of smoking technologies

Sensory evaluation of smoked fish for the technologies

Sensory evaluation showed significantly higher acceptability scores for fish processed using improved technology.

Table 9

Sensory evaluation scores (9-point hedonic scale)

Attribute	Stationary smoking technology	Mobile smoking technology
Color	6.4 ± 0.049	8.8 ± 0.05
Aroma	6.7 ± 0.15	8.9 ± 0.06
Texture	6.3 ± 0.03	8.6 ± 0.03
Taste	6.5 ± 0.1	8.8 ± 0.05
Overall Acceptability	6.8 ± 0.17	8.7 ± 0.04

The results obtained in Figure 13 showed that the electric fish smoker consistently achieves higher sensory scores across all parameters. This improvement is due to uniform smoke penetration, controlled heating preventing burning, better moisture balance in the final product and reduced contamination from ash, but the fuelwood energy sourced smoker products showed darker coloration and slightly burnt flavor as well as reducing consumer preference. The same funding pattern for fish smoking technologies was reported by *Tahir et al. (2020).* This study was limited to tilapia fish, specific smoking conditions, and the experimental setup; therefore, the findings may not be directly applicable to other fish species or commercial-scale operations. Future studies should evaluate these technologies under diverse environmental conditions, processing parameters, and large-scale production systems.

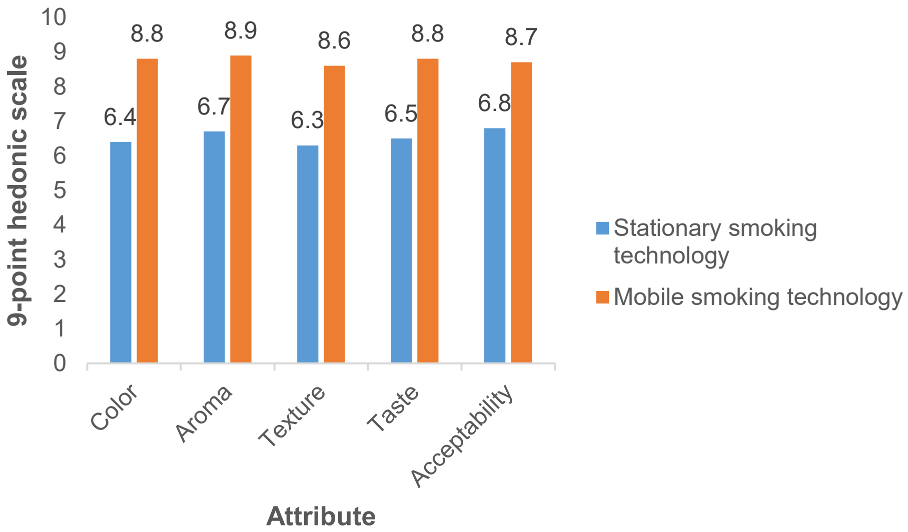

Fig. 13 - Sensor evaluation of smoked fish

CONCLUSIONS

The electric or mobile fish smoking technology was experimentally investigated at three levels of smoking temperature (70, 80, and 90°C) as well as two levels of smoking time (2 and 4 h) in terms of key performance indicators for the tilapia fish species. According to the investigation findings, with increasing smoking temperature from 70 °C to 90°C, the moisture content reduction increased from 57.6% to 81.4%; the drying rate increased from 0.47 kg h^{-1} to 0.69 kg h^{-1}, the thermal efficiency rose from 45.6% to 69.8%, and the fuel consumption reduced from 2.49% to 0.5%. Based on the analysis of variance results, the smoking temperature, smoking time and their interaction effects could influence the moisture content reduction, drying rate, fuel consumption, and thermal efficiency of an electric fish smoker; however, the combination effect did not influence thermal efficiency. The least significant difference all pairwise comparisons test revealed that the treatment means were significantly different from one another at 5% level, except for the test of fuel consumption for treatment based on the comparisons test. The comparative evaluation was carried out for electric and fuelwood fish smoking technologies with respect to key performance indicators. The study revealed that electric fish smoking technology significantly outperformed fuelwood smoking systems across all evaluated parameters. This study was limited to tilapia fish, specific smoking conditions, and the experimental setup; therefore, the findings may not be directly applicable to other fish species or commercial-scale operations. The study revealed that the electric fish smoking technology is strongly recommended for demonstration and scaling up to end users, particularly in areas where traditional smoking methods remain dominant.

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