



Integrating Garlic Derivatives to Optimize the Nutritional, Technological, and Sensory Profile of Fish Burgers

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Abstract

This study examines the integration of garlic derivatives—fresh garlic, garlic powder, and garlic peel—as partial substitutes for mackerel flesh to improve the nutritional, functional, and sensory qualities of fish burgers. The findings indicated that garlic derivatives enhanced culinary performance, moisture retention, and microbiological safety, while exhibiting significant antioxidant activity linked to their phenolic and flavonoid constituents. Garlic peel, a fiber- and mineral-rich by-product, showed the most promise for improving nutritional value and encouraging the use of waste as a resource through waste valorization. Fresh garlic and garlic powder had stronger antimicrobial effects, which made the product much safer to use and store. Sensory evaluation showed that moderate levels of substitution kept high consumer acceptability by balancing nutritional improvement with good taste and texture. The study presents an innovative, eco-efficient methodology for the development of functional fish products through the incorporation of garlic by-products within a circular food production system.

Keywords: Garlic derivatives, Nutritional enhancement, Antioxidant activity, cooking properties, Microbial inhibition.

1. Introduction

Recently, researchers highlight extensive research efforts directed toward improving the nutritional, functional, and sensory qualities of bakery products through the incorporation of unconventional ingredients and natural bioactive compounds. Several studies focused on fortifying bread and bakery items with nutrient-dense seeds, flours, and plant by-products such as amaranth, milk thistle, garden cress, chufa tubers, quinoa, naked barley, and psyllium, aiming to enhance dietary fiber, protein, and mineral content while supporting health conditions like obesity and celiac disease. [1-11] Other works explored the extraction and utilization of bioactive compounds from globe artichoke and the use of functional plant sources such as golden berries, carrot, and tangerine peel in baked goods. [1, 6, 10, 12] Additionally, some studies extended to evaluating the health benefits of natural ingredients in animal models, such as the anti-obesity activity of psyllium and the role of beetroot juice in combating iron deficiency anemia. [3, 13] Early contributions also examined the nutritional potential of young green barley and coriander seeds in bread making, reinforcing the significance of natural fortification strategies in improving staple foods. [14, 15] Collectively, these studies emphasize the growing interest in functional bakery products as vehicles for delivering enhanced nutrition and health benefits.

Garlic (*Allium sativum* L.) is cultivated globally across more than 1.44 million hectares, yielding over 28 million tons annually, with China as the leading producer. [16] Belonging to the Amaryllidaceae family, garlic is part of the *Allium* genus, which comprises over 1,000 species including onions, shallots, and leeks. [17] Garlic cultivars are generally classified into hardneck (*Ophioscorodon*) and softneck (*Sativum*) types. Hardneck varieties, known for their robust flavor and large cloves, are favored in cooler climates, while softneck varieties are more adaptable to warmer regions and offer extended shelf life. [18]

Beyond its culinary appeal, garlic has a long history of medicinal use. Its bioactive sulfur compounds, particularly allicin and diallyl sulfides, are credited with potent antioxidant, anti-inflammatory, and antimicrobial effects. [19] Rich in phenolics, vitamins, and minerals, garlic has demonstrated benefits in managing cardiovascular diseases, cancer, hypertension, and infections. [20, 21] These health-promoting effects vary with their form—fresh, dried, powdered, or as an extract—each exhibiting distinct chemical and functional profiles. [22]

Simultaneously, seafood—especially fish—is a valuable source of high-quality protein and polyunsaturated fatty acids, notably omega-3s, while being low in cholesterol and saturated fats. [23] Fish-based products such as fish burgers are increasingly recommended for individuals managing hypertension, hyperlipidemia, and cardiovascular risks. [24] The growing demand for nutritious yet convenient foods have made fish burgers an attractive option in fast-food and ready-to-eat markets.

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Earlier studies on the inclusion of garlic in meat and fish products have mostly focused on the application of fresh or powdered garlic as natural antioxidants or antibacterial agents to inhibit lipid oxidation and prolong product shelf life. For example, Majumdar et al. [25] showed that garlic extract made Thai pangas surimi more stable against oxidation and better for microbes. Mancini et al. [26] observed that garlic powder increased the quality of meat and lowered the number of microbes in rabbit burgers. In the same way, Yan et al. [27] said that fermented garlic powder made pigs grow better and made their meat taste better. Nonetheless, these investigations predominantly focused on garlic's preservation function rather than its extensive technical and nutritional benefits. Furthermore, garlic peel, although a plentiful by-product abundant in phenolics, minerals, and dietary fiber (Ifesan et al., [28] Azmat et al., [29]), has seldom been investigated as a functional component in fish-based products. Consequently, this study enhances existing knowledge by methodically comparing fresh garlic, garlic powder, and garlic peel as partial substitutes for fish meat in burger formulations, assessing their cumulative effects on chemical composition, antioxidant capacity, cooking efficacy, microbial safety, and sensory attributes. This integrative method offers novel insights into the valorization of garlic by-products and the development of nutritionally enhanced, sustainable, and functionally superior fish products.

This study proposes the enhancement of fish burgers through the incorporation of garlic derivatives-fresh garlic, garlic powder, and garlic peel. In particular, garlic peel, a typically discarded by-product, offers high fiber and mineral content, presenting a sustainable and functional ingredient. The aim is to assess the effects of these garlic forms on the chemical composition, cooking characteristics, microbiological quality, antioxidant potential, and sensory properties of fish burgers. By optimizing garlic derivative inclusion, the study seeks to develop a nutritionally enriched, microbiologically safer, and organoleptically acceptable fish burger aligned with modern consumer expectations.

2. Materials and Methods

2.1. Materials

Frozen Mackerel fish, garlic cloves (*Allium sativum*), and other fish burger ingredients (spice mix, soybean flour, rusk, salt, and sunflower oil) were purchased from a local market in Kafr El-Sheikh City, Egypt. Analytical-grade chemicals and solvents used in analyses were supplied by El-Gomhoria Company for Chemicals and Drugs (Tanta, Egypt). Standards and reagents including Trolox (TE; 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid), phenolic standards, and DPPH (2,2-diphenyl-1-picrylhydrazyl) were obtained from Sigma-Aldrich (St. Louis, MO, USA).

2.2. Preparation of Garlic Derivatives

Garlic cloves were peeled manually. The peels and cloves were washed thoroughly and pre-dried on paper towels for 1 hour at room temperature. The peeled garlic was divided into four portions: one was used as fresh garlic, while the remaining three portions were oven-dried at 60 °C for 18 hours to reach ~10% moisture. The dried cloves and peels were separately milled and sieved through a 60-mesh screen to obtain garlic powder. All samples were sealed in polyethylene bags and stored at 5 ± 2 °C until use.

2.3. Preparation of Fish Burgers

Fresh mackerel fish were first washed thoroughly, deheaded, filleted, and then minced using a meat grinder equipped with a 1 mm diameter plate (National Meat Grinder, Matsushita Electric Industrial Co., Japan). The minced fish was then blended with soybean flour, rusk, salt, sunflower oil, and a standardized spice mixture. To examine the impact of garlic derivatives on burger quality, ten formulations were prepared by partially replacing the fish meat with different levels of garlic-based ingredients. These included 2.5%, 5%, and 7.5% fresh garlic; 1%, 2%, and 3% garlic powder; and 2.5%, 5%, and 7.5% garlic peel powder. A control sample without garlic derivatives was also included for comparative analysis. The detailed formulation of all samples is presented in Table 1. The formulation process was adapted from the method of Badawy and Ali (2018)[30] with minor modifications to accommodate the test ingredients.

The components were mixed until a homogeneous texture was achieved, and the mixture was shaped into patties weighing approximately 100 g each. The patties were divided into two groups: one group was subjected to pan-frying, while the other was stored at -18 ± 2 °C for further chemical, microbiological, and sensory evaluations.

Table 1: Ingredients used to prepare fish burger formulations

Ingredients(g)	Formula									
	1(control)	2	3	4	5	6	7	8	9	10
Meat fish	85.5	83.0	80.5	78.0	84.5	83.5	82.5	83.0	80.5	78.5
Rusk	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Soya bean	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
Salt	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Spices mixture	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Fresh garlic	-	2.5	5.0	7.5	-	-	-	-	-	-
Garlic powder	-	-	-	-	1.0	2.0	3.0	-	-	-
Garlic peel powder	-	-	-	-	-	-	-	2.5	5.0	7.5

Note: Formulas 1–10 represent ten different fish burger treatments: Formula 1: is the control without any garlic derivative, Formulas 2–4: contain 2.5%, 5%, and 7.5% fresh garlic, respectively, Formulas 5–7: contain 1%, 2%, and 3% garlic powder, respectively, Formulas 8–10: contain 2.5%, 5%, and 7.5% garlic peel powder, respectively.

2.4. Thermal treatment

Burger samples were shallow-fried in sunflower oil at $160 \pm 10^\circ\text{C}$ for 6 minutes, flipping after 3 minutes per side using a stainless-steel pan. All analyses were performed in triplicate.

2.5. Chemical Composition Analysis

Moisture, crude protein, ether extract (fat), crude fiber, and ash were determined using AOAC (2010). [31] All analyses were performed in triplicate. Total carbohydrate content was calculated by difference:

$$\text{Carbohydrates (\%)} = 100 - (\text{moisture} + \text{protein} + \text{fat} + \text{ash} + \text{fiber})$$

2.6. Mineral Content Determination

Minerals (Ca, Mg, Zn, Fe) were analyzed using a Zeiss FMD3 atomic absorption spectrophotometer. Sodium and potassium were quantified using a flame photometer. Phosphorus was determined colorimetrically at 650 nm via the phosphomolybdate method. [32] All analyses were performed in triplicate.

2.7. Determination of Total Phenolic Compounds (TPC)

Phenolic compounds were extracted following Nara et al. (2006). [33] The Folin–Ciocalteu method [34] was used to quantify TPC, expressed as mg gallic acid equivalents (GAE) per 100 g dry weight. All analyses were performed in triplicate. The total phenolic content was determined using the subsequent linear calibration equation (1):

$$Y = 0.0126X + 0.0334 \quad (1)$$

where Y denotes the absorbance of the sample, whereas X corresponds to the phenolic content in mg GAE/100g dry sample.

2.8. Determination of Total Flavonoid Content (TFC)

The overall flavonoid content of the sample extracts was assessed using the methodology outlined by Kim et al. (2003). [35] All analyses were performed in triplicate. The flavonoid concentration was determined with a linear calibration formula (2):

$$Y = 0.0031X + 0.014Y \quad (2)$$

Y signifies the absorbance of the sample, whereas X indicates the flavonoid content, quantified as milligrams of quercetin equivalent per 100 grams of the dry sample.

2.9. Antioxidant Activity (DPPH Assay)

The antioxidant activity of fresh garlic, garlic powder, and garlic peel extracts was evaluated by the DPPH assay outlined by Binsan et al., (2008) [36] with a UV/VIS Spectrophotometer (PG Instruments T80). All analyses were performed in triplicate. The percentage inhibition (PI) of the DPPH radical was determined using the following formula (3):

$$PI = [(AC - AT) / AC] \times 100 \quad (3)$$

where AC = absorbance of the control at $t=1\text{min}$, AT = Absorbance of the sample + DPPH at $t = 16\text{ min}$.

2.10. Physical Properties of Burgers

Physical indices such as the Protein-Water Coefficient (PWC), Protein-Water-Fat Coefficient (PWFC), and Water-Protein Coefficient (WPC) were calculated by Badawy and Ali (2018). [30] Feder value was determined following Koots et al. (1994). [37] All analyses were performed in triplicate.

2.11. Texture Profile Analysis (TPA)

Texture characteristics of cooked fish burgers were measured using a TA.XTplus Texture Analyzer (Stable Micro Systems, UK) equipped with a 50 mm cylindrical probe. Each sample (cut to 2 cm thickness) was compressed twice to 50% of its original height at a crosshead speed of 1 mm/s. Parameters including hardness, cohesiveness, springiness, gumminess, and chewiness were automatically computed from the force–time curves according to Bourne (1978).

2.11.1. Color Measurement

Color parameters were measured using a **HunterLab colorimeter (Model D25, USA)** and expressed in the **CIE L^* , a^* , b^*** system, where L^* represents lightness, a^* redness/greenness, and b^* yellowness/blueness. Measurements were taken on the burger surface at three different points per sample, and the mean was reported. **Total color difference (ΔE)** was calculated relative to the control sample using the equation:

$$\Delta E = \sqrt{(L - L^*)^2 + (a - a^*)^2 + (b - b^*)^2}$$

2.12. Cooking properties

Cooking yield, cooking loss, moisture retention, oil uptake, and shrinkage were calculated using standard formulas (Badawy and Ali (2018)).[30] Three replicates were used for each treatment.

2.13. Microbiological Analysis

Microbiological evaluation was conducted to assess the antimicrobial effects of garlic derivatives in fish burgers by determining the Total Plate Count (TPC) and yeast and mold count. For TPC, 10 g of each burger sample were aseptically transferred into 90 mL of sterile distilled water, held at 4 °C for 30 minutes, and shaken for 2–3 minutes. Serial dilutions were prepared in 0.1% peptone water. From suitable dilutions, 1 mL was plated in duplicate onto nutrient agar (containing peptone, yeast extract, glucose, and agar) and incubated at 30 ± 1 °C for 48 hours. Colonies were counted and expressed as CFU/g, following FDA-BAM protocols.[38]

For Yeasts and Molds, diluted samples were plated on acidified Potato Dextrose Agar (pH 3.5) and incubated at 28 ± 1 °C for 48–72 hours. Colonies were counted based on morphology and reported as log CFU/g.[39, 40] All tests were performed in triplicate under aseptic conditions. These analyses evaluated the microbiological stability imparted by garlic derivatives in the burger formulations. All analyses were performed in triplicate.

We looked at coliform bacteria to see how clean the fish burgers were and how likely they were to get contaminated after they were made. We also looked at the total plate count and the number of yeast and mold.

Using Violet Red Bile Agar (VRBA), the coliform count was figured out according to the FDA-BAM (2020) and ISO 4832:2006 standards. As indicated for the total bacterial count, serial dilutions were made, and the plates were kept at 37 ± 1 °C for 24 to 48 hours. We counted the typical dark red colonies that were surrounded by a precipitated bile zone and reported them as colony-forming units per gram (CFU/g). Adding coliform analysis to formulations with garlic derivatives gave another sign of how well they were cleaned and how safe they were from germs.

2.14. Sensory evaluation

Ten trained panelists from the Food Technology Department at Kafrelsheikh University evaluated the sensory properties (color, odor, taste, tenderness, texture, and overall acceptability) using a 9-point hedonic scale.[41] Evaluations were performed under controlled conditions.

The sensory evaluation was done by a trained group of 10 people (six women and four men) from the Food Technology Department at Kafrelsheikh University. They were all between the ages of 24 and 45. We chose the panelists because they had already evaluated fish and meat-based items and could tell the difference between sensory qualities like color, smell, taste, tenderness, and texture. All participants attended two initial training sessions to ensure a consistent comprehension of rating criteria and to acclimate them to the 9-point hedonic scale, with “9” denoting extreme like and “1” indicating extreme disliking.

The examination took place in a sensory lab where the temperature was kept between 22 ± 2 °C, the lighting was neutral, and there were no smells. To reduce bias, each fish burger sample (about 25 g) was given a random three-digit code and served heated on white plates in a random order. Panelists cleaned their palates with water and unsalted crackers between sampling. The characteristics that were looked at were color, taste, smell, tenderness, texture, and general acceptance. The data were recorded as mean $\pm$ standard deviation, and a one-way ANOVA followed by Tukey's HSD test at $p < 0.05$ was used to analyze the data.

2.15. Statistical analysis

All experimental results were analyzed using one-way ANOVA. [42] Differences among means were considered significant at $P \leq 0.05$. Tukey's HSD test was applied for multiple comparisons. Data were reported as mean $\pm$ standard deviation (SD).

All experimental data were represented as mean $\pm$ standard deviation (SD) of three replicates. Before statistical analysis, the data were checked for normality and homogeneity of variances to make sure they met the requirements for ANOVA. We used the Shapiro–Wilk test to check if the data were normal and Levene's test to check if the variances were the same across treatment groups. Once these assumptions were met, a one-way analysis of variance (ANOVA) was used to see how varying quantities of garlic derivatives affected the observed parameters. We thought that differences between means were statistically significant at $p < 0.05$. For post-hoc multiple comparisons, we utilized Tukey's HSD test. We used SPSS software version 22.0 (IBM Corp., Armonk, NY, USA) to do the statistical analyses.

3. Results and Discussions

3.1. Proximate chemical composition of fresh garlic, garlic powder, and garlic peel

The proximate composition of fresh garlic, garlic powder, and garlic peel showed notable nutritional differences as presented in Table 2. Fresh garlic had the highest moisture content at 67.0%, while garlic powder and garlic peel had much lower values of 10.5% and 10.6%, respectively, due to dehydration. Protein content was similar in fresh garlic and garlic powder at 17.1% and 17.0%, but significantly lower in garlic peel at 7.1%, reflecting its fibrous and less nutrient-dense structure. Fat content ranged from 0.9% in garlic powder to 1.5% in garlic peel, while ash content was slightly higher in fresh garlic and garlic powder at 5.2% and 5.1%, compared to 4.2% in garlic peel. The most pronounced difference

was in crude fiber, with garlic peel containing 30.5%, compared to 3.9% in both fresh garlic and garlic powder. Garlic peel also recorded the highest total carbohydrate content at 87.2%, supporting its potential use as a valuable, fiber-rich ingredient in functional food formulations.

Table 2: Chemical composition of fresh garlic, garlic powder, and garlic peels (on dry weight basis).

Contents	Fresh garlic	Garlic powder	Garlic peel
Moisture	67.00±1.00 ^a	10.51±0.02 ^b	10.62±0.03 ^b
Dry matters	33.00±1.00 ^b	89.49±0.02 ^a	89.38±0.03 ^a
Crude protein	17.11±0.01 ^a	17.0±0.00 ^a	7.10±0.20 ^b
Ether extract	1.0±0.06 ^a	0.9±0.11 ^a	1.5±0.20 ^b
Ash	5.2±0.01 ^a	5.1±0.02 ^b	4.2±0.00 ^c
Crude fibers	3.9±0.01 ^b	3.9±0.01 ^b	30.5±0.00 ^a
Total carbohydrates*	76.7±0.05 ^b	77.0±0.13 ^c	87.2±0.00 ^a
Available carbohydrates	72.8±0.06 ^b	73.1±0.13 ^a	56.7±0.00 ^c

* Total carbohydrates were calculated based on dry weight without moisture

Values are expressed as mean ± standard deviation (n = 3).

Different superscript letters (a, b, c) in the same row indicate statistically significant differences among means at $P \leq 0.05$, according to one-way ANOVA followed by Tukey's HSD test.

These findings are consistent with earlier reports by Otunola et al. (2010), [43] who noted that garlic powder contains approximately 16.5–17.2% protein, 0.8–1.0% fat, and around 4% crude fiber—values closely matching those in this study (17.0% protein, 0.9% fat, 3.9% fiber). Similarly, Mariam and Devi (2016), [44] reported comparable protein levels in garlic powder. Garlic peel, often considered a waste by-product, demonstrated substantial nutritional value in this study, with 30.5% crude fiber and 87.2% carbohydrates—significantly higher than in fresh garlic (3.9% fiber, 76.7% carbs) and garlic powder (3.9% fiber, 77.0% carbs). [28] also emphasized the functional potential of garlic peel due to its high fiber content and low fat. These results confirm that drying enhances nutrient concentration and that garlic peel, in particular, can serve as a valuable, fiber-rich ingredient in food formulations aimed at improving dietary fiber intake and promoting functional health benefits.

3.2. Mineral Content of Fresh Garlic, Garlic Powder, and Garlic Peel

Fig. 1 presents the mineral composition of garlic powder, garlic peel, and fresh peeled garlic, highlighting substantial variations among the samples. Garlic powder exhibited the highest levels of essential macrominerals, including potassium (1193 mg/kg), magnesium (1139 mg/kg), and sodium (790 mg/kg). Garlic peel also showed considerable concentrations of these minerals, with potassium at 900 mg/kg, magnesium at 842 mg/kg, and sodium at 504 mg/kg. Both garlic powder and garlic peel were also rich in calcium, containing 291 mg/kg and 286 mg/kg, respectively—amounts beneficial for maintaining bone structure and mineral density. Phosphorus, iron, and zinc levels were comparatively lower across all samples, although garlic powder retained a functional level of zinc (9 mg/kg), consistent with findings by Mariam and Devi (2016). [44]

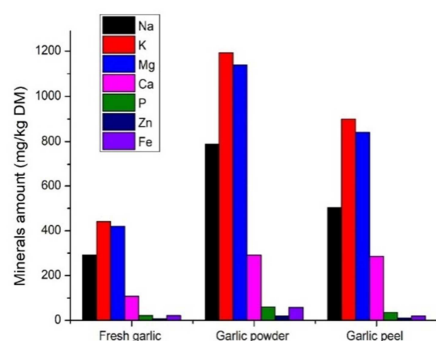


Figure 1: Minerals content of fresh garlic, garlic powder, and garlic peel (mg/Kg, DM)

The elevated potassium and magnesium concentrations in garlic derivatives are noteworthy, as these minerals play critical roles in cardiovascular function, neuromuscular signaling, and electrolyte balance. [45, 46] The presence of calcium further enhances the nutritional appeal of garlic products, particularly in supporting skeletal health. [47] Despite the moderate sodium content, which necessitates controlled intake to prevent hypertension risks, [48] the mineral profile of garlic peel and powder underscores their potential as value-added ingredients in functional foods. Moreover, incorporating garlic peel into food formulations offers a sustainable strategy for upcycling agricultural by-products while enhancing the micronutrient density of processed foods. [49]

3.3. Phenolic, Flavonoid Compounds, and Antioxidant Activity of Fresh Garlic, Garlic Powder, and Garlic Peel

The data presented in Fig. 2 illustrate the total phenolic and flavonoid contents, as well as the antioxidant activity of fresh garlic, garlic powder, and garlic peel. Garlic peel exhibited the highest concentration of phenolic compounds, while fresh garlic contained the highest flavonoid content, followed by garlic powder and garlic peel (Fig. 2A). In terms of antioxidant capacity, the samples showed comparably high activity, ranging between 67% and 73.6% (Fig. 2B), with only slight variations among them. This robust antioxidant potential is likely attributed to the cumulative presence of phenolic and flavonoid constituents across all samples.

These findings are supported by Gorinstein et al. (2005), [50] who reported a total polyphenol content of 47.3 mg/100 g and antioxidant activity of 68.9% in fresh garlic (fresh weight basis). Similarly, de Queiroz et al. (2014) [51] found that raw garlic contained 121.82 mg/100 g of total polyphenols and 123.3 mg/100 g of flavonoids on a dry weight basis. Ifesan, et al (2014) [28] further demonstrated the antioxidant efficacy of garlic peel extract, showing a reduction in thiobarbituric acid-reactive substances (TBARS) from 11.23 mg malonaldehyde/kg in untreated meat to 2.62 mg/kg when treated with 10.8 mg of the extract on day 9. Additionally, Mariam and Devi (2016) [44] highlighted the strong antioxidant activity of garlic powder, attributed in part to its high vitamin C content.

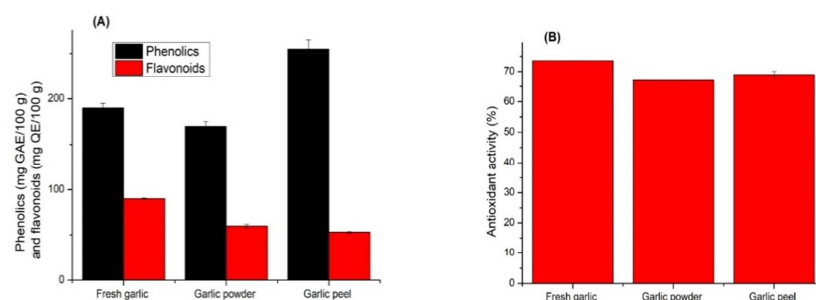


Figure 2: Phenolics, flavonoids (A), and antioxidant activity (B) of fresh garlic, garlic powder, and garlic peels (on a dry weight basis)

The antioxidant activity noted in this study (DPPH scavenging ~67.0–73.6%) and the elevated total phenolic content in garlic peel correspond with prior findings that illustrate garlic's significant radical-scavenging ability. For instance, Ifesan et al. [28] demonstrated significant antioxidant effectiveness of garlic peel extracts, evidenced by a pronounced reduction in lipid oxidation indicators, with TBARS decreasing from 11.23 to 2.62 mg MDA/kg in treated cooked beef. [40] Majumdar et al. [25] likewise shown that garlic extract enhanced the oxidative stability of restructured fish products during refrigerated storage. Our findings corroborate that both concentrated extracts and the direct integration of garlic derivatives, particularly garlic peel, into the formulation can provide significant antioxidant protection within a complex food matrix, in contrast to previous investigations. The comparable or elevated phenolic contents in garlic peel, a by-product, endorse its practical application as a cost-effective antioxidant component. [29]

3.4. Chemical Composition of Uncooked Fish Burgers

Table 3 summarizes the chemical composition of uncooked fish burgers formulated with varying levels of fresh garlic, garlic powder, and garlic peel. The control burger sample contained 71.59% moisture, 45.90% protein, 17.30% fat, 3.21% ash, 0.9% crude fiber, and 32.67% total carbohydrates. Incorporating garlic derivatives altered the nutritional profile of the burgers, with garlic peel showing the most pronounced impact. As the level of garlic peel increased, the protein content significantly declined, dropping from 45.90% in the control to 39.50% in the 7.5% garlic peel group. This reduction is attributed to the relatively low protein content of garlic peel compared to fish meat. Conversely, the inclusion of garlic peel led to higher crude fiber and ash contents, reflecting its rich dietary fiber and mineral profile. These results are consistent with Taşkaya et al. (2003) [52] who observed that fiber-rich plant additives dilute the protein concentration in meat products.

Among the garlic treatments, garlic peel exerted the most significant influence on the burgers' chemical composition, markedly increasing fiber and mineral content while reducing protein. Haq et al. [53] similarly reported that fish burgers typically contain 69.46% moisture and 16.42% protein, values influenced by added ingredients. The enhanced ash levels suggest improved mineral contribution, although they may alter the product's flavor and mouthfeel.

While the nutritional enhancements from garlic peel—particularly in fiber and minerals—are beneficial, they must be balanced against possible reductions in protein and changes in texture. Excessive fiber can contribute to a firmer or grainier texture, potentially affecting consumer acceptance. [54] Therefore, optimizing garlic peel levels in future formulations is recommended to achieve an ideal balance between nutritional enhancement and sensory quality.

Table 3: Chemical composition of uncooked fish burgers prepared with fresh peeled garlic, garlic peel and garlic powder (on dry weight basis)

Formulations		Moisture	Protein	Fat	Ash	Crude fiber	Total Carbohydrates
Control		71.59±0.18 ^a	45.90±0.01 ^a	17.30±0.01 ^a	3.21±0.01 ^c	0.90±0.00 ^{cd}	32.67±0.01 ^d
Fresh garlic	2.5%	71.50±0.05 ^a	45.62±0.01 ^b	17.25±0.01 ^a	3.22±0.00 ^c	1.0±0.01 ^c	32.91±0.03 ^d
	5%	71.60±0.90 ^a	45.42±0.01 ^{bc}	17.21±0.01 ^a	3.24±0.01 ^c	1.1±0.01 ^{de}	33.02±0.01 ^c
	7.5%	71.70±0.20 ^a	45.23±0.00 ^c	17.13±0.01 ^b	3.26±0.00 ^c	1.2±0.01 ^d	33.18±0.01 ^{fc}
Garlic peel	2.5%	69.81±0.10 ^b	42.42±0.19 ^d	17.10±0.01 ^b	3.32±0.02 ^c	2.0±0.01 ^c	35.15±0.22 ^b
	5%	69.12±0.01 ^c	40.20±0.13 ^c	16.94±0.03 ^c	3.51±0.01 ^b	3.1±0.00 ^b	36.25±0.11 ^a
	7.5%	68.45±0.23 ^d	39.50±0.01 ^f	16.46±0.02 ^d	3.71±0.01 ^a	4.3±0.01 ^a	36.01±0.02 ^a
Garlic powder	1%	71.41±0.01 ^a	45.22±0.01 ^b	17.30±0.00 ^a	3.21±0.01 ^b	1.0±0.00 ^c	33.28±0.01 ^{bc}
	2%	71.22±0.00 ^a	44.80±0.10 ^c	17.30±0.01 ^a	3.37±0.01 ^a	1.1±0.01 ^b	33.41±0.11 ^b
	3%	70.12±0.08 ^b	43.50±0.30 ^d	17.30±0.01 ^a	3.41±0.01 ^a	1.2±0.02 ^a	34.56±0.28 ^a

Values are expressed as mean ± standard deviation (n = 3).

Different superscript letters (a, b, c) in the same row indicate statistically significant differences among means at $P \leq 0.05$, according to one-way ANOVA followed by Tukey's HSD test.

3.5. Chemical composition of cooked fish burger

Table 4 outlines the chemical composition of cooked fish burgers formulated with varying levels of fresh garlic, garlic powder, and garlic peel. The control sample contained 65.61% moisture, 45.13% protein, 22.31% fat, 3.21% ash, 0.7% crude fiber, and 28.65% total carbohydrates. The addition of garlic derivatives led to notable compositional changes, particularly with garlic peel inclusion. As the level of garlic peel increased, protein content decreased significantly—from 45.13% in the control to 39.42% in the sample with 7.5% garlic peel. This reduction is likely due to the low protein density of garlic peel compared to fish meat. In contrast, ash and crude fiber contents increased with garlic peel supplementation, attributed to its high mineral and insoluble fiber content.

Among the tested garlic derivatives, garlic peel had the most pronounced effect on the chemical profile of cooked burgers. Its high dietary fiber, particularly insoluble fiber, contributes to increased structural firmness and may impact the product's texture and consumer acceptance.[55] Moreover, while the elevated mineral content enhances nutritional value, an excess of ash may impart undesirable flavors.[29]

Although garlic peel enhances fiber and mineral content—both of which are beneficial for health—its use also leads to a reduction in the protein content, which is a critical feature of fish burgers marketed as high-protein products. Protein plays an essential role in muscle growth and maintenance; thus, its dilution could affect the nutritional positioning of the product. [56] On the other hand, increasing dietary fiber is beneficial given widespread fiber deficiencies in many populations. To achieve a nutritionally balanced and sensorially acceptable product, future formulations should consider blending garlic peel with complementary protein-rich ingredients. This strategy may help maintain the fiber and mineral benefits while preserving the high-protein appeal of fish burgers.

Table 4: Chemical composition of cooked fish burgers prepared with fresh peeled garlic, garlic peel, and garlic powder (on a dry weight basis).

Formulations		Moisture	Protein	Fat	Ash	Crude fiber	Total Carbohydrates
Control		65.61±0.01 ^b	45.13±0.01 ^a	22.31±0.01 ^a	3.21±0.00 ^{bc}	0.7±0.01 ^c	28.65±0.01 ^c
Fresh garlic	2.5% *	65.50±0.01 ^c	44.90±0.00 ^b	22.20±0.00 ^a	3.25±0.01 ^b	0.8±0.00 ^{de}	28.85±0.01 ^d
	5%	65.50±0.01 ^c	44.70±0.00 ^{bc}	22.11±0.01 ^a	3.31±0.01 ^b	0.9±0.01 ^d	28.97±0.03 ^d
	7.5%	65.63±0.00 ^b	44.51±0.01 ^c	22.00±0.01 ^b	3.40±0.00 ^b	1.0±0.00 ^d	29.08±0.01 ^d
Garlic peel	2.5%	65.71±0.00 ^b	42.23±0.01 ^d	21.93±0.01 ^b	3.10±0.01 ^c	1.91±0.01 ^c	30.83±0.03 ^c
	5%	65.92±0.00 ^b	40.11±0.01 ^c	21.86±0.02 ^b	3.02±0.01 ^c	3.1±0.01 ^b	31.92±0.03 ^a
	7.5%	66.10±0.00 ^a	39.42±0.20 ^f	21.53±0.02 ^c	3.58±0.00 ^a	4.2±0.02 ^a	31.26±0.20 ^b
Garlic powder	1% *	65.62±0.01 ^b	44.80±0.01 ^b	22.31±0.01 ^a	3.21±0.00 ^b	0.8±0.00 ^c	28.88±0.01 ^c
	2%	65.46±0.02 ^b	44.61±0.01 ^b	22.22±0.01 ^a	3.35±0.02 ^{ab}	1.1±0.01 ^a	28.71±0.02 ^c
	3%	65.51±0.01 ^b	43.31±0.00 ^c	22.11±0.00 ^a	3.51±0.01 ^a	0.9±0.00 ^b	30.17±0.01 ^b

At a significance level of $P \leq 0.05$, values preceded by the same letter in the column are not significantly different.

*Used concentrations were chosen from many primary experiments in the laboratory

3.6. Physicochemical Properties

Table 5 presents the physicochemical indices, including the Protein-Water Coefficient (PWC), Protein-Water-Fat Coefficient (PWFC), Water-Protein Coefficient (WPC), and Feder value of fish burgers formulated with varying levels of fresh garlic, garlic powder, and garlic peel. A slight reduction in both PWC and PWFC was observed in garlic peel-enriched samples compared to the control, suggesting that the structural integrity of the protein matrix may have been

partially disrupted. This effect is likely due to the dilution of protein content and possible interactions between fiber components and proteins during cooking.

Conversely, WPC values increased with the inclusion of garlic powder or peel, indicating improved water retention. This enhancement could be attributed to the hydrophilic nature of dietary fiber and the mild protein denaturation or aggregation during heat treatment. Despite these changes, the Feder values remained largely unaffected by garlic incorporation, signifying that the overall nutritional balance of water, protein, and fat was maintained. These observations are consistent with findings by Yan et al. (2011)[27] and Majumdar et al. (2015)[25] who reported similar effects of garlic derivatives on the structural and functional characteristics of food protein matrices.

Table 5: Physical characteristics of fish burgers made with various quantities of garlic (in wet weight)

Formulations		PWC	PWFC	WPC	Feder value
Control		0.23±0.00 ^a	0.21±0.00 ^a	4.22±0.00 ^c	2.56±0.00 ^a
Fresh garlic	2.5%	0.23±0.00 ^a	0.21±0.00 ^a	4.21±0.00 ^c	2.54±0.00 ^a
	5%	0.23±0.00 ^a	0.21±0.00 ^a	4.22±0.00 ^c	2.54±0.00 ^a
	7.5%	0.23±0.00 ^a	0.20±0.00 ^a	4.29±0.00 ^c	2.57±0.00 ^a
Garlic peel	2.5%	0.22±0.00 ^a	0.19±0.00 ^a	4.53±1.16 ^b	2.55±0.00 ^a
	5%	0.20±0.00 ^a	0.18±0.00 ^a	4.82±0.01 ^{ab}	2.57±0.00 ^a
	7.5%	0.20±0.00 ^a	0.18±0.00 ^a	4.94±0.00 ^a	2.60±0.00 ^a
Garlic powder	1%	0.23±0.00 ^a	0.21±0.00 ^a	4.26±0.01 ^{ab}	2.56±0.00 ^a
	2%	0.23±0.00 ^a	0.21±0.00 ^a	4.23±0.00 ^b	2.54±0.00 ^a
	3%	0.22±0.00 ^a	0.20±0.00 ^a	4.38±0.01 ^a	2.55±0.00 ^a

At a significance level of $P \leq 0.05$, values preceded by the same letter in the column are not significantly different.

Where: PWC (Protein - water coefficient), PWFC (Protein water fat coefficient), and WPC (water-protein coefficient)

3.1. Cooking Properties of Fish Burgers

The cooking characteristics of the fish burgers, shown in Table 6, reveal that the addition of garlic derivatives—particularly garlic peel—positively influenced several functional parameters. Cooking yield increased notably, rising from 76.3% in the control to 80.70% in the sample with 3% garlic powder and reaching 82.42% in the burger containing 7.5% garlic peel. This enhancement is likely due to the moisture and fat retention capacity of garlic components, as supported by Badawy and Ali (2018)[30] and Alakali et al. (2010)[57] who reported similar improvements using functional plant-based additives.

Table 6: Cooking properties of fish burgers prepared with varying amounts of fresh garlic, garlic peel and garlic powder

Formulations		Cooking yield %	Moisture retention %	Cooking loss (%)	Shrinkage (%)	Oil uptake %
Control		76.3±0.06 ^c	91.64±0.01 ^d	23.4±0.00 ^a	11.7±0.01 ^a	56.21±0.00 ^b
Fresh garlic	2.5%	76.7±0.01 ^c	91.53±0.00 ^d	23.0±0.00 ^b	11.7±0.00 ^a	56.93±0.02 ^a
	5%	78.0±0.01 ^d	91.48±0.01 ^d	22.0±0.00 ^c	11.6±0.01 ^a	56.61±0.01 ^b
	7.5%	80.2±0.00 ^c	91.51±0.01 ^d	21.71±0.01 ^c	10.8±0.00 ^b	55.08±0.10 ^b
Garlic peel	2.5%	81.0±0.00 ^b	94.12±0.01 ^c	19.00±0.00 ^d	3.8±0.00 ^c	45.54±0.11 ^f
	5%	80.55±0.57 ^c	95.37±0.08 ^b	18.79±0.05 ^d	3.1±0.03 ^d	42.25±0.12 ^g
	7.5%	82.42±0.01 ^a	96.56±0.07 ^a	17.58±0.00 ^c	2.0±0.00 ^c	40.46±0.30 ^h
Garlic powder	1%	78.87±0.01 ^b	91.89±0.01 ^b	21.13±0.01 ^b	5.8±0.10 ^b	55.26±0.01 ^b
	2%	79.25±0.02 ^b	91.91±0.01 ^b	20.75±0.02 ^b	4.7±0.01 ^c	54.32±0.02 ^c
	3%	80.80±0.10 ^{b-a}	93.42±0.01 ^a	19.30±0.00 ^c	4.0±0.00 ^d	47.67±0.00 ^d

Values are expressed as mean ± standard deviation (n = 3).

Different superscript letters (a, b, c) in the same row indicate statistically significant differences among means at $P \leq 0.05$, according to one-way ANOVA followed by Tukey's HSD test.

Moisture retention also improved with the increasing levels of garlic derivatives. This may be attributed to the swelling of fiber, the water-binding capacity of proteins, and the gelatinization of starch during cooking. [58] As moisture retention enhances juiciness and palatability, this is a desirable trait in burger formulations. Additionally, cooking loss decreased with garlic addition, reflecting improved water and fat retention. A similar pattern was observed in reduced shrinkage and oil uptake, indicating that garlic derivatives help stabilize the burger matrix during heat treatment. Among all ingredients, garlic peel—due to its high fiber content—had the most pronounced impact, improving overall cooking performance and texture.

3.2. Texture and Color Properties

Adding garlic derivatives had a big effect on the color and texture of the fish burgers. Adding more garlic peel made the food harder and chewier, which is in line with its high fiber content and ability to hold water, which makes the structure firmer. Formulations with fresh garlic or garlic powder, on the other hand, stayed tender because the moisture that was kept in the food made it softer and less protein cross-linking happened during cooking.

In terms of color, burgers with garlic peel had somewhat lower L* (darker) values and higher a* (reddish) values. This is probably because the heat treatment caused phenolic oxidation and Maillard browning. Adding a moderate amount of garlic powder ($\leq 3\%$) or fresh garlic ($\leq 5\%$) kept the natural golden-brown color, which was the most acceptable to the senses. These results are consistent with the observations made by Mancini et al. (2020) [62], who noted analogous color and texture patterns in rabbit burgers enhanced with garlic powder.

Table 7: Texture and Color Parameters of Fish Burgers with Garlic Derivatives

Formulations	Hardness (N)	Chewiness (N·mm)	Springiness	L*	a*	b*	Remarks
Control	12.5 ± 0.2 c	6.2 ± 0.1 c	0.86 ± 0.01 a	68.4 ± 0.3 a	6.5 ± 0.2 b	17.8 ± 0.4 a	Soft, bright color
Fresh garlic 2.5%	12.8 ± 0.3 c	6.5 ± 0.1 c	0.87 ± 0.02 a	67.9 ± 0.4 a	6.8 ± 0.2 b	18.1 ± 0.3 a	Slightly firmer, golden color
Fresh garlic 5%	13.4 ± 0.3 b	6.9 ± 0.2 b	0.85 ± 0.02 a	66.5 ± 0.5 b	7.2 ± 0.1 a	17.6 ± 0.4 a	Balanced texture and color
Fresh garlic 7.5%	14.2 ± 0.4 b	7.1 ± 0.2 b	0.83 ± 0.01 b	65.9 ± 0.5 b	7.5 ± 0.2 a	17.3 ± 0.5 a	Slight firmness, stronger garlic flavor
Garlic peel 2.5%	14.6 ± 0.3 b	7.4 ± 0.3 b	0.82 ± 0.02 b	65.3 ± 0.3 b	7.8 ± 0.3 a	16.9 ± 0.3 b	Firmer, slightly darker surface
Garlic peel 5%	15.8 ± 0.2 a	8.2 ± 0.2 a	0.80 ± 0.01 b	64.1 ± 0.4 c	8.2 ± 0.2 a	16.5 ± 0.3 b	Noticeably firm, darker color
Garlic peel 7.5%	16.5 ± 0.4 a	8.6 ± 0.3 a	0.78 ± 0.02 c	63.4 ± 0.3 c	8.5 ± 0.3 a	16.0 ± 0.2 b	Firm, reddish-brown tone
Garlic powder 1%	13.0 ± 0.3 b	6.8 ± 0.1 b	0.86 ± 0.01 a	67.5 ± 0.2 a	7.0 ± 0.1 a	18.0 ± 0.3 a	Tender, golden-brown
Garlic powder 2%	13.2 ± 0.3 b	7.0 ± 0.2 b	0.85 ± 0.01 a	66.9 ± 0.3 a	7.3 ± 0.1 a	17.4 ± 0.3 a	Balanced color and texture
Garlic powder 3%	13.9 ± 0.2 b	7.2 ± 0.2 b	0.83 ± 0.02 b	65.6 ± 0.4 b	7.7 ± 0.2 a	17.0 ± 0.3 b	Slightly darker but acceptable

3.3. Microbiological Analysis

As shown in Table 7, the inclusion of garlic derivatives significantly reduced microbial counts in the fish burgers. Fresh garlic led to the most substantial microbial inhibition, decreasing the total plate count more effectively than garlic powder or garlic peel. Garlic powder reduced bacterial counts from 118 to 31 CFU/g, while garlic peel lowered the count from 118 to 58 CFU/g, reflecting its moderate antimicrobial potential.

The decreases in total plate counts seen here (control ≈ 118 CFU/g $\rightarrow$ a low ≈ 31 CFU/g with garlic powder; fresh garlic and peel also caused considerable, dose-dependent drops) are in line with what other studies said about garlic's ability to kill bacteria. Tsao and Yin [59] identified diallyl sulfides as the primary antibacterial components of garlic, and many practical investigations have demonstrated comparable preservation properties when garlic or its derivatives are incorporated into meat products. Majumdar et al. [25] found that surimi products treated with garlic extract had less microbial growth, whereas Mancini et al. [26] found that rabbit burgers with garlic powder added had better microbiological profiles. Our data indicate that moderate inclusion levels of garlic powder (1–3%) yield microbial reductions similar to those observed for concentrated extracts, suggesting that whole-ingredient additions can serve as an effective and easier intervention in processed fish products. Garlic peel exhibited modest antibacterial effects, inferior to those of fresh garlic or powder at comparable inclusion levels, however it resulted in substantial decreases in yeast/mold and total counts, aligning with previous findings regarding the antimicrobial properties of peel extracts.

These results agree with the findings by Tsao and Yin (2001) [59] who attributed garlic's antimicrobial efficacy to diallyl sulfide compounds, including disulfide, trisulfide, and tetrasulfide. Likewise, Azam et al. (2020) [60] demonstrated that garlic peel extract significantly reduced microbial growth in cooked beef, and Khashan (2014) [61] confirmed garlic's inhibitory effect against *Staphylococcus aureus*. The antimicrobial activity of garlic and its derivatives support their potential for improving food safety and shelf life in fish-based products.

Table 8: Microbial Counts (Total, Molds, and Yeasts) in Fish Burgers with Varying Levels of Garlic, Garlic Peel, and Garlic Powder

Formulations		Total count	Molds and yeasts count
Control		118 ± 2.00 ^a	2 ± 1.00 ^a
Fresh garlic	2.5%	88 ± 6.00 ^b	0.67 ± 0.58 ^c
	5%	61 ± 2.00 ^d	0 ± 0.00 ^d
	7.5%	47 ± 0.00 ^f	0 ± 0.00 ^d
Garlic peel	2.5%	64 ± 1.00 ^c	1 ± 0.00 ^b
	5%	61 ± 1.00 ^d	0 ± 0.00 ^d
	7.5%	58 ± 1.00 ^c	0 ± 0.00 ^d
Garlic powder	1%	38 ± 0.00 ^b	0.33 ± 0.58 ^b
	2%	34 ± 1.15 ^{bc}	0 ± 0.00 ^c
	3%	31 ± 1.00 ^c	0 ± 0.00 ^c

Values are expressed as mean ± standard deviation (n = 3).

Different superscript letters (a, b, c) in the same row indicate statistically significant differences among means at $P \leq 0.05$, according to one-way ANOVA followed by Tukey's HSD test.

Coliform testing revealed once again that the fish burger recipes were clean and effective against germs. The control samples had the most coliforms, which suggests that untreated formulations could be contaminated with microbes. Adding garlic derivatives, especially fresh garlic and garlic powder, made the coliforms much less common. Allicin and other organosulfur compounds have bactericidal properties that can break down bacterial cell walls and stop enzyme systems that are important for coliform survival (Tsao and Yin, [59]; Bhatwalkar et al., [62]). Majumdar et al. [25] and Mancini et al. [26] both found that garlic derivatives had the same effect on the growth of coliform and *E. coli* in meat and fish products. The lack of coliforms or their significant reduction in the current formulations indicates enhanced microbiological safety and sanitary quality, affirming that garlic derivatives function not only as natural antioxidants but also as efficient bio-preservatives. This research supports the idea that garlic can help fish-based meals last longer and lower the risk of contamination after processing.

Table 9 shows that coliform bacteria levels go down when the levels of garlic derivatives go up, compared to the control. This shows that garlic components work as antimicrobials in the fish burger recipes. The control sample (25 ± 1.00 CFU/g) exhibited detectable coliforms, suggesting possible contamination or microbial proliferation post-processing, characteristic of unprotected fish-based goods.

On the other hand, adding fresh garlic significantly lowered coliform counts in a concentration-dependent way, bringing them down to 3 CFU/g at 7.5% inclusion. This decrease shows how strong the bactericidal effects of allicin and other organosulfur compounds are. These compounds stop coliform bacteria by breaking down cell membranes and interfering with enzyme function.

Garlic powder also had excellent antibacterial properties, with coliform counts dropping to 2 CFU/g at the 3% level, which meant that coliforms could no longer be found. Garlic powder may work better since it has more stable sulfur compounds and is simpler to spread throughout the burger matrix, which makes sure that microbial cells come into touch with it evenly.

Garlic peel, while somewhat less powerful than fresh garlic or powder, nonetheless produced notable reductions—from 12 CFU/g at 2.5% to 6 CFU/g at 7.5%—illustrating its moderate inhibitory capacity. The antibacterial properties are probably due to the phenolic acids and flavonoids in the peel, which cause oxidative stress in microbial cells).

In general, all of the treated formulations stayed well within the permitted microbiological safety limits for ready-to-eat fish products (≤ 100 CFU/g per FDA and ICMSF criteria). This shows that garlic derivatives indeed improve hygienic quality. Garlic powder at 2–3% and fresh garlic at $\geq 5\%$ were the most effective treatments among the studied substances. They almost completely killed coliforms without the need for synthetic preservatives.

These results confirm that garlic derivatives can be both natural antimicrobials and functional bio-preservatives. This means that they can be used to make fish-based foods safer and last longer while still being environmentally friendly by using garlic by-products like the peel.

Table 9: Coliform Count of Fish Burgers with Garlic Derivatives

Formulations	Coliform Count (CFU/g)	Remarks
Control	25 ± 1.00 a	Detectable coliforms indicating possible contamination
Fresh garlic 2.5%	10 ± 0.58 b	Noticeable reduction due to antimicrobial compounds
Fresh garlic 5%	5 ± 0.00 c	Low count, within acceptable limits
Fresh garlic 7.5%	3 ± 0.00 c	Nearly undetectable
Garlic peel 2.5%	12 ± 0.58 b	Moderate inhibition effect
Garlic peel 5%	8 ± 0.58 c	Improved microbial control
Garlic peel 7.5%	6 ± 0.00 c	Significant reduction
Garlic powder 1%	7 ± 0.00 c	Effective inhibition
Garlic powder 2%	4 ± 0.00 c	Strong antimicrobial activity
Garlic powder 3%	2 ± 0.00 c	Coliforms nearly eliminated

3.4. Sensory Evaluation

Sensory evaluation results presented in Table 9 reveal statistically significant differences ($p \leq 0.05$) in color, texture, flavor, and overall acceptability among burger samples treated with garlic derivatives compared to the control. Moderate levels of garlic, especially fresh garlic and garlic powder, were positively received by the panel, enhancing flavor and aroma without introducing off-flavors.

The sensory evaluation showed that adding moderate amounts of garlic derivatives, like 2.5–5% fresh garlic and 1–2% garlic powder, made fish burgers taste, smell, and overall taste better. However, adding more of these ingredients made the sensory scores go down (Table 9). There are a number of compositional and sensory reasons why people don't like higher quantities (such 7.5% garlic or garlic peel). First, adding too much fresh or powdered garlic can make the fish taste and smell bad because it has a strong sulfurous flavor and smell. This is because it has high levels of allicin and other organosulfur compounds, which can overpower the fish flavor and make people not want to eat it (Dorman and Hiltunen (2004) [63]; Mancini et al. (2020) [26]). Second, garlic peel has a lot of crude fiber (30.5%), which makes the burger less juicy and harder because fiber interacts with proteins and makes moisture less mobile in the burger matrix (Kim and Paik,

2012 [54], Yousefi et al., 2018 [55]). This mechanical action accounts for the diminished tenderness and texture ratings noted at 5–7.5% peel inclusion levels.

The light hue and fiber particles of garlic peel powder can also change the way a product looks, making the surface look a little duller or grainier. This could also change how the panel thinks about the quality. These results are consistent with the findings of Majumdar et al. (2015) [25] and Ifesan et al. [28], who saw analogous reductions in sensory scores at elevated concentrations of plant-based or garlic-derived additives in fish and meat products. These data suggest that garlic derivatives improve flavor, antioxidative protection, and microbiological safety; however, their ideal incorporation level must reconcile functional advantages with sensory acceptability. The present investigation determined that inclusion levels of 3% garlic powder or 2.5–5% fresh garlic were optimal for attaining this equilibrium.

Table 10: Sensory evaluation of fish burgers with varying levels of garlic, garlic peel, and garlic powder

Formulations		Color	Taste	Odor	Texture	Overall acceptability
Control %		8.80±0.00 ^a	8.70±0.00 ^a	8.67±0.06 ^b	9.20±0.00 ^a	8.84±0.01 ^a
Fresh garlic	2.5%	8.70±0.00 ^a	8.76±0.06 ^a	8.77±0.06 ^a	9.20±0.00 ^a	8.86±0.03 ^a
	5%	8.50±0.00 ^b	7.80±0.10 ^b	8.07±0.06 ^b	8.80±0.00 ^b	8.29±0.04 ^b
	7.5%	8.20±0.10 ^c	6.90±0.10 ^d	7.44±0.06 ^c	8.50±0.00 ^b ^c	7.76±0.02 ^d
Garlic peel	2.5%	8.30±0.10 ^c	7.20±0.00 ^b	7.80±0.00 ^b	8.87±0.06 ^b	8.04±0.04 ^c
	5%	7.50±0.00 ^d	6.30±0.10 ^d	6.40±0.00 ^d	8.10±0.00 ^c	7.08±0.03 ^c
	7.5%	6.70±0.01 ^e	5.20±0.10 ^e	5.80±0.10 ^e	7.50±0.10 ^d	6.30±0.00 ^f
Garlic powder	1%	8.80±0.10 ^a	8.33±0.06 ^{ab}	8.83±0.06 ^a	9.00±0.00 ^{ab}	8.74±0.05 ^a
	2%	8.50±0.00 ^{ab}	7.90±0.10 ^b	8.87±0.06 ^a	8.98±0.06 ^{ab}	8.56±0.04 ^a
	3%	8.00±0.00 ^b	6.80±0.01 ^c	7.67±0.06 ^b	8.80±0.10 ^b	7.82±0.02 ^b

Values are expressed as mean ± standard deviation (n = 3).

Different superscript letters (a, b, c) in the same row indicate statistically significant differences among means at $P \leq 0.05$, according to one-way ANOVA followed by Tukey's HSD test.

4. Conclusion

This study showed that adding fresh garlic, garlic powder, and garlic peel to fish burger recipes improves the nutritional, technical, and microbiological quality in many ways. Garlic peel, a by-product abundant in fiber, minerals, and phenolic compounds, had the most antioxidant potential of all the investigated derivatives. It also greatly improved cooking yield, moisture retention, and oil reduction, proving that it is a useful ingredient for long-term use. Fresh garlic and garlic powder had better antibacterial properties, lowering the number of microorganisms and making the product safer. Sensory examination revealed that moderate inclusion levels (2.5–5% fresh garlic and 1–3% garlic powder) attained optimal flavor and acceptability, while elevated concentrations or excessive fiber from garlic peel somewhat diminished palatability and softness.

These findings underscore the potential of garlic by-products, especially garlic peel, as useful and sustainable ingredients that can improve the nutritional value, safety, and shelf stability of fish-based foods. The study adds to the expanding body of research on how to make use of agro-industrial waste and offers a viable model for making functional foods that are good for the environment and high in nutrients within the framework of the circular economy.

Our antioxidant and microbial inhibition data corroborate previous findings on garlic extracts' effectiveness in fish and meat products, while demonstrating that direct inclusion of garlic derivatives—particularly garlic peel—can deliver combined antioxidative, antimicrobial, and nutritional benefits in fish burgers, with the additional advantage of valorizing agro-industrial waste.

5. Consent for publication

All authors read and approved the final version of the manuscript.

6. Data Availability Statement

All data was provided in this paper.

7. Ethics approval

Not applicable.

8. Credit authorship contribution statement

All authors equally participated in the conceptualization, design of the methodology, validation procedures, data collection, statistical analysis, result interpretation, and the drafting and revision of the manuscript.

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11. Conflicts of Interest

No conflict of interest was reported by all authors.

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