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Design, Performance and Cost Analysis of Automated Smoking Machine for Village-level Smoked Fish Production

Gee Jay C. Bartolome[1*], Camilo A. Polinga[3], Vennus Florence N. Vicedo[2], John Patrick D. Buco[2], Kevin M. Titiwa[3], Patrick Ronald S. Bernarte[1], John Lester D. Mones[2], Michael James M. Andres[1], Errol R. De Guzman[1], Rogelrose M. Antonio[1] and Michael M. Ramos, Jr.[1]
[1]Department of Engineering
[2]Research and Extension
Cavite State University – CCAT
Rosario, Cavite 4106 Philippines

[3]Department of Agricultural and Food Engineering
Cavite State University – Main Campus
Indang, Cavite 4122 Philippines
[*]*gjcbartolome@cvsu.edu.ph*

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Abstract

The automated smoking machine is a pilot initiative towards the development of integrated processing machinery for the village-level production of smoked fish in Cavite, Philippines. Considering the traditional processing activities and the code of practice for the processing and handling of smoked fish, the machine was designed and fabricated with an estimated capacity of 75 kg per batch of operation. The machine can accomplish both hot and cold smoking processes by maintaining temperatures between 70-90 and 30-60 °C. Using sawdust and wood trimmings as biomass fuel, preliminary tests were conducted to examine the function of machine components and to establish the fuel feed rate and fuel ignition time. Meanwhile, at full capacity testing, smoked fish was produced for sensory analysis while monitoring the smoking temperature and relative humidity in the processing chamber. Results revealed that the minimum, maximum and average temperatures during hot smoking were 60.90, 72.58 °C and 79.93±5.01 °C, respectively, with an average relative humidity of 58.30%. When loaded at full capacity, the average smoking temperature reached 71.72±13.46 °C with no significant difference in the smoking temperature and relative humidity across the sections of the processing chamber. On average, the sensory properties that include the color, aroma, texture and taste of the smoked fish products scored 8.43 (extremely liked) among the participants of the sensory evaluation. A simple economic analysis revealed an initial investment of Php 170,000.00 that is recoverable in 1.59 years, a benefit-cost ratio of 1.29 and a return of investment of 34% – indicative of the machine's financial viability.

***Keywords**:* automated smoking machine, low-cost technology, postharvest technology

1. Introduction

As an archipelagic country, the Philippines is abundant in marine and fishery resources. However, until today, the fisheries sector is still facing challenges due to unsustainable fisheries management and practices. It was estimated that 70% of the total consumption of fishery products is in fresh or chilled form while the remaining 30% is processed into other forms. Traditional processing of fishery products, commonly practiced by coastal communities, is associated with two core problems: postharvest losses and less competitive fish products. In resolving these issues, the use of innovative technologies and venturing into infrastructure machinery and equipment are highly important (Bureau of Fisheries and Aquatic Resources [BFAR], 2018).

Post-harvest practices assure the maximum benefit from fishery products with little or no losses. The common methods of preserving and adding value to fish products are drying and smoking. In a drying chamber, water is vaporized from the product by application of the latent heat to the drying air. The increasing temperature, the velocity of the air and low humidity of the drying air result in a faster and better drying rate and enhance moisture removal from the product surface (Idi Ogede *et al.*, 2018). Meanwhile, in countries where refrigeration and integrated infrastructure for efficient transportation of perishable products are not of concern, smoking is considered not a preservation technique but a means to enhance the flavor of fish. This process that combines drying, smoking and cooking in a single operation has been proven successful by rendering the spoilage and food poisoning microorganisms harmless by altering the environment where they mostly survive (Olayemi *et al.*, 2013). Aside from enhancing the product flavor, smoking also prolongs shelf-life and improves packability and ease of transport and marketing (Adigio *et al.*, 2015).

Fish smoking is extensively used in the processing industry and is carried out using different smoking equipment at varying temperatures. The two common modes of fish smoking include hot and cold smoking (Philippine National Standards/Food and Drug Administration [PNS/FDA], 2010). The characteristics and the quality of the smoked products are affected by several factors, particularly by the smoking temperature (Tahir *et al.*, 2020). As a general requirement, the temperature during hot smoking should range from 70-90 °C to allow complete coagulation of proteins. On the contrary, the temperature during cold smoking should range only from 30-60 °C to prevent heat coagulation of proteins (PNS/FDA, 2010). In some cases, where smoking temperatures are much lower, smoking time range from 25 min to 48 h (Tahir *et al*., 2020). Products that are smoked at much lower temperatures such as 12-25 °C or < 30 °C may also require cooking or baking before consumption (Sikorski *et al*., 2010). In hot smoking, the process must be optimized to achieve the best effect by the quality of salt, smoke and heat. Proper smoking combined with thermal treatment can ensure that the growth of foodborne pathogens such as *Escherichia coli* and *Clostridium botulinum* is ceased while increasing the concentration of basic nutrients in the fish meat.

Until 1995, the equipment used in smoking fish were traditional ovens with low capacities and long smoke-drying times that mismatched the large quantities of raw materials during the peak season. Traditional ovens and kilns, which are fuel-inefficient, also produce fish of uneven quality with their minimal control over the temperature of the fire and smoke density. Hence, more research must still be carried out to investigate fish smoking techniques and processes (Michael *et al*., 2019).

Attempting to improve fish smoking, Oduntan *et al*. (2019) optimized the tray-loading of a locally fabricated smoking kiln. The results showed that for the design of such equipment with an optimal load of 52 kg, the smoking kiln produced dried fish in hygienic conditions. Chinda (2019) compared the effect of an incorporated blower in an improved smoking kiln with its traditional counterpart. The observations revealed that the improved smoking kiln reduced the smoking time by 2.41 h with a moisture loss of 0.32 Lh^{-1}. With the observed significant difference in proximate composition and organoleptic properties of the smoked fish, the use of the improved smoking kiln was recommended. Idi Ogede *et al*. (2018) also developed a pneumatic smoking kiln consisting of a solar-powered fan chamber, charcoal chamber and smoke chamber. They found that increasing drying time from 2-3 h while maintaining the temperature between 60-83 °C can keep the fish longer without further spoilage. Meanwhile, Alakali *et al*. (2011) designed and fabricated an improved smoking kiln and evaluated the machine using different biomasses. The combustion of the biomass produced varying temperatures and a significant effect on the organoleptic properties of smoked catfish. The best quality of smoked fish was obtained using biomass from iron trees while samples smoked with sawdust and rice hull were least preferred. In the Philippines, there were limited documented efforts to improve the fish smoking process with modern technologies. One of which was the four-in-one portable smokehouse device developed by Fernandez (2003) which features a marinating chamber, boiling chamber and smoke-drying chamber that is collapsible for mobility (dela Cruz, 2006).

Despite the efforts on institutional reforms and interventions, the core issues in the fisheries sector are amplified by several interlinked problems including the prevalence of uncompetitive products due to inferior quality and safety standards and postharvest losses in terms of physical, nutritional and value losses (BFAR, 2006). These are widely observed among backyard fish processing enterprises that are still into traditional processing, which are unregulated nor regularly inspected by concerned authorities. In addition, there exists an inadequacy in terms of the availability of suitable and locally-fabricated machinery and equipment and capital to finance processing activities. Large manufacturers produce smoked fish for both local and foreign markets; however, there are very few processing plants that use advanced technology such as mechanized smokehouses and dryers to meet quality standards (Food and Agriculture Organization, 2022). One of the strategic solutions is to improve postharvest infrastructure with locally-developed and innovative technologies at par with local and international standards and relevant to the needs of the industry.

In this premise, the study aimed to develop and test an automated smoking machine for village-level operation. The machine was designed according to the traditional practices of local smoked fish processors from Cavite, Philippines and the codes of practice for the processing and handling of smoked fish. Upon establishing the specifications and processing conditions, the researchers also looked into the sensory properties of the smoked products and some indicators to test and determine the economic viability.

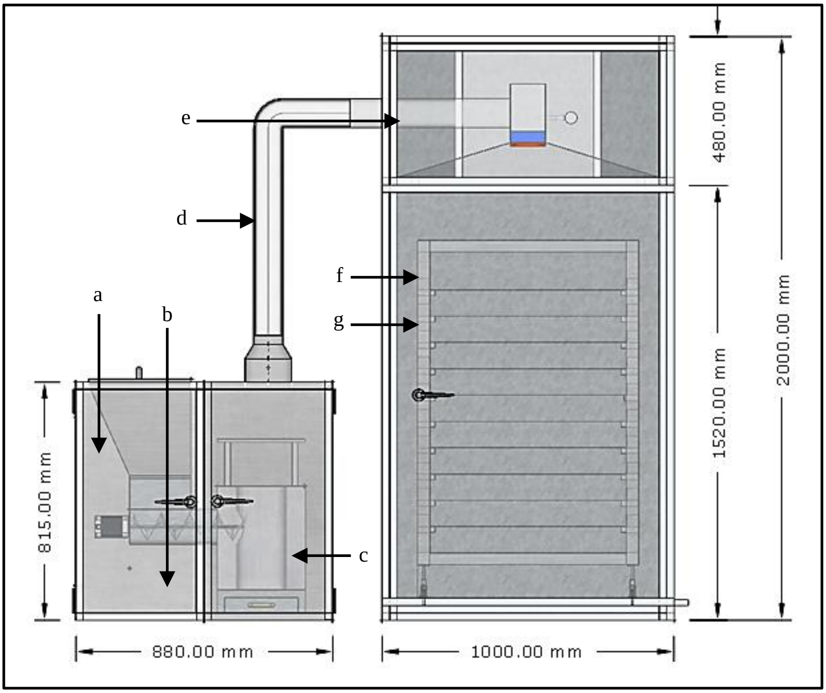
2. Methodology

2.1 Design Considerations

The automated smoking machine was a pilot initiative toward the development of integrated processing machinery for the village-level production of smoked fish in Cavite, Philippines. The smoking machine was developed using locally available, environmentally-safe and hygienic food-grade materials. The machine was designed to be operated by at least two persons who will manage the loading of raw materials, manipulation and unloading of smoked products. For the best quality of smoked products, the machine must be able to control and maintain the smoking temperature and processing time that can meet the recommended practice for processing and handling smoked fish (PNS/FDA, 2010). The hot and cold smoking temperatures should range between 70-90 and 30-60 °C, respectively. The relative humidity should follow temperature changes but must be sufficient to prevent case hardening of the product and poor smoke deposition. Lastly, the smoked fish must exhibit characteristic taste, smoked flavor, aroma, firm texture and color, and must be free from any off-flavors or off-odors that may indicate the onset of rancidity or microbial spoilage.

2.2 Machine Description

The machine (Figure 1) consists of a smoke generator that ignites the biomass fuel to produce smoke and a smoking chamber where hot or cold smoking takes place.



smoke generator (a); screw conveyor (b); firepot (c); smoke channel (d); plenum chamber (e); processing chamber (f); trolley (g)

Figure 1. Representation of the design of the smoking machine showing the cross-sectional view and the major parts

The smoke generator had overall dimensions of 0.88 x 0.55 x 0.815 m (length [L] x width [W] x height [H]) and a loading capacity of 1-5 kg of biomass fuel. Fuel ignition was controlled with a heating coil and the fuel was delivered to the combustion chamber at a uniform rate using a screw conveyor. The ignition coil automatically turned on and off to achieve the desired temperature for hot and cold smoking. The smoking chamber had overall dimensions of 1.00 x 1.00 x 2.00 m (L x W x H), a working volume of 1.33 m^3, and a maximum loading capacity of 75 kg per batch. The fabrication materials were food-grade stainless steel (USS 316 or 304) and the major components were heat-resistant. The smoke generator and the smoking chamber were insulated with mineral wool to ensure the safety of the machine operators. All the construction materials were carefully selected (Table 1).

Table 1. Summary of construction materials for the major components of the automated smoking machine

Major component	Part/item	Specifications
Smoke generator Casing/chassis	Material	Stainless steel 304, no. 24
	Insulation	Mineral wool
	Length x width x height (mm	885 x 585 x 820
	Diameter of caster wheel (mm)	101.6
Hopper	Material	Stainless steel 304, no. 24
	Volume (m^3)	0.029
Screw conveyor	Length x diameter (mm)	420 x 101.6
Prime mover	Capacity (kg-cm)	30
Firepot	Material	Concrete
	Height x width (mm)	355 x 250
	Diameter of combustion cylinder (mm)	170
Heating coil	Rated power (kW)	1.2
	Maximum operating temperature (°C)	150
Smoke channel	Material	Galvanized iron pipe
	Total length x diameter (mm)	870 x 101.6
	Wall thickness (mm)	3.5
Plenum chamber	Material	Stainless steel 304, no. 16
	Length x width x thickness (mm)	400 x 950 x 950
Fan	Diameter (mm)	203.2
	Maximum backpressure (Pa)	380
	Maximum fan air velocity (ms^{-1})	4,550
	Rated voltage (V)	12-24
	Current draw (A)	4.3

Table 1 continued.

Smoking chamber	Material	Stainless steel 304, no. 24/16
	Insulation	Mineral wool
	Height x width x thickness (mm)	2,000 x 1,000 x 1,025.4
	Volume (m^3)	2.05
Trolley	Material	Stainless steel 304, square tube, 1 x 1 x 3/8
	Length x width x height (mm)	760 x 780 x 1100
	Number of trays	10
Heating coil	Rated power (kW)	2
	Maximum operating temperature (°C)	1,300

2.3 Principles of Operation

The automated smoking machine controls the smoke temperature and smoking time and allowed the regulation of the relative humidity and volumetric flow of the smoke. First, biomass fuels are manually loaded into the hopper of the smoke generator. A manual fuel feed gate controls the feeding rate. A screw conveyor powered by a stepper motor delivers the biomass fuel to a concrete firepot. A heating coil placed in the firepot ignites the biomass fuel. When smoke is detected by a smoke sensor MQ135 (Maker Lab Electronics, Philippines) the heating coil is automatically turned off while the conveyor delivers fuel at a uniform rate. From the fire pot, the smoke travels a smoke channel toward the plenum chamber where it will equalize.

In the plenum chamber, the smoke temperature and relative humidity of the smoke are monitored with temperature sensors DS18B20 (Maxim Integrated Products Inc., United States) and humidity sensors DHT22 (Adafruit Industries, United States). When hot smoking is selected, a heating coil ignites to raise the temperature of the smoke and maintain it between 70-90 °C. A variable speed axial-flow fan installed in the plenum chamber helps in the uniform air distribution in the smoking chamber. From the plenum chamber, the smoke passes through rectangular openings on the left and right sides of the ceiling of the chamber.

Smoking takes place in the processing chamber where the fish to be smoked (gutted, washed, brined, and pre-cooked) are placed on stainless steel mesh arranged in a trolley. Smoking time commonly ranges between 30-and 60 min but can be extended depending on the preference of the machine operator. When smoking, the smoke temperature, relative humidity, and smoking time are monitored at various points in the machine and these process parameters can be viewed on a liquid-crystal display (LCD) panel.

The processing chamber was insulated with mineral wool to minimize heat loss and provide protection to the operators. The doors were built with silicone gaskets and lock latches to seal in the smoke. An air vent with a shutter was also installed on the lower rear part of the smoking chamber to provide exhaust for excess smoke and to allow complete circulation of smoke during operation. When smoking is complete, the blower and the heating coil automatically turn off and the excess moisture, condensing from the smoke, and the raw materials are drained into the bottom of the chamber. The ashes produced during fuel combustion are collected in an ash pan. The product is allowed to stabilize in the chamber for a few minutes and cooled down to room temperature before packaging.

2.4 Testing and Evaluation Procedures

Preliminary tests were conducted to examine the functional components of the machine. The smoke generator was subjected to a series of preheating and combustion tests to determine the appropriate fuel feed rate, ignition time and ignition temperature of the biomass fuel. Sawdust and wood trimmings were selected as biomass fuel because of their wide availability; they are also commonly used by local fish processors. The smoke temperature, relative humidity and smoke velocity were monitored for 60 min of operation at various points in the machine using a data-logging device with DHT22 temperature and humidity sensors and a digital anemometer (DAM100B, Dawson Tools Inc., United States). The monitoring points included the (a) exit point of the smoke channel (from the smoke generator to the plenum chamber), (b) the upper and lower sections of the processing chamber and the (c) air vent. Observations without load were done in three trials. Afterward, the machine was loaded at full capacity to produce smoked fish for sensory analysis.

2.5 Sensory Analysis of Smoked Fish Products

The sensory properties (color, aroma, texture and taste) of the smoked fish products were evaluated by 30 non-trained participants, who are consumers of smoked fish using a nine-point Hedonic scale (Alakali *et al*., 2011; Chinda, 2019) (Table 2).

2.6 Simple Cost Analysis

A simple cost analysis of the machine was carried out to determine its economic viability. The payback period (PBP) (in years), breakeven point

(BEP) (in kg of smoked fish), benefit-cost ratio (BCR) and return on investment (ROI) (Department of Agriculture, 2020) were computed using the Equations 1, 2, 3 and 4, respectively.

$$PBP = \frac{Capital\ investment\ cost}{Average\ annual\ benefits} \tag{1}$$

$$BEP = \frac{Total\ fixed\ cost}{Custom\ rate - \frac{Variable\ costs}{Capacity}} \tag{2}$$

$$BCR = \frac{Net\ income}{Total\ cost \times operating\ period} \tag{3}$$

$$ROI = \frac{Net\ benefits}{Initial\ cost + total\ annual\ costs} \tag{4}$$

Table 2. Nine-point Hedonic scale for the evaluation of the sensory properties of the smoked product

Scale	Description
8.12-9.00	Like extremely
7.23-8.11	Like very much
6.34-7.22	Like moderately
5.45-6.33	Like slightly
4.56-5.44	Neither like nor dislike
3.67-4.55	Like slightly
2.78-3.66	Dislike moderately
1.89-2.77	Dislike very much
1.00-1.88	Dislike extremely

2.7 Statistical Analysis

The data collected were analyzed using independent samples T-*t*est and frequency distribution tables using IBM-SPSS version 27. Relationships between and among variables were confirmed with Pearson *r* correlation with an alpha of 0.5.

3. Results and Discussion

3.1 Psychrometric Properties of Smoke

The automated smoking machine was fabricated according to the design specification (Figure 2). The ambient air temperature and relative humidity during the preliminary testing were 33 °C and 72%, respectively. Preheating and fuel ignition tests of the smoke generator revealed that in 60-min operation, the temperature in the firepot can reach ≥ 98 °C. The biomass fuel (average moisture content on a wet basis of 9.78%) ignited at 45 °C. The amount of fuel consumed was estimated at an average of 0.68 kgh^{-1}. With this fuel consumption rate, the temperature of the smoke at the exit of the smoke channel ranged between 32.5-54.3 °C (mean = 49.35±4.38 °C), and the relative humidity was 61.1-76.8% (mean = 46.40±6.90%). The air velocities were 0.27-1.18 ms^{-1} (mean = 0.59±0.31 ms^{-1}).

Figure 2. The actual look of the automated smoking machine

The Pearson *r* correlation coefficients showed that the smoke temperature and air velocity had a strong positive relationship (*r* = 0.838) (Figure 3) in contrast with temperature and relative humidity where a strong negative relationship existed (*r* = -0.873) (Figure 4). These proved that the increasing temperature increased the air velocities and decreased the relative humidity of the smoke entering the processing chamber.

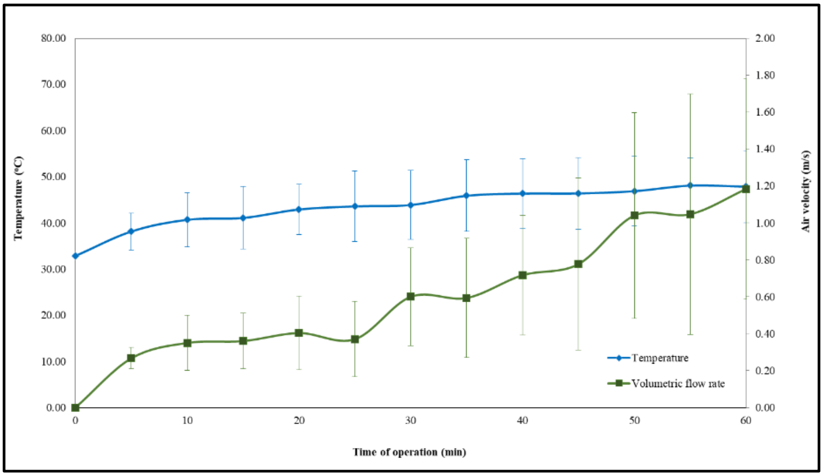


Figure 3. Average air velocity and temperature in the smoking chamber in 60-min operation of the smoking machine

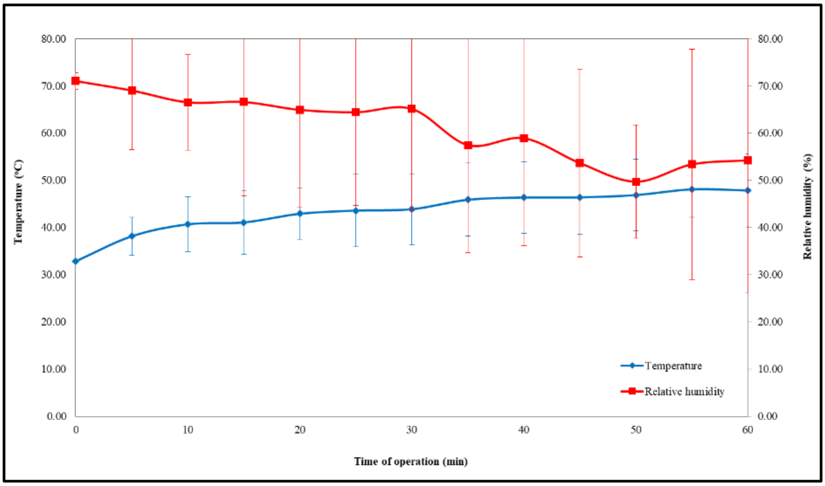


Figure 4. Average relative humidity and temperature in the smoking chamber in 60-min operation of the smoking machine

3.2 Temperature and Relative Humidity of Smoke in Smoking Chamber

Statistical analysis of the smoke temperature in the upper and lower sections of the smoking chamber during actual hot smoking operations revealed no significant difference (Figure 5). This suggested that air and temperature were approximately even throughout the chamber. These observations revealed average temperatures of 75.04, 70.63 and 72.06 °C in three testing trials of the smoking machine (Figure 6). The heating coil in the plenum chamber and the axial-flow fan helped in increasing the temperature of the smoke by an average of 27.45 °C and the velocity by 1.10 ms^{-1}. The temperature values were within the permissible range of 70-90 °C based on PNS/FDA (2010).

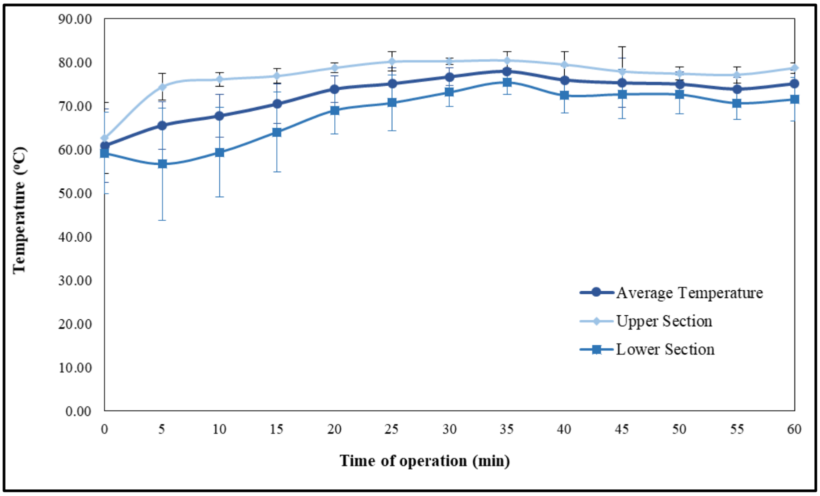


Figure 5. Average temperature and air velocity in the smoking chamber in 60 min-operation of the smoking machine

In the same trials, the average relative humidity values obtained were 68.03, 51.37 and 56.53%. The lowest RH obtained was 39.80% while the highest was 76.20% with an average of 58.39±3.18% (Figure 6). The average temperature and relative humidity were found to have a very weak relationship (r = 0.012) (Figure 7). Although it was previously mentioned that relative humidity followed temperature changes, this weak relationship may imply that the heating coil and the axial-flow fan may have significant effects on manipulating these processing parameters to maintain the desired conditions.

3.3 Sensory Properties of Smoked Products

The sensory properties of the product were rated by selected participants as follows: color - 8.33; aroma - 8.60; texture - 8.60; and taste - 8.47. The product got an overall rating of 8.43 indicating that the product was extremely liked by the consumers. In the observations of the physical characteristics of the final product, there were no visible signs of objectionable flavors and odor, the texture was firm, and the color was acceptable as a smoked product.

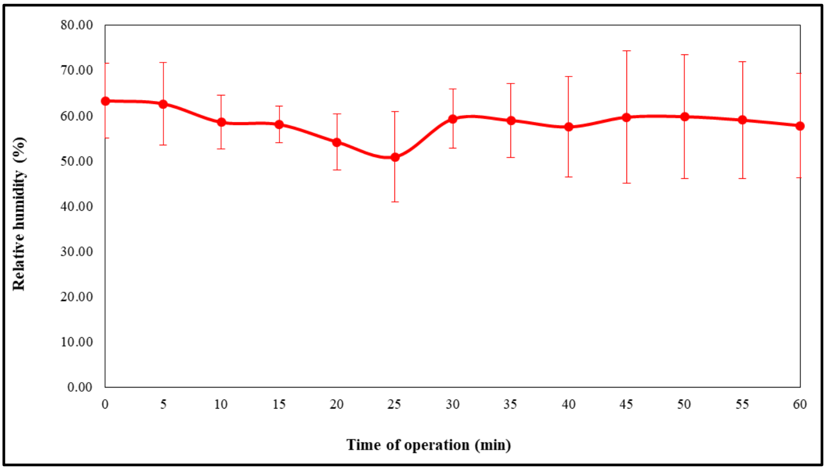


Figure 6. The changes in relative humidity in the smoking chamber during the actual hot smoking test

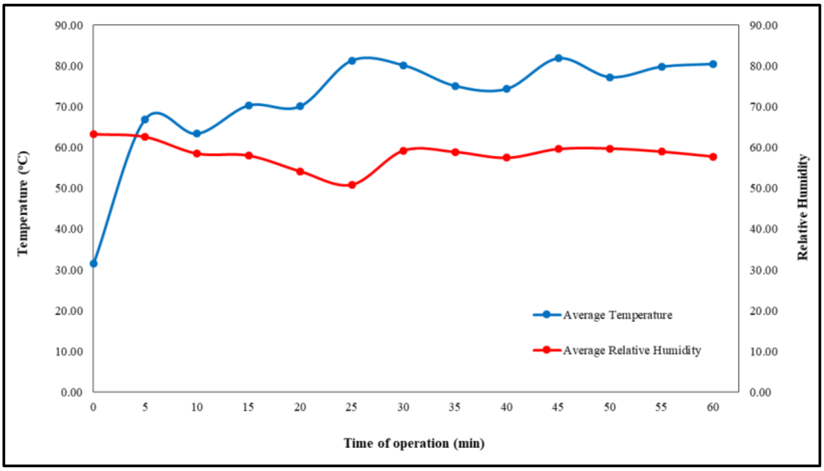


Figure 7. Mean plots of the smoke temperature and relative humidity in the processing chamber at full capacity testing

3.4 Cost-and-Return Analysis of Smoking Machine

The fabrication of the smoking machine required an initial capital investment of Php 170,000.00. The analysis of cost and benefits was based on certain assumptions (Table 3).

Table 3. Basic assumptions on the cost and benefits for the machine operation

Basic Assumptions	Value
Initial capital investment (IC) (Php)	170,000.00
Annual depreciation (Php)	30,600.00
Electricity (Php)	29.12
Salvage value (10% of IC)	17,000.00
Useful life in years (n)	5.00
Interest on investment (2.25% of IC) (Php)	3,825.00
Taxes, insurance, and housing (1% of IC) (Php)	1,700.00
Repairs and maintenance (4% per year)	4.53
Days of operation per year (at 5 hours per day)	300.00
Custom rate (one machine operator at Php 373 per day)	2.44
Machine capacity (kghr^{-1})	75.00
Annual capacity (kg)	75,000.00
Annual expenses (Php)	162,386.27
Gross benefits (Php)	274,500.00
Net benefits (Php)	112,113.73
Discount rate (%)	15

Based on the prevailing minimum wage for labor and variable costs, the customs rate and the operating cost per kilogram were Php 2.44 and 1.44. At its maximum capacity of 75 kghr^{-1}, a break-even point of 36,249.46 kg was estimated at an annual cost of Php 198,511.27. The initial capital investment can also be recovered in a payback period of 1.59 years. In addition, the annual expenses and gross benefits were computed to be Php 162,386.27 and Php 274,500.00, respectively. These values yield a benefit-cost ratio of 1.29 and a return on investment of 34% suggesting that the investment in the smoking machine is financially viable.

4. Conclusion and Recommendation

An automated smoking machine for village-level production was designed, fabricated and tested to establish the technical performance and specifications. The machine primarily comprised a smoke generator and a processing chamber that can maintain temperatures for both hot and cold smoking. With the adequate processing conditions, the smoked products were satisfactory in terms of their sensory properties. To improve the machine's operation, it is highly recommended to introduce a PID-based control system to refine the control of the smoke temperature and other parameters. Once optimized, experiments on smoking temperature and processing time and their effects on the physicochemical properties, microbiology and nutritional quality of smoked fish products can be conducted. The sensory properties of smoked products must also be assessed by a panel of food science experts to generate more reliable and unbiased information. Generally, the simple cost-and-return analysis of the machine revealed that it is financially viable in village-level operations. With the design specifications meeting the recommended practices for smoked fish processing, the automated smoking machine possess a huge potential to significantly impact the fish industry by providing access to cheap, local postharvest equipment. Furthermore, the machine is recommended for field testing to assess its potential for commercialization.

5. Acknowledgement

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