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Effect of smoking and gamma irradiation on the nutritional and sensory quality of Atlantic chub mackerel in Ghana

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ABSTRACT

This study investigated the nutritional, color and sensory quality of smoked and irradiated Atlantic chub mackerel. Smoking significantly decreased the moisture but increased the protein contents. The total saturated fatty acids (SFAs) and polyunsaturated fatty acids (PUFAs) were significantly increased ($p < 0.05$) while the monounsaturated fatty acids (MUFAs) were significantly reduced ($p < 0.05$) by smoking. The lipid quality indices, atherogenic index (AI) and index of thrombogenicity (TI) were below 1.0, indicating potential reduced risks of atherosclerosis and coronary thrombosis from consuming these products. The polyene index (PI) was greater than 1.0, implying a high retention of PUFAs in the products. All amino acids, significantly increased after smoking. The ratio of essential amino acid (EAA) to non-essential amino acid (NEAA), in all cases, was all greater than 1. Irradiation at 1.5 and 3 kGy had no significant effect ($p > 0.05$) on the nutritional (except in EAA of 3 kGy samples relative to smoked samples), color and sensory quality of the smoked fish.

1. Introduction

Fish is an excellent high-protein food that has gained popularity among health-conscious consumers worldwide. The Atlantic chub mackerel (*Scomber colias,* Gmelin, 1789) belongs to the family *Scombridae* and is very important in the commercial fisheries sector throughout its range (Collette et al., 2011). In Ghana, it is mainly exploited by the artisanal fleets, and catches fluctuate annually. Due to the fluctuation in catches, frozen chub mackerel is mainly imported and distributed in the country (FAO, 2016). Mackerel is a fatty fish, rich in omega-3 and other unsaturated fatty acids and is also an excellent source of riboflavin, vitamins B6 and B12, protein, selenium and niacin B12, that are essential to human health (Nogueira et al., 2013).

Fresh fish however deterioriates soon after harvest due to their almost neutral pH, high water activity, fast onset of rigor mortis and high amounts of nutrients that promote development of microorganisms (de Alba et al., 2019). A degree of processing is therefore required to maintain the quality and shelf life of fresh fish. Fish smoking is a traditional and affordable method employed to preserve the quality of fish in Ghana and most developing countries (Asamoah et al., 2021). Chub mackerel is mainly consumed smoked and it is a delicacy enjoyed by most Ghanaians, both in Ghana and abroad since its relatively cheap (Asamoah et al., 2021). The demand for smoked products is however mostly hampered by the susceptibility of the product to spoilage, mainly from microbial contamination and loss of nutritional quality (Badr, 2012). In Ghana, chub mackerel is mostly soft smoked, sold unpackaged in open markets at ambient temperature (about 30 ± 2 °C) and has a shelf life of between 1 and 3 days (Pemberton-Pigott et al., 2016). There is therefore the need to explore further interventions to improve the quality and shelf life of smoked chub mackerel.

Food irradiation is one such intervention that has been proven to successfully ensure food safety and extend shelf life by inactivating pathogens, without deteriorating the functional, nutritional, and sensory properties of the product (Arvanitoyannis, 2010; Özden and Erkan, 2010). Foods, depending on the type, can be gamma irradiated from below 1 kGy to more than 10 kGy, but the acceptable dose for fish is 3 kGy (EU, 2009). With the development of national and international standards following research outcomes, more than 60 countries allow food irradiation of at least one food product (Badr, 2012). Studies have been conducted on the potential of gamma irradiation in improving the

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safety and quality of vegetables, poultry, fermented maize and cassava products and seafood such as sardines, anchovies and shrimps in Ghana (Adu-Gyamfi and Appiah, 2012; Duah et al., 2018). Ghana has the requisite capacity, therefore, to use this technology to ensure safe and shelf-stable fish products, not only for the domestic market, but also for export.

Radiation, due to its high-energy input, may however initiate fat oxidation and breakdown of amino acids that results in off-odors and flavors (Lyu et al., 2018). These changes can affect consumer acceptation of the product (Özden and Erkan, 2010). The purpose of this study was therefore to determine the effects of smoking and gamma irradiation on nutritional and sensory quality of smoked Atlantic chub mackerel.

2. Materials and methods

2.1. Sample collection and preparation

Frozen Atlantic chub mackerel (of average weight and length 225.46 ± 53.39 g and 25.2 ± 3.1 cm respectively), purchased on February 2019 from a commercial cold store facility in Takoradi (Western Region), was used for the assessment. Fish samples to be smoking (90 kg) were thawed at ambient temperature for about 2 h, then gutted and subjected to brining, by immersion in 8% brine solution (fish: brine ratio of 1: 2 w/v) for 30 min at 4 °C. After brining, the samples were placed on racks to drain for 30 min at ambient temperature (about 30 ± 2 °C) before smoking. The mackerel were smoked whole for approximately 4 h in the Abuesi gas fish smoker (AGFS). The AGFS was designed by the Ghana Regional Appropriate Technology Industrial Service (GRATIS) Foundation, in consultation with smoked fish processors, to produce hygienic products that would meet both local and international safety requirements (Kleter, 2004). It uses liquified petroleum gas (LPG) in the cooking and drying of fish and agricultural wastes like sugarcane bagasse and coconut husks to impart the smoky flavour. After smoking, the samples were cooled at ambient temperature for about an hour, after which they were packed into 500 g airtight polythene bags and sent for irradiation. The samples were divided into 3 lots of approximately 20 kg each; one lot served as the Control (no irradiation) whiles the other two were irradiated at 1.5 and 3 kGy respectively. Analyses were carried out on fresh, smoked and irradiated chub mackerel samples. Samples for sensory, proximate and color analyses were immediately sent to the Sensory Laboratories of the Department of Nutrition and Food Science, University of Ghana and Food Research Institute, Accra respectively. The pre-packaged samples for fatty acid and amino acid composition were further vacuum packed, frozen at −20 °C and airlifted to the National Food Institute of the Technical University of Denmark for analyses. For chemical analysis of each sample, whole fish were deboned and de-headed and minced into fish meal using a mixer. The fish meal was then stored at −40 °C prior to analyses.

2.2. Gamma irradiation of samples

Gamma Irradiation of smoked chub mackerel was carried out in a category (IV) wet storage Cobalt-60 multipurpose gamma irradiator facility (Type CoS43HH) at the Radiation Technology Centre of Ghana Atomic Energy Commission, Accra, Ghana. The packaged smoked mackerel samples were placed in cardboard boxes for irradiation. Each package weighed about 500 g and the box with smoked fish weighed 5 kg. Two doses, 1.5 and 3 kGy were targeted and for each dose. The irradiation was performed at a dose rate of 0.495 kGy/h and cartons were turned 180° halfway into the processing time to ensure homogenous distribution of the dose delivered under the same conditions. Doses delivered were confirmed using Ethanol-chlorobenzene dosimeters placed inside and outside the cartons. The delivered doses were 1.65 ± 0.11 and 3.35 ± 0.13 kGy. Fish samples were kept at ambient temperature of 26 ± 3 °C during irradiation. Non-irradiated (control) fish samples were kept in polystyrene boxes at similar temperature.

2.3. Proximate composition

The moisture, protein fat and ash analyses were carried out using the air-oven method (AOAC 32.1.03), Kjeldahl (AOAC 4.2.09), Soxhlet (AOAC 4.5.01) and dry ashing (AOAC 32.1.05) methods respectively (AOAC, 2005). The results were expressed as g/100 g sample.

2.4. Fatty acid composition

Total lipids were then extracted with chloroform, methanol and water, following the method of Bligh and Dyer (1959). Extractions and analysis were performed in duplicate for each sample. The lipid extracts were used to prepare fatty acid methyl esters (FAMEs) according to AOCS (1998a).

2.4.1. Gas chromatographic conditions

FAMEs were analysed by gas chromatography following AOCS (1998b). The gas chromatography (Agilent Technology Model 7890A series GC, China) was fitted with automatic sampler (Model 7693, Agilent Technology), fused silica capillary column (HP-88, 100 m × 0.25 mm x 0.20 μm film thickness: Agilent Technology), split injector, and flame ionization detector (FID). The carrier gas was helium with a flow rate of 0.38 mL/min and an inlet pressure of 51 psi. The oven temperature programme for separation was from 160 to 200 °C, 200–220 °C, and 220–240 °C at 10.6 °C/min. For separation, DB127-7012 column (10 m × ID 0.1 mm × 0.1 μm film thickness, Agilent Technologies, Palo Alto, CA, USA) was used. Injection volume was 0.2 μL in split mode (1:50). The peaks were identified by comparison of their retention times against the internal standard, C23:0 (methylester in-Heptane). The result of each fatty acid test was expressed as g fatty acid/100 g lipid.

2.4.2. Lipid quality indices

The lipid quality indices, polyene index (PI), atherogenic index (AI) and thrombogenic index (TI) were calculated using the following equations (Rosa and Nunes, 2003; Chaula et al., 2019):

$$PI = \frac{C20:5 + C22:6}{C16:0} \quad \text{Equation 1}$$

$$AI = \frac{C12:0 + (4xC14:0) + C16:0}{\sum MUFA + \sum PUFA_{\omega-6} + \sum PUFA_{\omega-3}} \quad \text{Equation 2}$$

$$TI = \frac{C14:0 + C16:0 + C18:0}{(o.5x\sum MUFA) + (0.5\sum PUFA_{\omega-6}) + (3x\sum PUFA_{\omega-3}) + \left(\omega - 3/\omega - 6\right)} \quad \text{Equation 3}$$

where: MUFA is monounsaturated fatty acids and PUFA is polyunsaturated fatty acids.

2.5. Amino acid composition

The amino acid composition was analysed using a Phenomenex EZ: fast amino acid analysis kit (California, USA). About 30 mg of the sample was hydrolyzed in 6 M HCl in a microwave oven (Microwave 3000 SOLV, Anton Paar, Austria) for 60 min at 110 °C. The hydrolysate was filtered into 1.5 mL screw-cap vial through a cellulose acetate 0.22 μm Q-Max RR syringe filter using a 1 mL syringe. The amino acid composition was determined by liquid chromatography with a mass spectrometry detector (Agilent 1100 series, LC/MSD Trap, Agilent Technologies, Denmark) using a Phenomenex Z:faast 4u AAA-MS column (250 × 3.0 mm, California, USA). The total protein concentration in the samples was calculated by summarizing all the amino acids and subtracting the water incorporated during hydrolysis (18 g H2O mol-1

amino acid) (Mols-Mortensen et al., 2017).

2.6. Color analysis

The skin and muscle color of smoked chub mackerel (irradiated and non-irradiated) were measured with a Minolta CR-310 chromameter (Minolta Camera Co., Ltd; Osaka, Japan). The chromameter was calibrated with a reference white porcelain tile before each measurement. The color intensity was described in L^*, a^*, and b^* notation on the CIE LAB color scale, according to Cyprian et al. (2017). . The L* measured lightness (black/white); a^* defined components on the red-green axis (redness/greenness), and b^* defined components on the yellow-blue axis (yellowness/blueness). Measurements were made at three locations from posterior to anterior and the mean and standard deviation calculated.

2.7. Sensory evaluation

The difference-from-control test (Lawless and Heymann, 2010) was used to determine if there were any differences between non-irradiated (control) and irradiated smoked chub mackerel immediately after smoking and irradiation. 15 panelists were screened in basic tastes identification, odor recognition, ranking test and a discrimination test, specifically the triangle test to determine their sensory acuity. Prior to testing, the head and tail regions of each fish was cut off to obtain a fairly uniformed mid-section. The remaining fish was divided longitudinally into three equal parts and each part divided transversely into halves to enable easy deboning, giving a total of 6 pieces per fish. After deboning, the skin of the fish was removed to reduce bias (the skins were lacerated). Each piece, was served into 80 ml disposal cups and served at 18 ± 2 °C to assessors in individually partitioned booths. Assessors first tasted a labelled control sample (R) and then proceeded to taste three test samples; Blind control (non-irradiated), Irradiated I (1.5 kGy) and Irradiated II (3 kGy) in a pre-determined randomized order. For each test sample tasted, assessors determined overall how different that test sample was from the labelled control sample on a 5-point labelled category scale with the following categories: 0 = No difference; 1 = Very slight difference; 2 = Slight difference; 3 = Moderate; 4 = Very different and 5 = Extreme difference. Overall product differences were evaluated and not attribute differences. Each session lasted for approximately 15 min and a forced 5-min break between each session. Assessments were done in duplicates to give 30 responses for each sample. Check-all-that-apply (CATA) list was provided for panelists to indicate where differences (if any) could be perceived.

2.8. Data analysis

All statistical analysis was performed using Microsoft Excel 2016 and XLSTAT (Addinsoft, New York, USA). Differences between means were determined using one-way analysis of variance (ANOVA) followed by post-hoc stepwise comparison, using Fisher's least significant difference (LSD) test at the 5% significance level. Results are presented as mean ± standard deviation.

3. Results and discussion

3.1. Proximate composition

The mean moisture, protein, fat and ash contents of the fresh and smoked chub mackerel are presented in Table 1. Smoking significantly reduced ($p < 0.05$) the moisture from 64.93 to 46.65 g/100g, while significantly increasing the protein content to 37.21 g/100g. Fat and ash contents were also higher in smoked samples but not significant. The increase in protein and fat contents and the decrease in moisture content could be attributed to dehydration during the smoking process (Arason et al., 2014). The reduced moisture content of the smoked mackerel (SM) samples could improve the shelf life of the product without negatively affecting the sensory quality (Asamoah et al., 2021). Protein constituted the greatest percentage of the dry matter in the smoked samples. The higher fat content in the smoked fish might increase its energy value, however, this could cause lipid oxidation that may affect the flavor, odor and general quality of the smoked fish (Arason et al., 2014). The increase in the ash content may have arisen from the deposition of mineral elements present in the salt during brining process and dehydration during smoking (Ikasari et al., 2017). There were no significant differences ($p > 0.05$) in the moisture, protein, fat and ash between the smoked and irradiated (SMg-1.5 kGy and SMg-3 kGy) mackerel. The slight changes observed were in consonance with studies that found that proximate composition was not affected by doses up to 3 kGy in cold-smoked salmon (Badr, 2012) and sun-dried sharpfin barracuda irradiated at 5 kGy (Prakash et al., 2015). Sinanoglou et al. (2015) attributed the insignificant changes in proximate composition to the low moisture content that likely prevents the formation of free radicals and the degradation of bioactive compounds.

Table 1
Proximate composition of fresh (F), smoked (S) and gamma irradiated (g) mackerel (M) (n = 3).

Parameter (g/100g)	FM	SM	SMg-1.5 kGy	SMg - 3 kGy
Moisture	64.93 ± 4.91[a]	46.65 ± 5.80[b]	45.98 ± 1.17 [b]	43.13 ± 2.30 [b]
Protein	25.30 ± 0.11[a]	37.21 ± 4.10 [b]	37.56 ± 7.37 [b]	43.29 ± 0.94 [b]
Fat	10.15 ± 5.89	12.03 ± 9.01	11.57 ± 2.91	11.55 ± 2.49
Ash	1.45 ± 0.13	1.98 ± 0.11	2.15 ± 0.46	1.97 ± 0.32

[a, b]Means of each species with different superscripts within a row are significantly different at $p < 0.05$.

3.2. Fatty acid composition

Thirty-three (33) fatty acids were identified and quantified in the fresh and smoked mackerel samples (Table 2), with the unsaturated fatty acids being relatively dominant (27), compared to the saturated ones (6). Of the unsaturated fatty acids identified, 18 were polyunsaturated fatty acids (PUFAs) and nine were monounsaturated fatty acids (MUFAs). Among the PUFAs, there were 9 omega-3 (ω-3) and 5 omega-6 (ω-6) fatty acids. The individual fatty acids that contributed the greatest proportions in all samples were palmitic, myristic and stearic acids (SFAs), oleic acid (MUFA) and eicosapentaenoic (EPA) and docosahexaenoic acids (DHA) (PUFAs). Similar findings were reported for irradiated seabreams (Erkan and Özden, 2007), Atlantic chub mackerel and other species captured in north-eastern Atlantic (Nogueira et al., 2013) and golden grey mullet and gold band goatfish from the Mediterranean Sea (Küçükgülmez et al., 2018). Oleic acid is important in human nutrition as it stimulates bile secretion, which aids in the digestion and absorption of fats (Nogueira et al., 2013). Fish provides a good source of docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) in human nutrition (Lyu et al., 2018), as can be seen from results of this study. EPA and DHA are also hypotriglyceridemic and very important in the prevention of cardiovascular and inflammatory diseases in humans (Nogueira et al., 2013). The DHA and EPA ranged from 8.78 to 17.02 g fatty acid/100 g and 6.91–7.36 g fatty acid/100 g respectively, with DHA being significantly higher ($p < 0.05$) in the smoked fish. The high levels of DHA, compared to EPA agree with reports by Lyu et al. (2018) and Chaula et al. (2019).

Smoking resulted in a significant increase ($p < 0.05$) in SFA and PUFA (about 52 and 38% respectively), although MUFA was significantly decreased by about 53%. These could be due dehydration during the smoking process (in the case of SFA and PUFA) and subsequent degradation of MUFA (Bouriga et al., 2020). The proportions of fatty

Table 2
Fatty acid composition of fresh (F), smoked (S) and gamma irradiated (g) mackerel (M) (g fatty acid/100 g oil sample) (n = 3).

Fatty acid		FM	SM	SMg-1.5 kGy	SMg-3 kGy
Myristic	14:0	5.70 ± 0.07^{a}	5.09 ± 0.40^{b}	5.07 ± 0.12^{b}	5.12 ± 0.04^{a}
Pentadecanoic	15:0	0.40 ± 0.02^{a}	1.48 ± 0.16^{b}	1.28 ± 0.11^{b}	1.41 ± 0.05^{b}
Palmitic	16:0	13.53 ± 0.18^{a}	21.68 ± 1.70^{b}	21.06 ± 0.44^{b}	22.61 ± 0.22^{b}
Margaric	17:0	0.43 ± 0.05	0.47 ± 0.38	0.65 ± 0.07	0.63 ± 0.03
Stearic	18:0	2.79 ± 0.05^{a}	6.23 ± 0.24^{bc}	5.56 ± 0.05^{bd}	5.89 ± 0.20^{b}
Arachidic	20:0	0.16 ± 0.03^{a}	0.44 ± 0.03^{b}	0.51 ± 0.01^{c}	ND^{d}
∑ SFA		**23.01 ± 0.19^{a}**	**35.39 ± 2.06^{b}**	**34.13 ± 0.57^{b}**	**35.65 ± 0.07^{b}**
Myristovaccenic	14:1	0.21 ± 0.02	0.21 ± 0.04	0.26 ± 0.01	0.28 ± 0.04
Palmitoleic	16:1 (n-7)	4.10 ± 0.08^{a}	5.89 ± 0.49^{b}	6.08 ± 0.08^{b}	6.07 ± 0.24^{b}
Oleic	18:1 (n-9)	15.06 ± 2.23^{a}	9.15 ± 0.74^{b}	9.89 ± 0.17^{b}	10.21 ± 0.39^{b}
Vaccenic	18:1 (n-7)	3.02 ± 0.11	2.68 ± 0.52	2.73 ± 0.00	2.74 ± 0.03
Gondoic	20:1 (n-9,11)	9.43 ± 1.96^{a}	1.15 ± 0.06^{b}	1.43 ± 0.75^{b}	0.99 ± 0.02^{b}
Paullinic	20:1 (n-7)	0.31 ± 0.02	0.38 ± 0.03	0.38 ± 0.01	0.35 ± 0.00
Setoleic	22:1 (n-11)	12.35 ± 0.08^{a}	0.37 ± 0. 10^{b}	1.04 ± 1.01^{b}	0.38 ± 0.02^{b}
•Erucic	22:1 (n-9)	ND^{a}	0.23 ± 0.11^{a}	0.35 ± 0.14^{b}	0.17 ± 0.07^{a}
•Nervonic	24:1 (n-9)	0.81 ± 0.14	0.62 ± 0.07	0.72 ± 0.10	0.75 ± 0.04
∑ MUFAs		**45.29 ± 0.92^{a}**	**20.68 ± 1.93^{b}**	**22.88 ± 1.90^{b}**	**21.95 ± 0.15^{b}**
•9,12-Hexadecadienoic	16:2 (n-4)	0.37 ± 0.01^{a}	0.75 ± 0.18^{b}	0.62 ± 0.10^{a}	0.75 ± 0.10^{b}
6,9,12-Hexadecatrienoic	16:3 (n-4)	0.40 ± 0.02^{a}	1.59 ± 0.00^{b}	1.47 ± 0.13^{b}	1.57 ± 0.10^{b}
11,14-Octodecadienoic	18:2(n-4)	0.09 ± 0.00^{a}	0.47 ± 0.02^{b}	0.45 ± 0.12^{b}	0.50 ± 0.00^{b}
8,11,14-Octodecatrienoic	18:3 (n-4)	3.86 ± 0.04^{a}	0.92 ± 0.12^{b}	1.19 ± 0.16^{b}	1.08 ± 0.08^{b}
∑ (n-4)		**4.73 ± 0.05^{a}**	**3.73 ± 0.28^{b}**	**3.72 ± 0.20^{b}**	**3.89 ± 0.13^{b}**
Palmitidonic	16:4 (ω-3)	0.35 ± 0.00	0.40 ± 0.09	0.47 ± 0.14	0.37 ± 0.02
α-Linolenic	18:3 (ω-3)	ND	0.02 ± 0.03	ND	ND
Stearidonic	18:4 (ω-3)	0.19 ± 0.04	ND	ND	ND
Dihomo-α-linolenic	20:3 (ω-3)	0.15 ± 0.02	1.25 ± 1.58	0.13 ± 0.01	0.13 ± 0.00
Eicosatetraeonic	20:4 (ω-3)	0.92 ± 0.06^{a}	0.42 ± 0.00^{b}	0.45 ± 0.02^{b}	0.44 ± 0.04^{b}
Eicosapentaenoic (EPA)	20:5 (ω-3),	6.91 ± 0.19	7.36 ± 0.68	7.32 ± 0.39	6.96 ± 0.08
Heneicosapentaenoic	21:5 (ω-3)	0.40 ± 0.06	0.47 ± 0.12	0.33 ± 0.03	0.40 ± 0.02
Docosapentaenoic (DPA)	22:5 (ω-3)	0.24 ± 0.09^{a}	1.42 ± 0.11^{b}	0.58 ± 0.04^{c}	1.04 ± 0.15^{d}
•Docosahexaenoic (DHA)	22:6 (ω-3),	8.78 ± 0.66^{a}	17.02 ± 1.98^{b}	17.25 ± 0.48^{b}	16.63 ± 0.18^{b}
∑ (ω-3)		**17.95 ± 0.54^{a}**	**28.36 ± 4.35^{b}**	**26.53 ± 0.21^{b}**	**25.97 ± 0.46^{b}**
Linoleic	18:2 (ω-6)	1.52 ± 0.01^{a}	1.36 ± 0.00^{b}	1.43 ± 0.01^{a}	1.41 ± 0.11^{a}
γ-Linolenic	18:3 (ω-6)	1.35 ± 0.06^{a}	1.05 ± 0.05^{a}	1.08 ± 0.00^{a}	0.83 ± 0.22^{b}
Dihomo-linoleic	20:2 (ω-6)	0.25 ± 0.01	0.32 ± 0.07	0.28 ± 0.04	0.27 ± 0.00
Dihomo-γ-linolenic	20:3 (ω-6)	ND^{a}	0.14 ± 0.04^{b}	0.12 ± 0.01^{b}	0.13 ± 0.01^{b}
Arachidonic	20:4 (ω-6)	0.41 ± 0.08	1.11 ± 1.39	1.87 ± 0.12	2.09 ± 0.12
∑ (ω-6)		**3.54 ± 0.02**	**3.99 ± 1.33**	**4.78 ± 0.10**	**4.74 ± 0.24**
∑ PUFA		**26.22 ± 0.51^{a}**	**36.08 ± 2.75^{b}**	**35.04 ± 0.52^{b}**	**34.59 ± 0.11^{b}**
ω-3/ω-6		5.07 ± 0.12	7.72 ± 3.36	5.55 ± 0.08	5.49 ± 0.37
PUFA/SFA		1.14 ± 0.03	1.02 ± 0.14	1.03 ± 0.00	0.97 ± 0.00
Polyene Index		1.16 ± 0.05	1.13 ± 0.21	1.17 ± 0.02	1.04 ± 0.00
Atherogenic index (AI)		0.54 ± 0.00^{a}	0.79 ± 0.08^{b}	0.76 ± 0.02^{b}	0.82 ± 0.00^{b}
Thrombogenic index (TI)		0.26 ± 0.01	0.32 ± 0.06	0.32 ± 0.00	0.35 ± 0.01

$^{a, b, c, d,}$ Means of with different superscripts within a row are significantly different at $p < 0.05$. ∑ = sum; SFA = saturated fatty acids; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; ND = not detected.

acids in FM was of the order MUFA > PUFA > SFA, similar to findings by Nogueira et al. (2013). In contrast, the SM and SMg samples were of the order PUFA ≈ SFA > MUFA, which varied from results from Erkan and Özden (2007).

The ratios of ω-3:ω-6 PUFAs were 5.07, 7.72, 5.55 and 5.49 in FM, SM, SMg-1.5 kGy and SMg-3 kGy respectively. There was a higher proportion of ω-3 PUFAs compared to ω-6, which agrees with the assertion that marine fish are richer in ω-3 than ω-6 (Cyprian et al., 2017). The ω-3:ω-6 ratio is a good index for comparing the relative nutritional value of fish, with higher ratios (>1) important in diminishing the risks of coronary heart diseases, plasma lipid levels, and cancer in humans (Küçükgülmez et al., 2018). The ratios from the present study were between 5.07 and 7.72 (FM and SM respectively). The PUFA to SFA ratios were about 1 (i.e., between 0.97 and 1.14, FM and SMg-3 kGy respectively). Regulska-Ilow et al. (2013) stated that a ratio ≥1 could decrease the possibility of atherosclerosis and coronary heart disease, which is in agreement with the results of this study. Irradiation at 1.5 and 3 kGy did not have any significant effect on the fatty acid composition of smoked fish, which agrees with assertions by (Erkan and Özden, 2007).

Lipid quality was assessed using three indices: the polyene index (PI), index of atherogenicity (AI) and index of thrombogenicity (TI) (Table 2). The PI, which, measures oxidative damage to PUFAs (Chaula et al., 2019) ranged from and 1.04 to 1.17 in SMg-3 kGy and SMg-1.5 kGy respectively. There were no significant differences ($p > 0.05$) in these ratios for all samples. The results of this study compare with those by Chaula et al. (2019) who found PI ratios greater than 1 in smoked and sun-dried sardine and inferred a high retention of PUFAs in the products. Consuming foods rich in fatty acids can directly affect the simulation or preclusion of atherosclerosis and coronary thrombosis due to their effect on blood cholesterol and low-density lipoprotein (LDL) cholesterol concentrations (Omri et al., 2019). According to Garaffo et al. (2011), AI and TI can be used to characterize these effects. The AI denotes the relationship between the main pro-atherogenic (saturated fatty acids that favor the adhesion of lipids to cells of the immunological and circulatory system) and anti-atherogenic (unsaturated fatty acids that inhibit the aggregation of plaque and diminishes the levels of esterified fatty acid, cholesterol, and phospholipids, thereby preventing the appearance of micro- and macro-coronary diseases) fatty acids. The TI defines the relationship between the pro-thrombogenetic (saturated) and the anti-thrombogenetic fatty acids (MUFAs, ω-6 PUFAs and ω-3 PUFAs) that have the tendency to form clots in blood vessels (Garaffo et al., 2011). From the results, AI was significantly lower ($p < 0.05$) in FM (0.54) compared to SM, SMg-1.5 kGy and SMg-3 kGy (0. 79, 0.76

Table 3
Amino acid composition of fresh (F), smoked (S) and gamma irradiated (g) mackerel (M) (mg/g) (n = 3).

Amino acids	FM	SM	SMg-1.5 kGy	SMg-3 kGy
Essential (EAA)				
Threonine	9.23 ± 0.89^{a}	17.95 ± 1.08^{b}	18.10 ± 1.03^{b}	18.08 ± 1.90^{b}
Methionine	4.93 ± 1.10^{a}	9.45 ± 0.26^{b}	12.07 ± 1.28^{b}	11.87 ± 3.99^{b}
Valine	19.80 ± 1.00^{a}	41.67 ± 2.54^{bc}	43.84 ± 2.32^{b}	49.38 ± 5.59^{bd}
Histidine	7.06 ± 1.41^{a}	15.84 ± 1.02^{bc}	22.01 ± 2.25^{bde}	25.57 ± 1.87^{bdf}
Lysine	25.26 ± 0.36^{a}	46.52 ± 4.29^{b}	48.30 ± 1.11^{b}	51.92 ± 4.28^{b}
Leucine	13.27 ± 0.49^{a}	29.26 ± 1.10^{b}	27.48 ± 2.01^{bc}	30.81 ± 2.52^{bd}
Phenylalanine	7.36 ± 0.07^{a}	16.26 ± 0.49^{b}	14.97 ± 1.11^{bc}	16.65 ± 0.19^{bd}
Tryptophan	6.44 ± 0.39^{a}	12.98 ± 0.29^{b}	12.57 ± 0.35^{bc}	13.82 ± 1.25^{bd}
Isoleucine	12.96 ± 1.86^{a}	31.58 ± 0.07^{b}	29.65 ± 1.26^{bc}	34.74 ± 3.20^{bd}
∑ EAA	**106.31 ± 4.03^{a}**	**211.50 ± 10.61^{bc}**	**228.98 ± 7.94^{b}**	**252.82 ± 24.79^{bd}**
Non-essential (NEAA)				
Serine	7.58 ± 0.74^{a}	14.12 ± 0.31^{b}	15.40 ± 0.89^{b}	16.70 ± 2.19^{b}
Alanine	7.97 ± 0.39^{a}	17.99 ± 0.69^{b}	18.11 ± 0.48^{b}	19.67 ± 2.24^{b}
Aspartic acid	17.89 ± 0.63^{a}	35.78 ± 3.55^{b}	39.38 ± 3.31^{b}	42.20 ± 7.44^{b}
∑ NEAA	**33.43 ± 1.72^{a}**	**67.90 ± 4.56^{b}**	**72.89 ± 4.69^{b}**	**78.57 ± 11.87^{b}**
Conditionally indispensable (CI)				
Glycine	6.29 ± 0.42^{a}	15.63 ± 1.07^{b}	15.11 ± 0.25^{b}	17.52 ± 2.33^{b}
Proline	5.21 ± 0.55^{a}	12.63 ± 1.28^{b}	13.12 ± 1.02^{b}	14.18 ± 1.25^{b}
Glutamine	28.72 ± 2.32^{a}	52.60 ± 0.56^{b}	52.51 ± 11.80^{b}	57.30 ± 9.95^{b}
Cysteine	1.10 ± 0.29^{a}	2.32 ± 0.12^{a}	2.60 ± 0.3^{b}	2.67 ± 0.48^{b}
Arginine	9.33 ± 0.91^{a}	24.77 ± 6.25^{b}	23.51 ± 3.77^{b}	26.38 ± 5.9^{b}
∑ CI	**50.65 ± 3.91^{a}**	**107.96 ± 9.28^{b}**	**106.86 ± 14.50^{b}**	**118.06 ± 19.92^{b}**
∑ TAA	**190.39 ± 9.66^{a}**	**397.36 ± 24.45^{b}**	**408.73 ± 27.12^{b}**	**449.46 ± 56.59^{b}**
∑ EAA/∑ NEAA+CI	1.27 ± 0.04	1.26 ± 0.04	1.28 ± 0.09	1.29 ± 0.08

$^{a, b,c,d,e,f}$ Means of with different superscripts within a row are significantly different at $p < 0.05$.
∑ = sum; EAA = essential amino acids; NEAA = non-essential amino acids; TAA = total amino acids.

and 0.82 respectively). The TI also ranged between 0.26 and 0.35 in FM and SMg-3 kGy respectively, and these were not statistically different ($p > 0.05$) from the other samples. According to Łuczyńska et al., 2017, AI and TI greater than 1.0 can be detrimental to human health. The results from the present study show AI and TI values below 1.0 (with FM having the lowest estimates), indicating there are reduced risks of atherosclerosis and coronary thrombosis from consuming these products.

3.3. Amino acid composition

A total of 17 amino acids (made up of 9 EAA, 3 NEAA and 5 CI) were identified in this study (Table 3). The presence of the 9 EAAs makes fish protein a 'complete protein', as reported by Otten et al. (2006). Smoking significantly increased ($p < 0.05$) the EAA, NEAA, CI and total amino acid (TAA) by about 100%. Irradiation, however, did not significantly ($p > 0.05$) affect the total amino acid composition compared to the SM samples or between the two doses (1.5 and 3 kGy). All the EAAs were significantly higher ($p < 0.05$) in the smoked samples than FM. Irradiation at the two doses significantly increased ($p < 0.05$) the histidine levels, whiles valine, leucine, phenylalanine, tryptophan, and isoleucine were significantly higher in the 3 kGy samples compared to the 1.5 kGy samples. A study by Al-Kahtani et al. (1998) found significant decreases in these amino acids in Spanish mackerel irradiated at 1.5 kGy. The contrary results could be attributed to fact that the samples were raw while those for the current study were smoked before irradiation. The EAA increased after irradiation, but only significantly in the 3 kGy samples, compared to SM samples.

The total NEAA showed SMg-3 kGy having the highest proportion (78.57 mg/g) and FM having the lowest (33.43 mg/g). Serine and alanine were significantly higher ($p < 0.05$) in all smoked samples, with aspartic acid being significantly higher in the SMg samples relative to both FM and SM. The total CI ranged between 50.65 and 118.06 mg/g for FM and SMg-3 kGy respectively. Glycine, glutamine, arginine and proline were significantly higher ($p < 0.05$) in all smoked samples, compared to the FM samples. Cysteine, on the other hand, was only significantly increased after irradiation. The TAA content in FM, SM and SMg-1.5 kGy and Smg-3 kGy were 190.39, 397.36, 408.73 and 449.46 respectively.

The dominant amino acids were valine, lysine, leucine and isoleucine (EAA); aspartic acid (NEAA); and glutamine (CI), which was comparable with findings by Rosa and Nunes (2003) and Erkan and Özden (2007). Kaya, Turan and Erdem (2008) reported that the lysine content in foods is reduced after smoking as a result of the high temperatures and smoke deposition during smoking and the reaction of lysine with carbonyls in smoke during browning or Mailard reaction. The result from the present study however contradicts these assertions, as lysine levels significantly increased in the smoked products. This could have been as a result of the indirect smoking and hence reduced smoke deposition in the Abuesi gas fish smoker used in the study. The benefits of amino acids in human nutrition have been examined by several authors. Mohanty et al. (2014) reported that aspartic acid, methionine arginine and glycine play an important role in wound healing and also in maintaining the solubility and ionic properties of proteins. Sarma et al. (2013) further reported that methionine, histidine, lysine and tryptophan have antioxidant properties. Again, Kim et al. (1999) stated that glutamine, proline, aspartic acid, glycine and leucine have cytotoxic abilities to kill or damage cancer cells. Irradiation at 1.5 and 3 kGy did not significantly affect these amino acids, meaning that the products i.e., FM, SM and SMg, were all of very good nutritional status.

Amino acids can also be used as quality indices in seafood. Histidine, tyrosine, arginine, tryptamine and lysine are very important during fish spoilage, as they can produce biogenic amines (via decarboxylation by microorganisms), like histamine, tyramine, agmatine, tryptophan and cadaverine respectively (Biji et al., 2016). From the results, the fresh and smoked samples had appreciable levels of these amino acids and hence care should be taken to ensure that microbial activities are diminished during storage to inhibit biogenic amine formation. Again, glutamic acid, aspartic acid, alanine and glycine, are responsible for characteristic flavor and taste of fish Erkan and Özden (2007). Irradiation did not significantly increase these amino acids, and thus caused no changes to the flavor and taste of the irradiated samples, as confirmed by the results sensory analysis. Higher irradiation doses however can change the

Table 4
Skin and muscle color characteristics of smoked (S) and gamma irradiated (g) mackerel (M) (n = 5).

Parameter		SM	SMg-1.5 kGy	SMg-3 kGy
Skin	Lightness (L^*)	34.45 ± 1.31	39.62 ± 2.62	43.91 ± 10.15
	Redness (a^*)	−0.62 ± 0.66	0.31 ± 2.16	−1.10 ± 0.19
	Yellowness (b^*)	5.93 ± 5.16	5.24 ± 0.88	11.66 ± 8.20
Muscle	Lightness (L^*)	60.56 ± 12.25	66.61 ± 6.75	66.62 ± 0.86
	Redness (a^*)	2.66 ± 2.49	3.96 ± 1.24	1.91 ± 0.47
	Yellowness (b^*)	20.03 ± 0.95	17.28 ± 2.13	20.66 ± 1.05

flavor and taste in foods, as reported by Erkan and Özden (2007). Aspartic and glutamic acid also play important roles as general acids in enzyme active centres and maintain the solubility and ionic character of proteins (Özden and Erkan, 2010).

The ratio of EAA to NEAA highlights the important contributions of each to the diet. From the present study, the ratios were 1.27, 1.26, 1.28 and 1.29 for FM, SM, SMg-1.5 kGy and SMg-3 kGy respectively. These were not significantly different ($p > 0.05$). The ratios were higher than those reported by Rosa and Nunes (2003) and Salma and Nizar (2015). It can therefore be inferred that fresh, smoked and irradiated mackerel (at 1.5 and 3 kGy) are important sources of essential amino acids.

3.4. Color analysis

The instrumental skin color measured showed that irradiation increased the lightness (L^*) and yellowness (b^*) from 34.45 to 43.91 and 5.93 to 11.66 in SM and SMg-3 kGy respectively (Table 4). The yellowness (b^*) was also highest in SMg-1.5 kGy. Similar results were obtained for the muscle color. In deciding to purchase dehydrated foods, consumers usually use the color as a quality indicator (Cyprian et al., 2017). In Ghana, the skin color of smoked fish ranges from black, dark brown, golden brown or light brown to dirty white, however, consumers prefer golden brown or dark brown color (Obodai et al., 2009). From the results of the yellowness, the product would be acceptable to most consumers. Irradiation at 1.5 and 3 kGy had no significant effect on the skin and muscle color of smoked mackerel. This agrees with results by Dvorak et al. (2005) that found no differences in color of rainbow trout (*Onchorynchus mykiss*) irradiated at a dose of 3 kGy.

3.5. Sensory analysis

The sensory characteristics of smoked fish mainly determine consumer acceptability of the product, more than any preservation purposes (Fuentes et al., 2010). The mean scores from the difference-from-control test by the trained sensory panel for SM, SMg-1.5 kGy and SMg-3 kGy were 2.3, 2.3 and 2.6 respectively, on the 5-point scale (slight to moderate difference). Irradiation did not affect the sensory quality of the smoked mackerel significantly ($p > 0.05$). The results from the Check-all-that-apply (CATA) showed important attributes such as color, juicy texture, umami flavor, smoked flavor and aroma and herring-like aroma were not significantly different between the treatments. It is not expected that the small differences that the sensory panel found will influence the acceptability of the smoked products, which is in agreement with Badr (2012) that found irradiation at a dose up to 3 kGy had no effect on the sensory acceptability of cold-smoked salmon.

4. Conclusion

The effects of smoking and irradiation at two doses (1.5 and 3 kGy) on the quality of mackerel was investigated. Smoking increased the nutritional profile (protein, fat, fatty acid and amino acid compositions) of the mackerel. Irradiation at 1.5 and 3 kGy had no impact on the nutritional composition (except for a significant increase in EAA of 3 kGy samples relative to smoked samples), sensory and color characteristics of the smoked mackerel. This study therefore suggests that smoked fish, with or without irradiation (at 1.5 and 3 kGy), offer a good source of nutrients in human diets. The effects of these treatments on the shelf life of the product should however be studied to ascertain their efficiency in preserving and extending the shelf life of the products.

CRediT authorship contribution statement

Eunice K. Asamoah: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Project administration, Visualization, Funding acquisition. **Francis K.E. Nunoo:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Samuel Addo:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Josephine O. Nyarko:** Methodology, Investigation. **Stanley A. Acquah:** Methodology, Gamma irradiation. **Grethe Hyldig:** Resources, Laboratory, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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