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A Novel Power-operated Fish Cutting Machine: Design and Performance Assessment

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Abstract

Fish, a critical source of protein, plays a vital role in global food security. Fish processing involves descaling, gutting, deheading, and cutting. Traditionally small vendors and retailers manually cut the fish steaks using Sharp metal knives. However, manual cutting methods are inefficient, labor-intensive, and pose safety risks. This study presents a novel power-operated fish-cutting machine design, development, and performance evaluation to address these limitations. The machine incorporates a mainframe, cutting blade, roller system, feeding section, and power transmission mechanism. Its performance was assessed using various fish species (Catla, Silver sillago, Flying Fish) by analyzing the influence of cutting blade speed, feeding angle, and distance between the cutting blades on cutting efficiency, cutting time, and damage. The results demonstrated that all three factors significantly impacted the cutting process. By optimizing these parameters, the machine achieved a maximum efficiency of 98.59% with a cutting rate of 0.5 minutes per kilogram of fish at a roller speed of 1200 rpm, a feeding angle of 120 degrees, and a distance between the cutting blades of 40 mm for silver sillago. Furthermore, the study revealed that fish variety, size, length, and distance between the cutting blades significantly influence the machine's performance, highlighting the need for potential adjustments based on specific fish characteristics.

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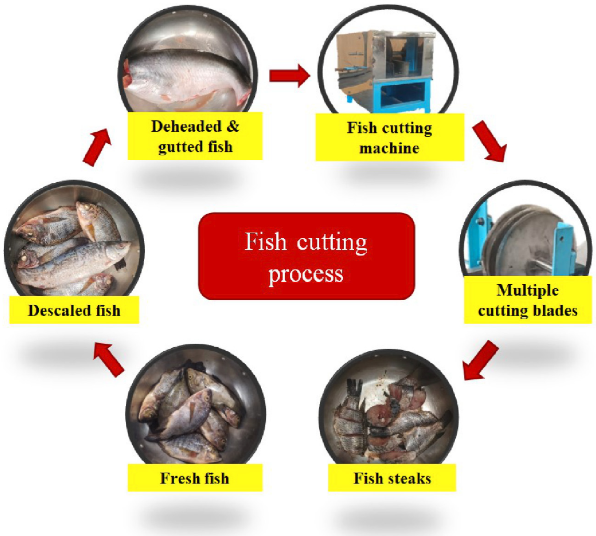


Fig. 1. Graphical abstract of fish cutting process

Introduction

Aquatic food resources are vital for providing essential nutrients, vitamins, and minerals, with fish being a key protein source due to its high-quality protein and numerous essential nutrients (Hixson, 2014). In 2022, global fisheries and aquaculture production reached 223.2 million tonnes, reflecting a 4.4% increase from 2020. Fish is considered a global superfood, with average consumption reaching 162.5 million tonnes in 2021, and per capita consumption rising from 9.1 kg in 1961 to 20.7 kg in 2022 (FAO, 2024). India, the second-largest fish producer, contributes 5.43% of the global fish output and ranks second in aquaculture production (Bodh & Yadav, 2020; FAOSTAT, 2023). Despite this, India's per capita fish consumption is only 6.31 kg per person, below the global average (Ravishankar & Elavarasan, 2023). Fish handling and preservation are critical due to their perishable nature, necessitating specific methods to maintain flavor, texture, and nutritional quality. Initial fish processing steps include descaling, deheading, evisceration, slicing, filleting, and skinning (Delfiya et al., 2019).

In India, fish processing is often done manually in small, disorganized markets using traditional tools, which is labour-intensive, time-consuming, and poses injury risks (Saha, Nag, & Nag, 2006). Therefore, technological advancements in fish processing are essential to improve efficiency, reduce processing time, and ensure worker safety.

A variety of fish slicing and cutting machines have been developed to enhance efficiency and precision in fish processing. The semi-automatic fish cutting machine designed by Kamaruzzaman, Mahfurdz, Hashim, and Bidin (2020) can produce butterfly cuts for the salted fish industry, achieving five times higher productivity than manual methods averaging 21 fish/minute and saves 81.2% time compared to the manual processes. However, it can be used to produce only butterfly cuts. Geunyoung (2023) designed a fixed-quantity meat slicer featuring a loading groove, vertical meat pressing, and horizontal driving mechanisms. The slicer includes a flange for meat ejection, a restriction cover, a cutter, and an input interface for slicing preferences, then streamlining meat slicing into a compact, efficient system. Oleynikova, Stepanov, Gukasyan, and Kosachevb (2021) designed a rotary fish-cutting machine for processing the Azov-Black Sea anchovy. In the design of a fish-cutting machine, it is important to ensure the removal of the viscera with a pulsed water-air jet at a certain position of the cartridge trunk. However, it is unable to process the different varieties and sizes of fish. The water–air jet pressure adjustable for each fish was very difficult and it was not suitable for bigger sized fishes. Ashwinkumar, Bhuvaneshkumar, and Adithya (2021) has developed a universal fish cutting apparatus that was capable of using different varieties of fish and it produced only one steak at a time which prolonged the duration. Moreover, this machine could make injury to labourers as the cutting section is not fully covered and manual handling of fish is required during processing.

The literature survey revealed that current technologies are often limited in fish types, sizes, or cut styles, and may lack safety features or require skilled operation. It was evident that there is a need to develop a versatile, efficient, and user-friendly fish cutting machine. This study aimed to address the above mentioned limitations by designing, developing, and evaluating an integrated unit which caters to the processing of various commercial fish species, and capable of producing different types of cuts, and consider operational safety and efficiency.

The research focused on developing a machine that could handle a wide range of fish varieties with minimal damage, while enhancing safety by means of a fully enclosed design. The primary objectives were to develop a versatile cutting device and evaluate its effectiveness based on cutting efficiency, processing capacity, and the quality of fish steaks produced. Key parameters for evaluation included blade rotational speed, feeding unit angle, and distance between cutting blades. The goal was to develop a prototype of fish cutting machine which can be used by both small-scale operators and larger industries, potentially reducing the need for highly skilled labour while improving productivity and versatility in fish processing operations.

Materials and Methods

Freshwater fish Catla (*Labeo catla*) and marine fishes Silver sillago (*Sillago sihama*) and Flying Fish (*Exocoetus sp.*) were bought from the Ukkadam Fish Market (10.9889° N, 76.9591° E) in Coimbatore, Tamil Nadu. Fish was cleaned using potable water and stored at 2±1 °C prior to the experimental studies. Key morphometric characteristics, such as total length, standard length, head length, maximum cross thickness, and weight were studied to design and select different components of the fish-cutting machine (Gaikwad, Ahmad, Yenge, & Singh, 2017).

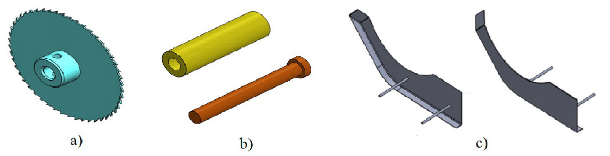
The primary aim of the machine is to produce dedicated fish steak cuts, which are highly preferred by consumers. The machine operates on the principle of shear and impact actions from the cutting blade. Based on the preliminary studies, the serrated circular cutting blade was selected for fish cutting, and supporting rollers and adjustable plates were also the major components of the cutting machine.

A serrated circular cutting blade was fabricated with stainless steel 304 material. The cutting blade was designed and developed with a diameter of 381 mm and 3 mm thickness (Table 2). The diameter of the cutting blade was determined based on the maximum cross thickness of the selected fish varieties. The cutting blade was mounted on a shaft (350 mm length and 20 mm diameter) using bush, nuts and bolts. The center of the cutting blade was placed at a height of 110 mm from the base of the cutting section.

The rollers are attached next to the feeding section, which guides the fish toward the cutting blade. The roller is made of nylon, with dimensions of 120×40×10 mm for height, outer diameter, and inner diameter, respectively. The roller is placed at an inclination with the compression spring, which enables it to adapt to different sizes and lengths of fish.

Two horizontal adjustable plates are placed on both sides of the cutting blade. Adjustable plates of 300 × 90 mm in length and height, respectively are provided to guide the different size fish and provide provisions to facilitate different cuts. The adjustable plates are attached in the outer cover using bolts and screw nuts. The steak thickness can be changed by adjusting the screw.

Fig. 2. Three-dimensional CAD diagram of major components of Power-Operated Fish cutting machine.



a) serrated circular cutting blade b) Supporting rollers and c) Adjustable plates

The power requirement was calculated based on the force needed to cut the fish. Preliminary studies using a Shimadzu EZ Test Food Texture Analyzer, determined the maximum cutting strength (force) required to be 52.532 N. The cutting strength analysis was done for all three selected fish varieties. The power requirement also depends on the torque to be generated on the main shaft (20 mm diameter) due to the rotation of the cutting blade to cut the fish, which in turn is influenced by the radius of the cutting blade. The designed cutting blade had a diameter of 381 mm (r - 190.5 mm). The torque (¬) to be made available at the center of the shaft was calculated by multiplying the force (F) required to cut the fish and the radius (r) of cutting blade.

Torque (¬) = F × r … (1)

Where,

F= Force (N),

r = radius (cm)

= 52.532 × 19.05

= 1000.73 N.cm (10.0073 Nm)

The values of torque (10.0073 Nm) and the revolutions of the rollers which is equal to the rpm of motor through the chain and sprocket mechanism i.e., 1200 rpm (957 m/min), is substituted in the following equation, to obtain the power requirement of the fish cutting machine.

$$P = \frac{n \times \pi \times T}{60} \quad \dots (2)$$

Where,

P – Power required (W),

n – Speed of the shaft (rpm)

$$P = \frac{\pi \times 957 \times 10.0073}{60}$$

$$= 501.44 \text{ W}$$

P = 0. 501.44 kW

P = 0.501 kW < 0.746 kW (1 hp)

The power requirement was calculated to be 501.44 W (0.501 kW). Hence, commercially available, one hp three phase electric motor (0.746 kW, 1200 rpm) was selected for designing the fish cutting machine.

The feed hopper, made of SS 304 material, comprises two main components: the fish holder and the conveyor. The holder measures 200 mm in length and 252 mm in width, positioned 400 mm above the cutting section. A sloped conveyor plate, set at an angle of 45°, is welded to the feed holder, extending to the cutting section to enhance fish friction. Supporting rollers are attached to the feeding section to prevent fish rotation. The machine's components are mounted on a rectangular frame measuring 450 × 315 × 650 mm (height × width × length). This frame, fabricated from 5 mm thick mild steel, ensures stable and continuous operation of the cutting blade. Stainless steel sheets are welded at strategic positions to provide support and accommodate various elements of the fish cutting ma-

Table 1. Experimental design for the performance evaluation of developed power-operated fish cutting machine

Independent variables	Coded levels		
	-1	0	+1
Rotational speed of cutting blade (rpm)	1000	1100	1200
Inclination angle of feeding section (°)	120°	140°	160°
Thickness of steaks (mm)	20	40	60

chine.

The main frame integrates the feed hopper and discharge units, which are welded together and fixed at the supporting frame. Constructed from mild steel, it features provisions for easy fish movement during the cutting process. The supporting structure is designed to handle fish safely and securely. The fish cutter is enclosed on all sides with SS 304 sheets. The feeding section features an easily operable door-type design. Each side of the outer cover is individually designed and attached to the main frame using stainless steel bolts and nuts. This comprehensive enclosure enhances operator safety and provides protection against potential injury.

Fig. 3. Developed power-operated cutting machine a) Iso-metric view, b) Top view, c) side view, d) Front view, e) Power transmission, f) Iso-metric view with outer cover and g) Front view with outer cover

The optimization of fish cutting process in power-operated fish-cutting machine was performed to know the effect of independent variables such as rotational speed of cutting blade (1000, 1100, 1200 rpm), inclination angle of feeding section (120°, 140°, 160°) and distance between the cutting blades (20, 40, 60 mm), on responses cutting efficiency, cutting time, and steak damage across different fish species. The independent variables and their value ranges were selected based on literature review and preliminary trials conducted using the selected fish varieties.

For the preparation of fish for cutting experiments, fresh fish were descaled and gutted using a sharp knife by manual method. The descaled and eviscerated fish were cleaned using potable water. Next, the fish were fed through the inlet of the developed power-operated fish-cutting machine. The inclination angle of the inlet could be adjusted to three different sliding positions relative to the continuously rotating disc-cutting blade. The cutting blade rotating speed was controlled with an adjustable frequency control setup. The fish were moved through the cutting section where it was cut into steaks by the rotating blade. These steaks were collected at the outlet and taken for further analysis. Experiments followed the IS (7897-1975) test code for chaff cutting.

Response Surface Methodology (RSM) for three factor, three level Box-Behnken Design (BBD) was employed to analyse the effect of rotational speed of cutting blade (A), inclination angle of feeding section (B), distance between the cutting blades (C), on dependent variables such as cutting efficiency, cutting time, and steak damage across different fish species (Ali, Singh, & Sharma, 2016). The independent variables of the experiments and their levels used in the present study are shown in Table 1.

Seventeen experimental runs with 5 center points were obtained using Design-Expert (DX7) software,

Table 2. Morphological characteristics of selected fish species

Fish species	Average dimensions (mm)						
	Overall length	Length of head	Length of body	Length of tail	Maximum thickness	Maximum cross thickness	Weight (g)
Catla fish	388.3 ± 5.25	76.48 ± 3.96	245.5 ± 8.07	66.22 ± 4.31	49.26 ± 4.25	38.14 ± 3.90	718.8 ± 46.39
Northern whiting	300.7 ± 6.58	78.05 ± 4.23	44.46 ± 5.03	178.2 ± 3.47	38.13 ± 3.83	15.91 ± 5.48	341.52 ± 58.44
Flying fish	293.46 ± 9.45	73.34 ± 4.36	73.93 ± 4.93	146.18 ± 6.47	46.61 ± 2.60	40.94 ± 3.65	446.33 ± 33.95

further data analysis and optimization process were also done using the same software. Experimental design combinations and their response values are shown in Table 3.

To probe the effect of independent variables and also their interactive effects on the response parameters, a quadratic equation was used as below:

$$Y = b_0 + \sum_{j=1}^{k} b_j X_j + \sum_{j=1}^{k} b_{jj} X_j^2 + \sum\sum_{i<j} b_{ij} X_i X_j \quad ....(3)$$

Where Y is the response parameter evaluated by model, k is the number of parameters, b_0, b_j, b_{jj}, b_{ij} are the constant, linear, second order and interaction coefficients respectively. X_i and X_j are the independent coded parameters.

Statistical analysis of variance (ANOVA) was performed by fitting the experimental data in Eq. (3) to analyze the statistical significance of each response at 1% significance level ($p<0.01$). The model adequacy was investigated using R^2, adjusted-R^2, predicted-R^2, sum of squares and lack-of-fit of models.

To find the optimal solutions, desired goals were set up (maximized cutting efficiency and minimized cutting time and steak damage) and merged into a desirability function D(x), given by:

$$D(x) = (Y_1 \times Y_2 \times Y_3 \ldots \ldots \times Y_i)^{1/n} \quad \ldots \ldots (4)$$

Where Y is the response factor and n is the number of response factors (i = 1, 2, 3…., n)

The desirability value ranges from zero to one. It shows how well the response factors are matched with independent variables. In order to encapsulate the relationship between the independent and response parameters, results of the fitted equation of each response parameter was demonstrated in three-dimensional surface graphs.

The efficiency of fish cutting machine was estimated based on the total number of fish steaks collected at the outlet of the machine and the number of damaged steaks from the five whole fish. The cutting efficiency (Gaikwad et al., 2017; Karate, Kamble, & Kad, 2022) was calculated using the following equation:

$$\alpha \text{ (cutting efficiency, \%)} = \frac{Nt - Nd}{Nt} \times 100 \quad ...(5)$$

Where,

α = cutting efficiency (%),

Nt = number of total steaks,

Nd = number of damaged steaks.

The cutting time was determined by recording the time required to cut five fish with three replications. A stopwatch was used for this purpose (Nayak & Rayaguru, 2017).

The damage percentage caused to the fish cut pieces during cutting process was determined by visual observation. The damage caused by fish cuts is due to friction and crushing of fish on the blade. The percentage of fish cuts damaged was calculated over the total number of cuts using the following formula (Gaikwad, 2015; Reddy et al., 2024).

Table 3. Experimental design combinations and responses of fish cutting process in power-operated fish cutting machine

Std	Factor 1 A: Rotational speed (rpm)	Factor 2 B: Inclination angle (°)	Factor 3 C: Distance between the cutting blades (mm)	Response 1 Cutter efficiency (%)			Response 2 Cutting time (Sec)			Response 3 Damage percentage (%)		
				Catla fish	Silver sillago	Flying fish	Catla fish	Silver sillago	Flying fish	Catla fish	Silver sillago	Flying fish
1	1000	120	40	89.43	89.16	85.44	20	18	22	8.33	3.33	2.45
2	1200	120	40	93.72	98.59	99.54	7	5	6	14.65	10.25	7.44
3	1000	160	40	82.28	80.22	86.24	36	26	20	4.54	3.66	3.33
4	1200	160	40	88.54	93.35	95.69	19	9	6	10.63	13.66	8.33
5	1000	140	20	90.24	84.07	86.36	17	21	25	10.21	7.44	3.33
6	1200	140	20	96.11	97.48	98.99	10	6	8	10.54	14.44	8.33
7	1000	140	60	83.88	83.37	89.62	25	22	19	12.33	4.21	3.33
8	1200	140	60	85.74	97.88	97.21	31	7	5	2.83	12.21	8.33
9	1100	120	20	80.34	94.61	93.39	27	10	19	10	10.33	6.53
10	1100	160	20	95.98	83.58	90.66	9	15	17	16.87	12.33	6.53
11	1100	120	60	79.38	93.64	93.81	39	9	11	3.03	11.63	7.44
12	1100	160	60	91.22	85.62	94.84	15	17	12	9.45	9.45	6.53
13	1100	140	40	81.92	90.45	92.5	35	11	15	0	11.63	7.44
14	1100	140	40	87.15	89.99	92.44	21	13	13	8.33	8.25	7.44
15	1100	140	40	89.57	91.55	91.83	19	13	17	11.63	10	6.53
16	1100	140	40	97.87	90.81	90.05	12	13	15	14.96	10.33	6.53
17	1100	140	40	81.43	88.29	92.13	16	12	15	13.33	11.63	7.44

$$D_p = \frac{Nd}{Nt} \times 100 \quad \text{... (6)}$$

Where,

Dp = damage percentage (%)

Nd = number of damages in fish steaks,

Nt = total number of fish steaks.

The operation cost of developed machine was assessed by comparing it to traditional manual fish cutting with a knife. The cost of operation of a power-operated fish-cutting machine was calculated based on the method described by (Delfiya et al., 2019; Obinna & Oluka, 2016; Yousif, Dahab, & El Ramlawi, 2013). The following equation was used to calculate the total operating cost per hour:

Total operating cost/hour =

$$\frac{\text{Maintenance cost}}{\text{Hour}} + \frac{\text{Labour cost}}{\text{Hour}} \quad \text{... (7)}$$

Where,

Maintenance cost (INR/h) =

$$\frac{\text{(percentage of maintenance x price of machine)}}{\text{(100 x annual hours of use)}} \quad \text{... (8)}$$

The percentage of maintenance is taken as 15% of the machine cost.

Results and Discussion

The morphometric characteristics of the selected fish species which are essential for the design and development of the power-operated fish cutting machine were determined and presented in Table 2. To analyze these parameters three kilograms of fish were used and the average values (n=3) are reported in Table 2. Based on Gaikwad et al. (2017) study, the average cross-distance between the cutting blades, overall length, and maximum distance between the cutting blades of fish are considered as factors influencing the dependable variables during performance evaluation.

Table 4. Analysis of variance for the effects of different combinations of A, B, and C on cutting efficiency, cutting time, and steak damage

Source	Cutting efficiency						Cutting time						Damages to fish steaks					
	Catla fish		Silver sillago		Flying fish		Catla fish		Silver sillago		Flying fish		Catla fish		Silver sillago		Flying fish	
	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value	F-value	P-value
Model	14.49	0.001	28.48	0.0001	30.42	< 0.0001	22.69	0.0002	123.64	< 0.0001	18.08	0.0005	8.83	0.004	10.7	0.0025	22.77	0.0002
A	92.59	< 0.0001	175.04	< 0.0001	242.87	< 0.0001	183.64	< 0.0001	913.04	< 0.0001	106.7	< 0.0001	68.12	< 0.0001	73.85	< 0.0001	175.26	< 0.0001
B	11.24	0.01	75.85	< 0.0001	2.86	0.13	9.97	0.01	158.51	< 0.0001	0.17	0.69	0.009	0.92	0.91	0.36	0.32	0.58
C	5.76	0.04	0.04	0.84	4.69	0.06	0.15	0.70	2.28	0.17	43.71	0.0003	2.72	0.14	3.59	0.09	0.36	0.56
AB	0.3061	0.59	1.88	0.21	5.48	0.05	5.85	0.04	8.12	0.02	0.76	0.40	0.0163	0.90	1.38	0.27	0.0001	0.99
AC	0.015	0.90	0.16	0.69	6.44	0.03	0.13	0.72	0	1	4.18	0.08	0.2008	0.66	0.14	0.71	0	1
BC	2.45	0.16	1.24	0.30	3.58	0.10	0.03	0.85	4.57	0.07	0.76	0.40	2.42	0.16	2.53	0.15	0.72	0.42
A^2	6.72	0.03	1.22	0.30	0.03	0.84	3.36	0.10	23.97	0.001	0.20	0.66	4.76	0.06	9.78	0.01	25.28	0.00
B^2	5.74	0.04	0.86	0.38	0.004	0.94	0.24	0.63	1.54	0.25	3.8	0.09	1.43	0.27	1	0.34	2.14	0.18
C^2	6.27	0.04	0.13	0.72	7.8	0.02	0.47	0.51	0.04	0.83	2.72	0.14	0.0862	0.77	3.57	0.10	0.05	0.81
Lack of Fit	5.22	0.07	1.52	0.33	0.92	0.50	6.33	0.05	0.10	0.95	2.08	0.24	3.03	0.15	0.72	0.58	1.34	0.37
Std. dev.	2.00		1.35		0.9930		2.68		0.7020		1.22		2.00		1.31		0.5339	
Mean	87.93		90.16		92.40		21.06		13.35		14.47		9.51		9.69		6.31	
R^2	0.9491		0.9734		0.9751		0.9669		0.9937		0.9803		0.9191		0.9323		0.9670	
Adj. R^2	0.8836		0.9392		0.9430		0.9242		0.9857		0.9549		0.8150		0.8452		0.9245	
CV (%)	2.27		1.50		1.07		2.76		1.26		1.46		2.10		1.55		1.46	

A - Rotational speed (rpm), B - Inclination angle (°), and C - Distance between the cutting blades of steaks (mm)

Based on the results reported in Table 2, the main frame was designed with the dimensions of 650 × 450 ×550 mm to avoid the jamming and deviation of fishes from the cutting line. The maximum overall length (388.3 ± 5.25 mm) of fish where the length of the main frame design has a 350 mm feeding section to the cutting point and 300 mm length after the cutting point to the discharge outlet. The maximum thickness (49.26 ± 4.25 mm) and maximum cross thickness (38.14 ± 3.90) were used to determine the radius of the cutting blade (120 mm) and position of the main shaft placed (120 mm) from the cutting bottom. The machine was designed to cut the length of 100 to 450 mm and cross distance between the cutting blades of maximum 100 mm of all variety of fishes.

Each response variable (Y) was modeled using a quadratic response surface approach. Table 3 presents the experimental combinations with the factors (A, B, and C) used for optimization of fish cutting process. Models were developed through regression analysis, and their statistical significance was assessed using analysis of variance (ANOVA). Table 4 lists the ANOVA results of the quadratic model and the significance of each response factor, estimated regression coefficients of the quadratic model for three responses (Y_1, Y_2, Y_3), along with R^2 and coefficient of variation (CV) values. A good model is characterized by CV values, high R^2 values (raw and adjusted), predicted-R^2, and lack-of-fit of model (Priyadharsini & Dawn, 2023). Results showed R^2 values for the response variables were greater than 0.90, indicating the models effectively explained the responses. For a good fit, R^2 should be higher than 0.80 (Neethu et al., 2024; Venkateshwari et al., 2024). ANOVA results (Table 4) demonstrated that each response model was significant at $p < 0.01$. The lack of fit tests indicated that the models were adequate for predicting cutter efficiency, cutting time, and damage percentage, as the lack of fit value is not significant for all responses. It is also evident from Table 4 that the values of R^2, adjusted-R^2, and predicted-R^2 of all responses are high which represents good relationship between the experimental and predicted values. Lower CV values also indicate a better prediction of the model.

The interaction effect of factors on the cutting efficiency of Catla is shown in Fig. 4. Increasing the rotational speed from 1000 to 1200 rpm increased the cutting efficiency from 79.38 % to 97.87 %. However, increasing the inclination angle from 120° to 160° reduced cutting efficiency due to a decrease in sliding speed (Fig. 4). The regression equation describing the relation between cutting efficiency for Catla and independent variables is given by:

Cutting efficiency for Catla =

$$88.99 + 6.80A - 2.37B - 1.69C + 0.5525AB + 0.1225AC + 1.56BC + 2.52A^2 - 2.33B^2 - 2.44C^2 \quad \ldots (9)$$

Cutting efficiency was directly proportional to rotational speed but negatively correlated with inclination angle, similar to the findings by Gaikwad (2015) & Simonyan and Yiljep (2008).

The cutting efficiency of Silver sillago was significantly improved by the distance between the cutting blades (20 to 60 mm) and decreased with increasing inclination angle (120° to 160°) (Fig. 4). The regression equation is as follows:

$$\text{Cutting efficiency for Silver sillago} = 90.22 + 6.31A - 4.15B + 0.0963C + 0.9250AB + 0.2750AC + 0.7525BC + 0.7247A^2 - 0.6128B^2 - 0.2427C^2 \quad \ldots (10)$$

Cutting efficiency for Flying fish increased with rotational speed and was slightly varied at 1100 rpm (Fig. 4). The model equation showing relationship between cutting efficiency for Flying fish and independent variables is given by

Table 5. Cutting time and damage to steaks using the power-operated fish cutting machine and manual cutting method

Fish varieties	Cutting time for one kg of fish (min)		Damage to steaks (%)	
	Cutting machine	Manual cutting method	Cutting machine	Manual cutting method
Labeo catla	1.55±0.26	4.33±0.16	9.16±0.50	26.49±1.44
Sillago sihama	1.23±0.10	4.20±0.23	7.62±0.87	22.47±1.31
Exocoetidae	1.38±0.19	5.52±0.18	6.96±1.13	18.23±1.72

Cutting efficiency for Flying fish = 91.79 + 5.47A - 0.5937B + 0.7600C - 1.16AB - 1.26AC + 0.9400BC - $0.0963A^2$ + $0.0337B^2$ + $1.35C^2$ … (11)

The model had an R^2 value of 0.9751, indicating a good fit of model to the data. Efficiency was significantly affected by the distance between the cutting blades, thinner steaks (20 mm) had higher cutting efficiency. The inclination angle negatively correlated with cutting efficiency, affecting the conveying speed and cutting line precision. Optimal efficiency was achieved at a 120° angle, with higher angles reducing the sliding coefficient and resulting in improper cuts.

Overall, the study showed that the rotational speed significantly improved the cutting efficiency across all fish species, while inclination angle and distance between the cutting blades have varying effects on the response. Fish length, height, and thickness significantly affected the cutting efficiency. Optimal conditions were identified for each species, demon-

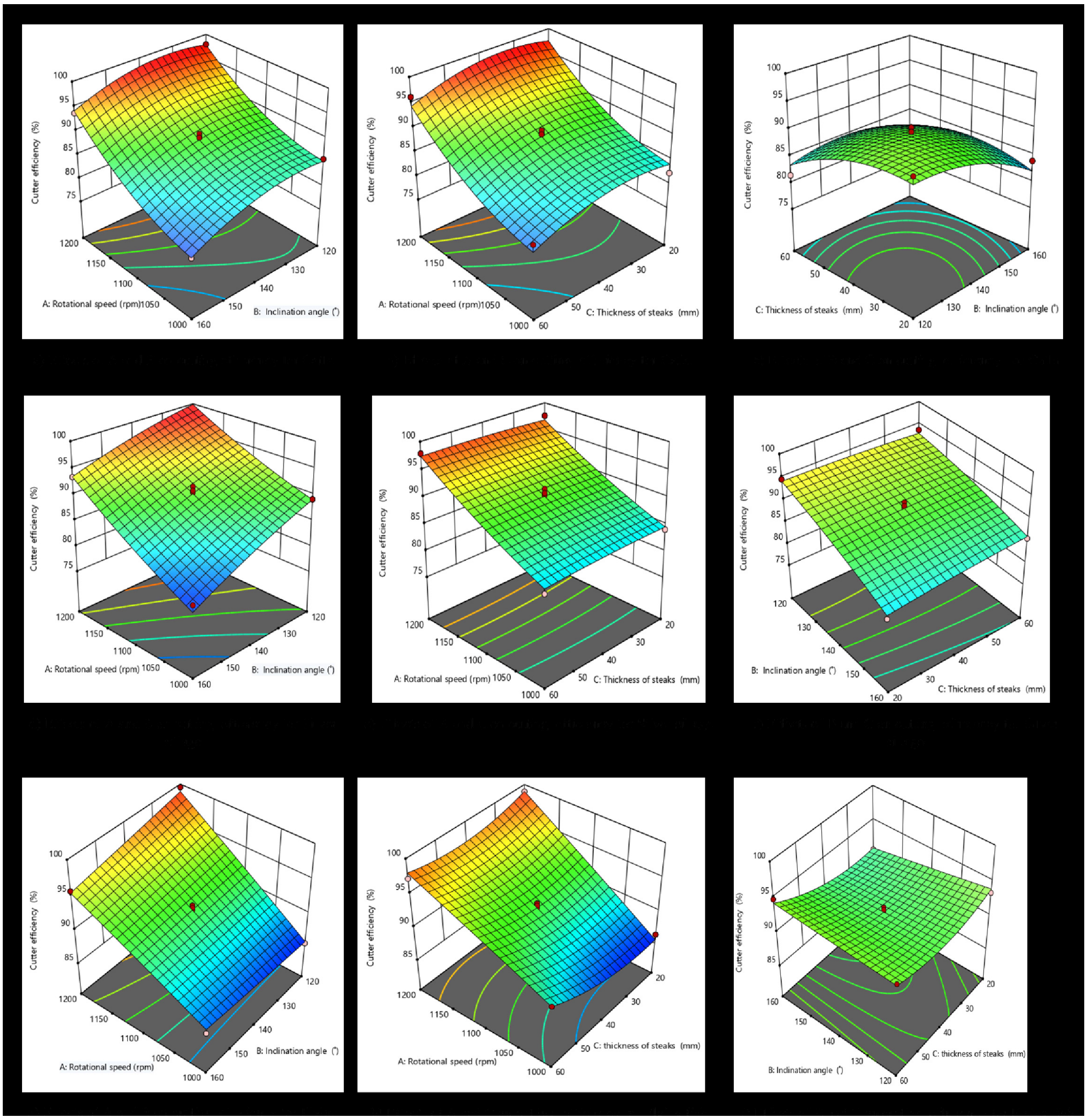


Fig. 4. Effect of Rotational Speed (A), Inclination Angle (B), and Distance Between the Cutting Blades (C) on cutting efficiency of the selected fish varieties

strating the model accuracy in predicting cutting efficiency.

Cutting time for Catla was significantly influenced by rotational speed, inclination angle, and blade distance. Increasing rotational speed from 1000 to 1200 rpm reduced cutting time from 39 to 7 seconds. An increased inclination angle from 120° to 160° increased cutting time (Fig. 5). The regression equation with an R^2 value of 0.9669 is:

Cutting time for Catla = $19.20 - 12.87A + 3.00B + 0.3750C - 3.25AB + 0.5000AC + 0.2500BC + 2.40A^2 + 0.6500B^2 + 0.9000C^2$ … (12)

Cutting time was inversely proportional to rotational speed but positively correlated with inclination angle and blade distance. This agrees with Kamaruzzaman et al. (2020), who found that increased rotational speed reduces cutting time.

For Silver sillago, increasing the rotational speed from 1000 to 1200 rpm reduced cutting time from 26 to 5 seconds (Fig. 5). The regression equation for Silver sillago cutting time is:

Cutting time for Silver sillago = $12.40 - 7.50A + 3.13B + 0.3750C - 1.00AB + 0.0000AC + 0.7500BC + 1.67A^2 + 0.4250B^2 - 0.0750C^2$ … (13)

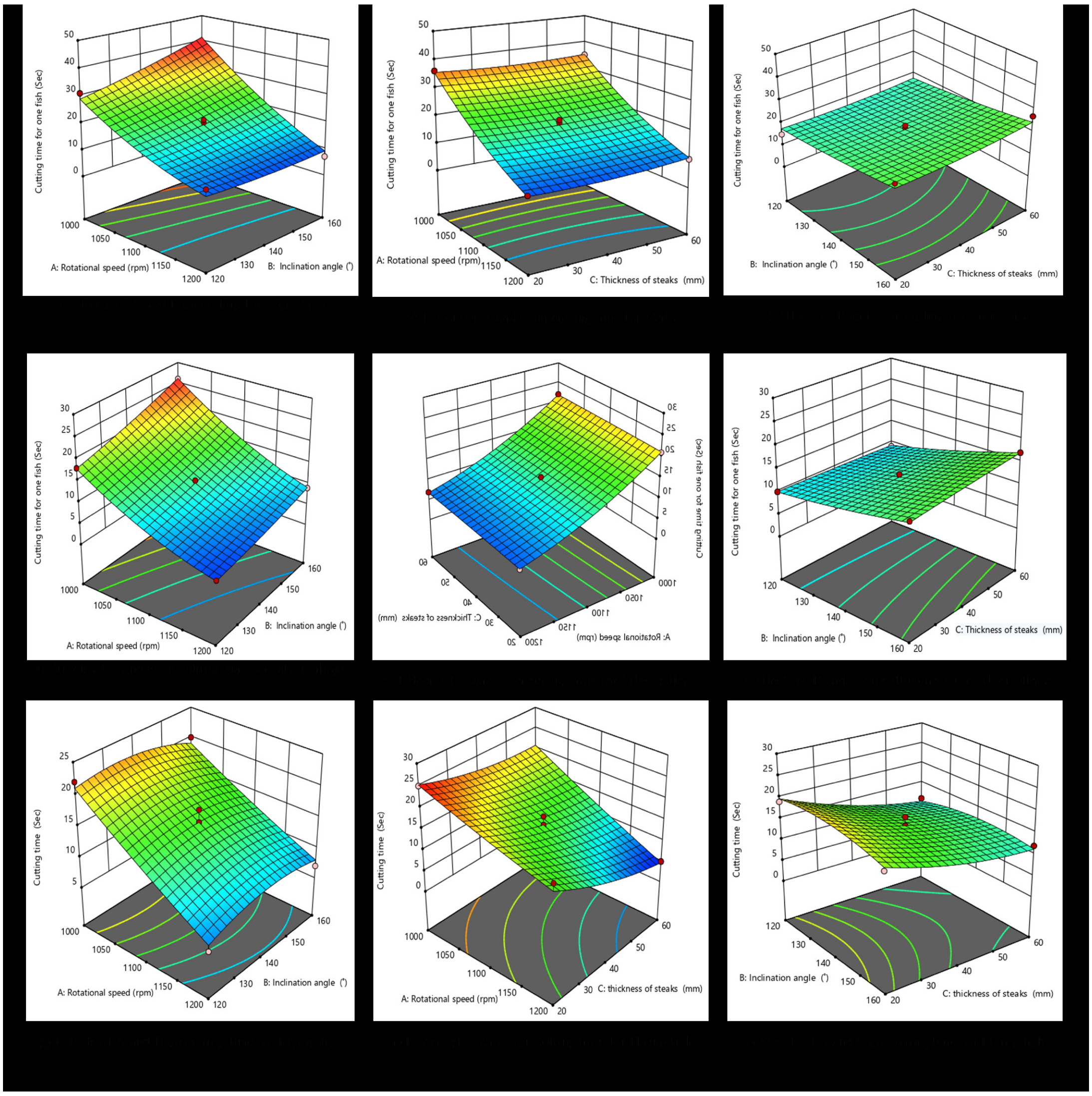


Fig. 5. Effect of Rotational Speed (A), Inclination Angle (B), and Distance Between the Cutting Blades (C) on the cutting time of the selected fish species

Cutting time was inversely proportional to rotational speed and directly proportional to inclination angle and blade distance.

For Flying fish, the cutting time was significantly affected by all factors. Increasing rotational speed from 1000 to 1200 rpm reduced cutting time from 22 to 5 seconds. An increased inclination angle from 120° to 160° increased cutting time (Fig. 5). The response surface model with an R^2 value of 0.9669 is:

$$\text{Cutting time for Flying fish} = 15.00 - 6.25A - 0.2500B - 4.00C + 0.7500AB - 1.75AC + 0.7500BC + 0.3750A^2 - 1.63B^2 + 1.38C^2 \quad \ldots (14)$$

Cutting time was inversely correlated with rotational speed, inclination angle, and blade distance. Increasing the rotational speed significantly reduced cutting time, demonstrating the importance of speed in optimizing the cutting efficiency.

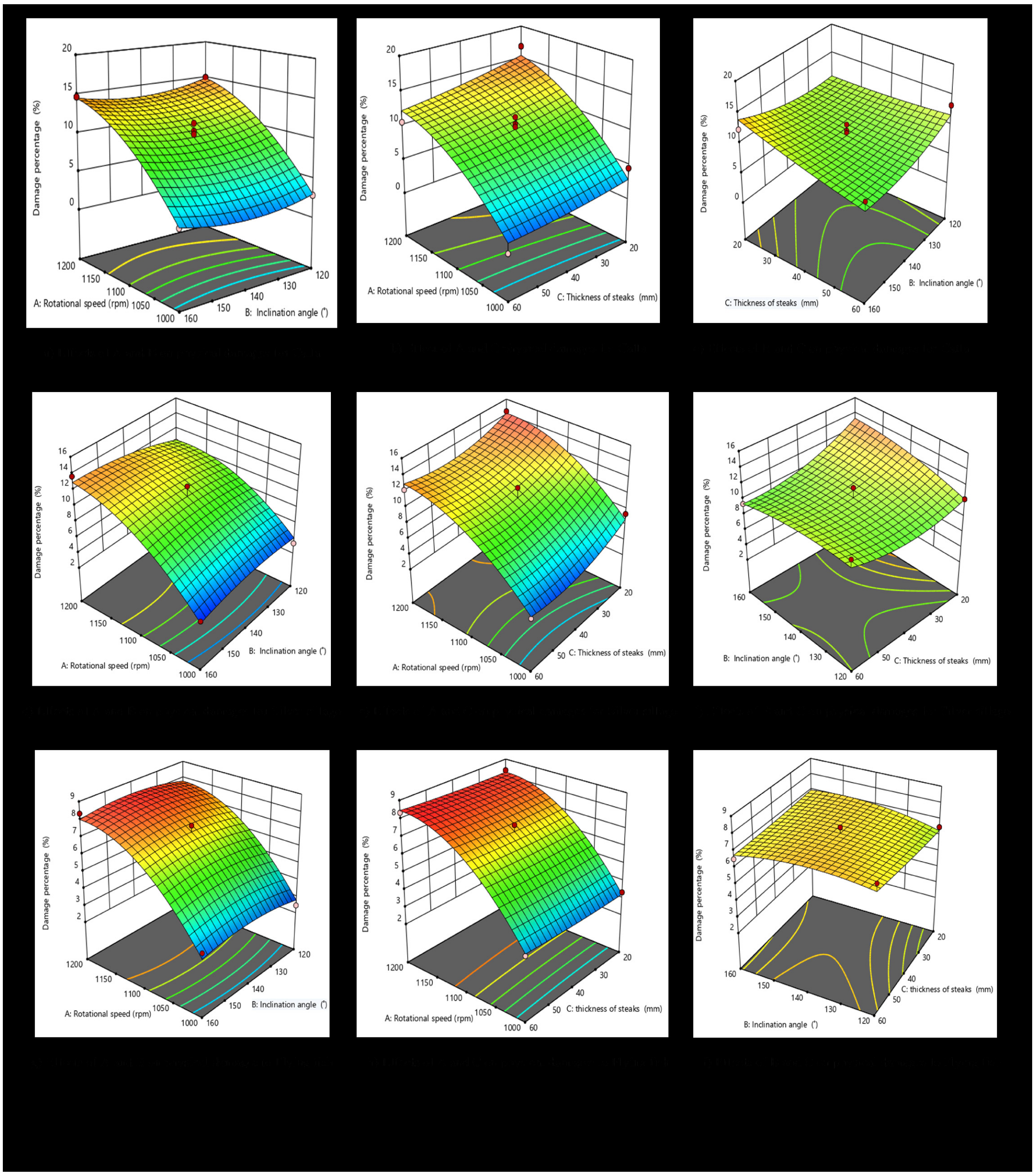


Fig. 6. Effects of Rotational Speed (A), Inclination Angle (B), and Distance Between the Cutting Blades (C) on the damage to fish steaks of the selected fish varieties

The damage to Catla fish steaks increased with higher rotational speeds and decreased blade distance. Increasing the rotational speed from 1000 to 1200 rpm increased damage from 0% to 16.87% (Fig. 6). The regression equation is given as:

Damage in Catla steaks = 9.83 + 5.83A - 0.0700B - 1.17C - 0.1275AB - 0.4475AC - 1.55BC - 2.12A² + 1.17B² + 0.2858C² … (15)

Damage was directly proportional to rotational speed and inversely related to inclination angle and blade distance, and the results are consistent with the reports by Kamaruzzaman et al. (2020).

For Silver sillago, increasing the rotational speed from 1000 to 1200 rpm increased damage from 3.33% to 14.44%. Damage also increased with decreasing blade distance from 60 to 20 mm. Minimum damage occurred at 1000 rpm, 140° angle, and 60 mm blade distance (Fig. 6). The model equation is given by,

Damage to Silver sillago = 10.37 + 3.99A + 0.4450B - 0.880C + 0.770AB + 0.250AC - 1.05BC - 2.00A² - 0.6415B² + 1.21C² … (16)

Damage was directly proportional to rotational speed and inclination angle and inversely related to blade distance.

For Flying fish, increasing the rotational speed from 1000 to 1200 rpm increased the damage of steaks from 2.45% to 8.33% (Fig. 6). Damage also increased with decreasing blade distance from 60 to 20 mm. The model equation is:

Damage to Flying fish steak = 7.08 + 2.50A + 0.1075B + 0.1138C + 0.0025AB + 0.0000AC - 0.2275BC - 1.31A² - 0.3805B² + 0.0620C² ... (17)

Damage was directly proportional to rotational speed, inclination angle, and blade distance. Increasing the rotational speed consistently increased the damage to steaks, highlighting the importance of balancing speed with other factors for optimal cutting quality.

Numerical optimization using the desirability function identified the optimum conditions for cutting selected fish species. Constraints for factors (independent variables) were kept within a range, and responses (dependent variables) such as cutting efficiency was kept as maximum, cutting time, and damage in fish steaks were kept in minimum range. The optimal processing conditions and responses were selected based on the maximum desirability values.

The optimum process parameters were observed as 1200 rpm, 144°, and 30 mm distance between the cutting blades, with 96.53% cutting efficiency, 8 seconds cutting time, and 14.2 mm damage to steaks for Catla with a desirability value of 0.977. The predicted and the experimental values were compared and found the deviation of 1.36% for cutting efficiency, 0% for cutting time, and 2.0% for steak damage.

Similarly, for Silver sillago, the optimum conditions were found to be 1200 rpm, 120°, and 40 mm, with 99.59% cutting efficiency, 4.29 seconds cutting time, and 10.2% damage to steaks and a desirability value of 0.991. The experimental values differed by 1.1% for cutting efficiency, 1.41% for cutting time, and 1.91% for steak damage. For Flying fish, the optimum cutting process conditions were observed as 1200 rpm, 123°, and 60 mm with 97.27% cutting efficiency, 3.32 seconds cutting time, and 8.27% damage to steaks and a desirability value of 0.976. The experimental values differed by 1.6% for cutting efficiency, 1.8% for cutting time, and 1.1% for steak damage.

The actual values were very close to the predicted values, with an error percentage of less than 2%, indicating that the model is a good fit for the prediction of optimum cutting process conditions of all fish species. The processing conditions of the power-operated fish cutting machine optimized using three different fish species showed that each type of fish required a specific combination of blade rotation speed, cutting angle, and distance between the cutting blades for best performance. Cutting efficiency exceeded 96%, cutting times were under 8 seconds, and damage to the steaks was minimal (less than 15%) for all three fish species. Notably, the actual results closely matched the predicted values, confirming the accuracy of the models in optimizing the cutting process parameters.

The final performance evaluation of the power-operated fish cutting machine revealed significant improvement in both cutting time and steak quality compared to traditional manual cutting methods.

Table 5 present the comparative results for three different fish varieties.

The power-operated fish cutting machine demonstrated substantially reduced cutting times across all tested fish species. For *Labeo catla*, the machine required only 1.55±0.26 min to process one kilogram, compared to 4.33±0.16 min using traditional methods. Similar improvements were observed for *Sillago sihama* (1.23±0.10 min vs. 4.20±0.23 min) and Exocoetidae (1.38±0.19 min vs. 5.52±0.18 min). These results indicate that the power-operated machine offers a 64.2, 70.7 and 75.0 % reduction in cutting time for *Labeo catla*, *Sillago sihama* and Exocoetidae respectively, when compared to traditional manual cutting methods.

In addition to improved cutting speed, the power-operated machine also resulted in significantly less damage to the fish steaks. The percentage of damaged steaks was reduced by 65.4% for *Labeo catla* (9.16±0.50 vs. 26.49±1.44%), 66.1% for *Sillago sihama* (7.62±0.87 vs. 22.47±1.31%) and 61.8% for Exocoetidae (6.96±1.13 vs. 18.23±1.72%) when compared to traditional cutting methods. The significant time savings and reduction in steak damage achieved by the power-operated machine suggest its potential to greatly enhance both efficiency and quality in fish processing operations. These improvements could be particularly beneficial for both small-scale fisheries and larger industrial settings, potentially leading to increased productivity and higher-quality fish products.

A local fish market survey in Coimbatore revealed that manual fish cutting takes 200 to 250 seconds/kg and costs Rs. 15/kg, producing 17.5 kg of steaks/hour. In contrast, the power-operated fish-cutting machine has an operating cost of Rs. 1.38/kg and produces 35 kg/hour, saving Rs. 13.62/kg compared to manual methods.

This study examined the impact of rotational speed, inclination angle, and distance between the cutting blades on the performance of a power-operated fish-cutting machine. Results showed that these factors significantly affected the cutting efficiency, cutting time, and damage percentage ($p<0.01$). Optimal parameters were identified as 1200 rpm, 144°, and 30-mm distance between the cutting blades for Catla; 1200 rpm, 120°, and 40 mm for Silver sillango; and 1200 rpm, 123°, and 60 mm for Flying fish. Optimal cutting efficiencies were 96.53% for Catla, 99.59% for Silver sillango, and 97.27% for Flying fish. A positive correlation was found between rotational speed and damage percentage, while thicker steaks resulted in less damage. The damage caused to the steaks were reduced by the use of developed machine, and further reduction in steak damage is possible by optimizing blade sharpness and the drive system. These findings suggest that the machine is promising for small scale fish processing units, offering high-quality steaks from descaled fish, at reduced costs. Future research should focus on scaling up the design, exploring diverse cuts, and conducting economic feasibility studies for small-scale processors and also integrating a descaling machine for smooth and fully automatic operations. Additionally, analyzing textural and cooking quality changes in steaks are also recommended.

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