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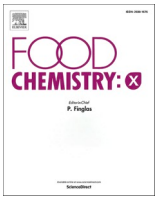

Effect of light treatmeat on oxidation and flavour of dry-cured Wuchang fish

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ABSTRACT

Lighting conditions are an important factor affecting dry-cured products. This study investigated the effects of treatments with different light intensities (0 lx, 1000 lx, 25000 lx) and different light sources including red light, blue light, UV-light on oxidation leve and flavor change in dry-cured Wuchang fish. The results showed that dry-cured Wuchang fish exhibited an attractive brown-yellow color, the highest oxidation degree of myoglobin (Mb), the highest fat oxidation under the light conditions of 25000 lx light intensity and UV-light irradiation. This phenomenon was observed that the degree of Mb oxidation was increased, while the degree of fat oxidation was increased. At 25000 lx light intensity and UV-light irradiation, dry-cured Wuchang fish showed an ignificantly decreased fatty acid conten (especially oleic acid and linoleic acid), significantly increased characteristic volatile compound contents (22 for 25,000 lx light intensity and 27 for UV-light irradiation), which contributed to the improvement of quality stability of dry-cured Wuchang fish. Our findings provide theoretical support for the industrial application of exogenous light in dry-cured Wuchang fish.

1. Introduction

Wuchang fish (*Megalobrama amblycephala*) is commonly known as bream, grass bream, and most of them are distributed in large and medium-sized lakes in the middle reaches of the Yangtze River, mainly in Hubei province, China. Wuchang fish has multiple advantages such as high spawning, reproduction, and survival rates in ponds, fast growth, easy breeding and fishing, high meat content, high nutritional value, and delicious taste, and it is deeply loved by consumers and farmers (Zhao, Hu, & Chen, 2022). Sun-drying is one of the processing methods of Wuchang fish products. Dry-cured Wuchang fish is rich in nutrients, salty, and fragrant. Fish meat is rich in unsaturated fatty acid (UFA), which is easily oxidized and decomposed during the drying and maturation process, thus forming the final flavor of the product. Many studies have found that the main flavor of dry-cured fish is formed in the process of drying and maturation, usually in sun-drying or stove drying (Zhao, Hu, & Chen, 2022). Under the action of protein enzymatic hydrolysis and unsaturated fatty acid oxidation, the degradation products and oxidation products further react to generate volatile flavor components with various contents and types, thus forming fish cured products with different flavors.

Sun-dried fish not only has a unique flavor, but also has less polycyclic aromatic hydrocarbons (PAHs) in volatile substances than smoke-dried fish, and thus sun drying can produce healthier fish products (Jiang et al., 2024; Mahugijaa & Njale, 2018). During sun drying, light is one of the important factors causing food photooxidation, which can change the flavor and quality of food. The existing studies mainly focus on the bad smell produced from milk photooxidation (Tan et al., 2023), the effect of photooxidation on the color change of meat (Qi, Dong, & Zhao, 2016), and the change of photosensitizer (Lu et al., 2021). Photooxidation occurs through two types of reactions (type I and type II). Type-I reaction is a free radical chain reaction in which free radicals

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or free radical ions can react directly with oxygen. In type-II reaction, photosensitizers such as riboflavin, porphyrin, and chlorine are excited by light and react with triplet oxygen in the initial stage of light exposure. Then, singlet oxygen is generated during the photodegradation cascade, which further reacts with proteins, vitamins, and lipids to generate volatile compounds (Tan et al., 2021). Our previous work has found that after light exposure, Wuchang fish can produce characteristic flavor substances including hexanal, nonanal, octanal, heptanal, 2-octanal,(E)-, 2-nonenal,(E), 3-methylbutanal, pentanol, hexanol, nonanol, heptanol, 1-octen-3- ol, 2-octen-1-ol, (E)-, 2-pentyl furan, and D-limonene (Chen et al., 2023).

At present, multiple drying technologies such as cold air drying, vacuum freeze drying, heat pump drying, microwave drying, and infrared drying have been introduced into the industry. The cost of these drying technologies is higher, and the product flavor processed by these technologies is not as rich as that processed by sun drying (Chen et al., 2023). However, due to the influence of environmental factors such as weather and temperature, it is not always possible to provide the best conditions for drying, which leads to great limitations in the processes of curing and drying of traditional dry-cured products, thus resulting in unstable product quality and susceptibility to pollution, discoloration, deterioration, eventually causing certain economic losses (Li et al., 2022). In order to overcome the influence of factors such as weather and environment on the drying of dry-cured fish, and provide stable light conditions to ensure the stability of product flavor, we try to make up for the lack of aroma of industrially-produced dry-cured fish by adding artificial light source to gently promote oxidation.

Therefore, this study added different exogenous light sources, changed the light intensity, used the artificial climate incubator with controlled temperature, humidity and other factors to simulate the light drying treatment of dry-cured Wuchang fish under natural sunlight. We investigated the sensitivity of photosensitizers in fish meat to light conditions, the degree of fat oxidation, and the formation of volatile substances in fish meat under different light conditions. This study was aimed to examine the quality and aroma changes of cured Wuchang fish under different artificial light conditions, and it will provide a reference for flavor regulation in the industrial production of dry-cured fish products.

2. Materials and methods

2.1. Materials

Fresh Wuchang fish, 2 years of age, were selected by 5 laboratory workers from a local seafood market in Hubei Province, China (Longitude, 114.33166002840042, Latitude 30.482391237904523). Wuchang fish with intact morphology and no trauma, weighing about 900 g, were selected for the experiment. Wuchang fish were placed in box filled with water and then they were transported quickly to the laboratory by car.

2.2. Dry-cured treatment

The fish were immediately stunned on the head, and then the gills were removed through an incision near the operculum. Additionally, and the guts were removed. The fish was then rinsed with sterile water. The next step was to drain the water and marinate the fish. Salt was precisely measured at 2 % of the fish's weight and evenly applied to the surface of the fish. The cured fish were neatly stacked in stainless steel tubs and placed in the refrigerator at 4 °C for preservation. Turn every 24 h for 2 days. At the end of the marination, the surface of the fish had been wiped clean of brine and water. For simulated photo-oxidation experiments, the cured fish should first be immersed in 0.001 % aqueous solution of sodium azide to inhibit bacterial growth and enzyme activity. The fish, after undergoing antimicrobial and enzyme inhibition treatments, were placed neatly and flatly in an artificial climate incubator. The fish were evenly divided into two large groups to explore the influence of two lighting factors (light intensity and light source) on Wuchang fish. Xenon light sources of different light intensities (0 lx, 10,000 lx, 25,000 lx) were added to the incubator as a light intensity group to simulate sunlight exposure across the full wavelength spectrum. Three light sources: red light (620–760 nm), blue light (446–464 nm), and UV light (10–380 nm) were added to the incubator as a light source group. Incubators for all groups were maintained at 10 °C and 50 % humidity.

2.3. Measurement of color

The colour of the dry-cured Wuchang fish meat was measured at room temperature by means of a portable colorimeter(CR-400, Konica Minolta Holdings, Inc.,Japan). A standard whiteboard was used for pre-measurement calibration. We tested the color of the back of the fish. Measurement data were expressed as a*, b*, and L*. Three fish were measured for each group.

2.4. Measurement of oxygenated myoglobin and ferromoglobin content

The method for referencing Krzywicki (1982) was slightly modified. Take 3 g of meat sample and add 10 mL of phosphate buffer (0.04 mol/L, pH 6.8). Homogenize the mixture at 13040.352 × g for 25 s, and let it stand at 4 °C for 1 h. Afterward, centrifuge at 1217.502 × g for 30 min. Take the supernatant. Filter the solution using filter paper, then adjust the volume to 25 mL using the same buffer. Finally, measure the filtered solution separately. Its absorbance at wavelengths of 525 nm, 545 nm, 565 nm, and 572 nm. Oxygenating Muscles:

$$MbO_2Content(\%) = (0.882R_1 - 1.267R_2 + 0.809R_3 - 0.36_1) \times 100$$

$$MetMb\ content(\%) = (-2.514R_1 + 0.777R_2 + 0.800R_3 + 1.098) \times 100$$

where R_1, R_2, R_3 are absorbance ratios A^{572}/A^{525}, A^{565}/A^{525}, A^{545}/A^{525}, respectively.

2.5. Determination of lipid oxidation

2.5.1. Total lipid extraction

Please refer to the method of Folch, Vaquero, Comellas, and Broto-Puig (1996) with slight modifications. 5.0 g of chopped fish was accurately weighed into a beaker. Then, 40 mL of a methanol-chloroform solution (1:2, v/v) was added and homogenized for 60 s under ice bath conditions. The resulting homogenate was transferred to a stoppered measuring cylinder and the volume was adjusted to 100 mL. It was then left for 1 h and filtered to remove protein and connective tissue. Next, 0.2 times the volume of physiological saline was added to the filtrate, which was then centrifuged at 1217.502 × g for 15 min. The upper layer was aspirated using a dropper to remove the liquid containing water, methanol, and ionic impurities. The lower layer solution was transferred to a pre-weighed spin vial, dried, and weighed. Finally, it was dried under vacuum in a water bath at 40 ℃ and weighed again.

2.5.2. Lipid separation

The method of Kaluzny, Duncan, Merritt, and Epps (1985) was referenced with slight modifications. Fifty milligrams of total lipids were weighed and dissolved in 5 mL of chloroform. The solution was then completely aspirated using a 500 mg ammonia-propyl solid phase extraction column. Before use, the column should be activated with 20 mL of hexane. The different lipid fractions were separated as follows: first, triglycerides were eluted with 20 mL of a chloroform-isopropanol solution (2:1, v/v). Then, free fatty acids were eluted with 20 mL of a 2 % mass fraction acetic acid-ether solution. Finally, phospholipids were eluted with 30 mL of anhydrous methanol solution. The eluates containing different lipid components were then transferred to a pre-weighed rotary vial and dried under vacuum in a water bath at 40 ℃.

The dried samples were subsequently weighed.

2.5.3. Determination of lipid oxidation

Determination of lipid oxidation. Fat extracted in section 2.5 was assayed for primary lipid oxidation products (LOPs) as Peroxide Value (PV), expressed in meq O/kg of fat, according to the standard titration method (ISO 3960, 2012). The secondary lipid oxidation products (LOPs), reacting with p-anisidine, were detected at 350 nm using the AnV method (ISO 6885: 2008). Additionally, the levels of conjugated dienes (CD) and trienes (CT) were measured using the method described by Pegg (2001) at wavelengths of 232 nm and 268 nm, respectively. All spectrophotometric assays were performed using the Specord 40 device (Analytic Jena, Germany).

2.5.4. Determination of relative fatty acid content

Fatty acid methylation refers to the method described by Garcia Regueiro, Giber, and Diaz (1994) with slight modifications. To the total lipids extracted in section 2.5, as well as the separated lipid components, 5 mL of a 0.5 mol/L sodium hydroxide-methanol solution was added. The mixture was then heated in a boiling water bath for 5 min. Next, 2 mL of a 14 % mass fraction boron trifluoride-methanol solution was added, and the mixture was again heated in a boiling water bath for 5 min. Finally, 1 mL of hexane and ultrapure water were added separately and shaken for 1 min. The upper liquid layer was then aspirated after being left to stratify. The upper layer was filtered through a 0.22 μm organic microporous membrane. Then, 25 μL of methyl nineteenth-alkanoate was added as the internal standard. The volume of *n*-hexane was fixed at 1 mL for gas chromatographic analysis. Gas chromatographic conditions: column: HP-FFAP (100 m × 0.25 mm, 0.25 μm); ramp-up procedure: initial temperature of 90 ℃, holding for 2 min, ramping up to 180 ℃ at a rate of 10 ℃/min, then ramping up to 240 ℃ at a rate of 5 ℃/min, holding for 12 min; carrier gas: high-purity helium gas (99.999 %), flow rate of 1.0 mL/min; injection volume: 1 μL; split ratio: 1:70; inlet temperature: 230 ℃; flame ionization detector temperature: 240 ℃. The retention time of each fatty acid was determined using a mixture of 37 fatty acid methyl esters as standards. Quantitative analysis was conducted using methyl nonadecanoate as the internal standard substance.

Studies have shown that chemical reactions, such as microbial growth and the simultaneous oxidation of protein and lipid in food, follow or at least approximate the first-order kinetics. The first-order oxidation kinetic model is defined as follows:

$$\int_{A_0}^{A_t} \frac{1}{A} da = kt \tag{1}$$

$$\ln \frac{A_t}{A_0} = kt \tag{2}$$

2.6. Gas Chromatography-Mass spectrometry analysis.

The SPME (Supelco, USA) method and GC–MS (Agilent, USA) analysis were consistent with our previous research methods (Chen et al., 2023).

2.7. Electronic nose analysis

The electronic nose's approach was consistent with our previous research methods (Chen et al., 2023).

2.8. Statistical analysis

All experimental results were based on three replicates. All statistical analyses were conducted using SPSS 22 software (IBM Corporation). ANOVA with Duncan's multiple comparison tests was performed to discriminate individual samples for each sensory attribute. The cluster heatmap of aroma compounds in dry-cured fish was created using TBtools v1.09861 software. Other figures were drawn with DataGraph and Graphpad Prism 9 respectively.

3. Results and discussion

3.1. Oxidation of Wuchang fish

3.1.1. Changes in color

Color variation is an important characteristic of dry-cured fish quality. Food presents color because of rich pigments contained in food. In general, the pigment structure in food is mostly a conjugated system composed of C═C double bonds, and there may be several double bonds of heteroatoms such as —C = 0, —N = 0, and —C═S. The desirable color of traditional dry-cured Wuchang fish is yellowish brown. Fig. 1(a) showed the color change of dry-cured Wuchang fish under different lighting conditions. As shown in Fig. 1(a), with the increasing light intensity, the brightness of fish flesh decreased, the yellowness value increased, and the color of fish meat changed from red to yellowish brown as a whole. Light intensity is one of the important conditions affecting photooxidation. Generally, the greater the light intensity, the faster the photooxidation rate. Mb is an oxygen storage protein retained in the intracellular structure, and it is the main pigment in the dark muscle of fish (Thiansilakul, Benjakul, & Richards, 2011). After strong light promotes the conversion of MbO_2 into MetMb, the color of Wuchang fish turns yellowish brown (Huo & Li, 2008). The same phenomenon was observed in the study of the effect of light intensity on beef color. When the light intensity was 500 lx, the color of beef did not change much. When the light intensity increased to 1500 lx, the maximum brightness of the meat color was observed (Cierach & Niedzwiedzj, 2014). Further, we examined the change in fish meat color under different light source conditions. The results showed that red light made dry-cured Wuchang fish redder, while blue-light and UV-light made fish meat yellowish brown (Fig. 1a). What makes muscles red is pigment, which mainly exists in the form of myoglobin, hemoglobin, and cytochrome. Mb is known to be a major contributor to muscle color, and musclue color mainly depends on the redox state of MbO_2 and MetMb and their concentrations (Faustman & Cassens, 1990). Porphyrin in the heme protein induces photooxidation in meat products (Folin, Gennari, & Jori, 1976). Our results showed that red light had little effect on MbO_2, and UV-light and blue light more effectively induced the oxidation of MbO_2 and promoted the conversion of MbO_2 into MetMb, thus reducing the redness degree of fish meat and increasing it yellowness degree. These results were consistent with the change in Mb content (Fig. 1(b)). The above findings suggested that 25000 lx light intensity and UV-light source could bring better color to dry-cured Wuchang fish.

3.1.2. Myoglobin content

Myoglobin (Mb) has photosensitivity, and it falls into different derivative types including oxymyoglobin (MbO_2) and Metmyoglobin (MetMb), which can be transformed into each other. Oxymyoglobin can change the valence state of iron ions under lighting conditions (Kondjoyan, Sicard, & Badaroux, 2022). The effect of lighting conditions on Mb was shown in Fig. 1(b). Our data showed that MbO_2 decreased with the increasing light intensity, while MetMb increased with the increasing light intensity. The highest MetMb content of 45.72 % was observed at light intensity of 25,000 lx. High light intensity can accelerate the generation of radicals in the process of fat oxidation. Radicals can not only convert Fe^{2+} into Fe^{3+}, but also destroy the activity of some enzymes in meat, including MetMb reductase, so that the MetMb produced in the meat storage process cannot be reduced in time. Among different light sources, blue light and UV-lightresulted in the more significant Mb conversion than that under long-wavelength red light. The highest MetMb content of 45.63 per cent was observed under UV light conditions. It has been reported that Mb contains about 3.8 % heme prosthetic and heme molecules are small molecules with a porphyrin

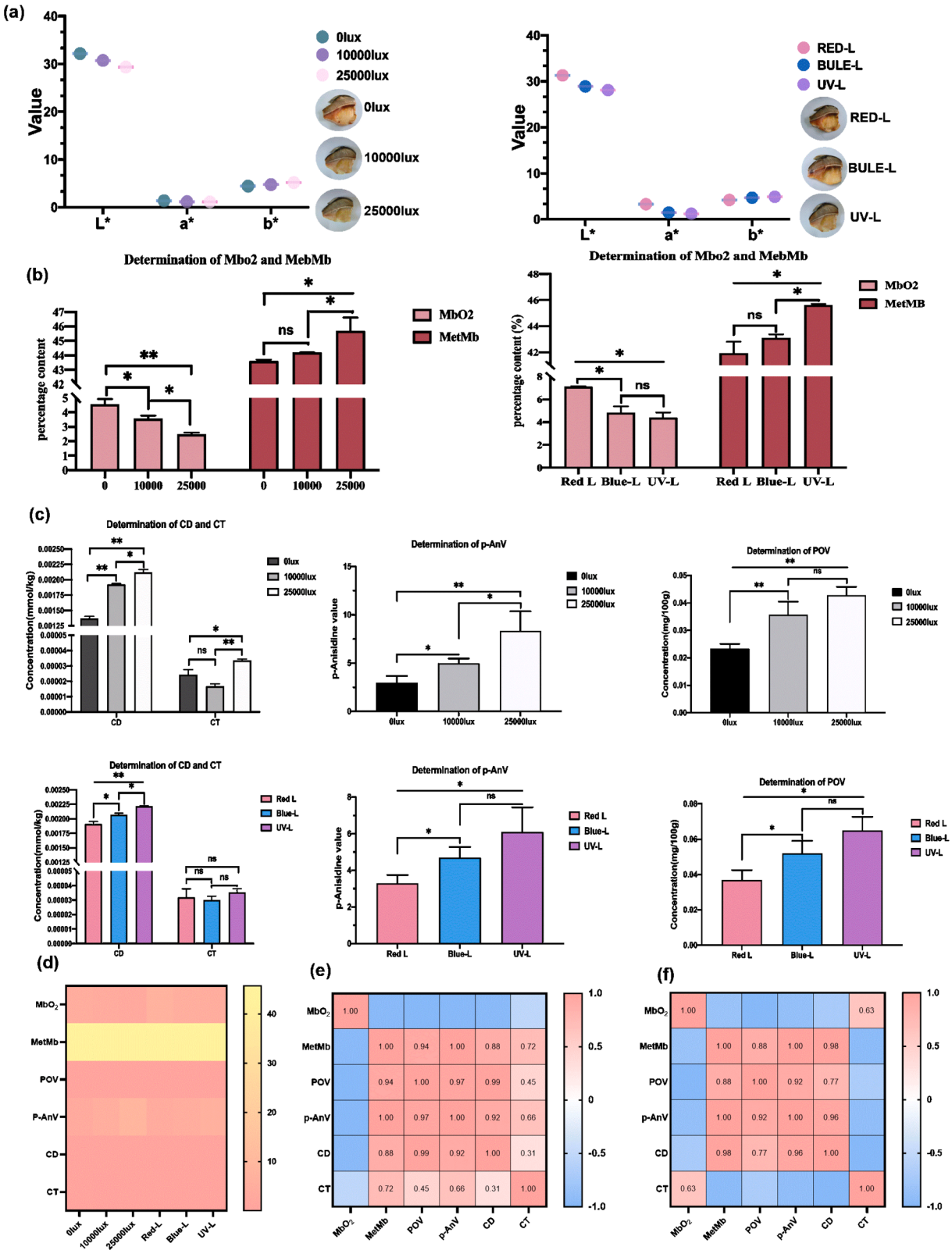

Fig. 1. (a) Effects of different light treatments on the color of dry-cured Wuchang fish. (b) Effects of different light treatments on myoglobin content in dry-cured Wuchang fish. (c) Effects of different light treatments on Lipid oxidation of dry-cured Wuchang fish. (d) Heatmap of the relationship between myoglobin oxidation and lipid oxidation. (e) Pearson analysis of oxidation index under different light intensity. (f) Pearson analysis of oxidation indices under different light source conditions.

ring structure (Voltarelli et al., 2023). The ferriporphyrin can absorb light with the above three wavelengths (Stoumpidi et al., 2023), but after excitation, the excited state of ferriporphyrin is different, and the energy transfer pathway in the late-stage process is also different, and thus the influence of ferriporphyrin on Mb redox varies to some degree. Taken together, lighting conditions of high light tensity and short wavelength can accelerate the oxidation of Mb.

3.1.3. Lipid oxidation

Lipid oxidation is the process by which the fat in a food is oxidised and it affects the flavour quality of the food (Shi et al., 2024). The changes of fat oxidation of fish meat under different lighting conditions were shown in Fig. 1(c). During the oxidation of unsaturated fatty acid, the double bonds of hydroperoxide molecules were rearranged to form a conjugated double bond structure. Conjugated diene (CD) and conjugated triene (CT) exhibit obvious ultraviolet absorption at 232 nm and at 270 nm, respectively, and CD and CT are often used to evaluate the primary oxidation degree of oil. As shown in Fig. 1(c), the CD value and CT value of fish meat fat increased significantly under the light condition of 25000 lx. Compared with that under 25000 lx, the CD value was relatively low under the light condition of 10000 lx and 0 lx, but there was no significant difference in CT value between 10000 lx and 0 lx. The CD value under UV-light was higher than that under the other two light conditions (red and blue lights), but there was no difference in CT value under 3 different light sources. These results indicated that visible light intensity and short-wavelength light could affect the conjugation effect of fatty acids in dried Wuchang fish. With the increase of light intensity and under the influence of short wavelength light source, the lipid oxidation rate of dried Wuchang fish was accelerated, and the formation of hydroperoxide containing conjugated double bonds was increased, UV absorbance was also increased. The effect of light intensity on the p-Anisidine value (p-AnV) of dry-cured Wuchang fish was significant (Fig. 1(c)). The highest p-AnV was observed at 25000 lx light intensity, and the lowest at 0 lx light intensity. The p-AnV of Wuchang fish was larger under UV light and blue light than under red light. Peroxide value (POV), expressed as hydroperoxides per kilogram of fat, is an important indicator of the degree of fat oxidation (Su, Ong, Mofijur, Mahlia, & Ok, 2022). Under the light intensity of 25000 lx, the POV was the highest, and under the light intensity of 0 lx, the POV was the lowest (Fig. 1(c)). The POV was the highest under the UV-light, and it was the lowest under the long-wavelength red light (Fig. 1(c)). These results indicated a higher degree of fat oxidation under high-light intensity and short-wavelength light.

The relationship between Mb oxidation and lipid oxidation

All the three characteristic indicators of fat oxidation indicated that short-wavelength light source and high-intensity light could promote lipid photooxidation. This was consistent with the trend of Mb oxidation (Fig. 1(d)), namely, UV-light and 25000 lx light intensity were more likely to promote the oxidation. There is a strong correlation between Mb oxidation and lipid oxidation by Pearson analysis (Fig. 1(e), (f)). Hutchins, Kliu, and Watts (1967) have found that there is a certain correlation between the accumulation of MetMb in meat and the oxidation value. Mb induction is considered to be one of the causes of lipid oxidation. This may be due to the oxidation of fat caused by photooxidation. The radicals generated during the oxidation process will attack the heme prosthetic part of myoglobin, and Mb, as a scavenger of reactive oxygen species (ROS) in muscles, can absorb radicals to oxidize OxyMb to MetMb. At the same time, lipid oxidation products such as 4-hydroxy-2-nonenal (HNE) can promote the oxidation of OxyMb (Yin et al., 2011). During the oxidation of OxyMb into MetMb, active intermediate superoxide anion free radicals ($\cdot O_2^-$ and $\cdot OOH$) will be generated, and further H_2O_2 is generated through disproportionation. The H_2O_2-MetMb produced from the combination of H_2O_2 and MetMb has a strong ability to induce lipid oxidation. In addition, Fe^{3+} generated from myoglobin oxidation is a catalyst for fat oxidation (Hansen, Skibsted, & Andersen, 1996, which can promote lipid oxidation (Fig. 2).

3.2. Change of flavor

3.2.1. Electronic nose analysis

As shown in Fig. 3(a), all 10 sensors responded to the aroma substances of Wuchang fish, but the differences in the response values were observed. Among them, five sensors W5S, W1W, W2W, W1S, and W2S were more responsive to samples. At the light intensity of 25000 lx, the response value of sensors W1W and W2W to dry-cured fish meat changed significantly; at 10000 lx, that of sensor W2S changed significantly; and at 0 lx, that of sensor W1S changes significantly. Relatively more sulfides and terpenes were produced under 25000 lx light; more alcohols, aldehydes, and ketones under 10000 lx light; and more methyl compounds under 0 lx light intensity. Under different lighting conditions, sensor W5S exhibited the highest response value to fish meat treated with 3 different light sources, indicating that the nitrogen oxide content was high in fish meat. Under the condition of red light, the response value of sensor W2S to fish meat was high, while under the condition of UV-light, sensors W2W and W1W displayed high response value to dry-cured Wuchang fish meat, and higher contents of terpenes and aromatic substances were observed under UV-light condition than under other two light conditions, which was consistent with the detection results of volatile organic compounds (Fig. 3(a)), indicating that UV-light was more conducive to the aroma substance formation of dry-cured Wuchang fish. Overall, different light conditions had a significant impact on the quality and aroma of dry-cured Wuchang fish.

3.2.2. Fatty acid analysis

There are three main types of lipid oxidation substrates including triglycerides, phospholipids, and free fatty acids. Relatively speaking, free fatty acids are most susceptible to oxidative degradation (Raudsepp, Bruggemann, & Lenferink, 2014). The degree of unsaturation, position of double bond, cis–trans configuration, and degree of binding are all closely related to the oxidation properties of fatty acids, indicating that the unsaturated fatty acids are more susceptible to oxidation than other

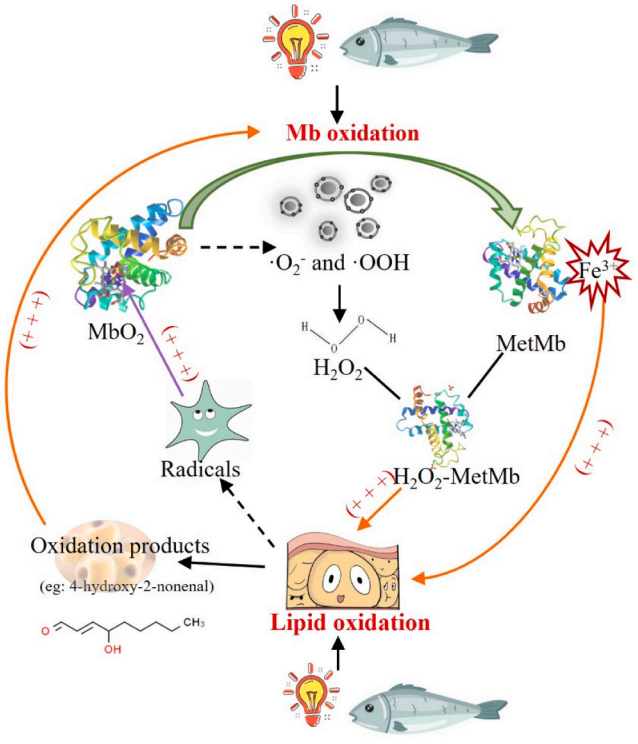

Fig. 2. Mutual promotion of Mb oxidation and lipid oxidation.

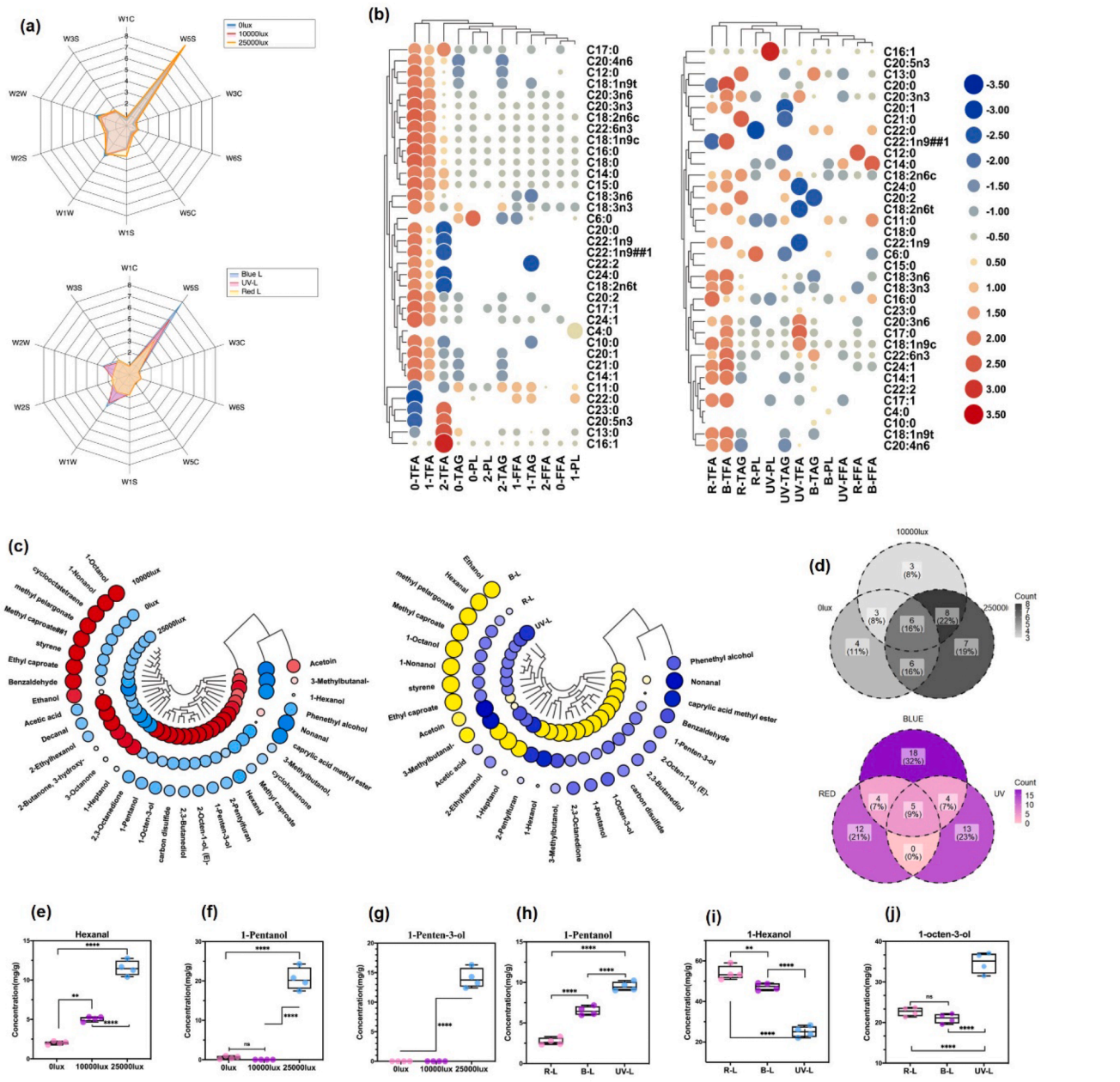

Fig. 3. (a) Effects of different light treatments on the electronic nose of dry-cured Wuchang fish. In the radar map of the electronic nose sensor, the corresponding attributes of each sensor are as follows: W1C, aromatic for benzene; W5S, broadrange; W3C, aromatic for amines; W6S, hydrogen; W1S, Broad-methane; W1W, Sulfur-organic; W2S, Broad-alcohol; W2W, Sulph-chlor; W3S, Methane-aliph. (b) Effects of different light treatments on fatty acids of dry-cured Wuchang fish. (c) Effects of different light treatments on volatile compounds of dry-cured Wuchang fish. (d) Venn diagram of volatile compounds under different light treatments. (e) Effects of different light intensities on hexanal content. (f) Effects of different light intensities on 1-pentanol content. (g) Effects of different light intensities on the content of 1-penten-3-ol. (h) Effects of different wavelength light sources on the content of 1-pentanol. (i) Effect of different wavelength light sources on 1-hexanol. (j) Effects of different wavelength light sources on the content of 1-octen-3-ol.

fatty acids. The photooxidation of lipids is caused by the double bond oxidation of unsaturated fatty acids, and essentially, it is the photooxidation reaction of alkenes. After the transition state, the unsaturated double bond and singlet oxygen ($^1O_2$) generate allyl hydroperoxide, and meanwhile the double bond displacement occurs (Griesbeck & Cho, 2009). When the oil contains photosensitive substances such as MbO_2 and riboflavin, these photosensitive substances will absorb the adjacent visible light or UV-light under direct light irradiation, thus exciting triplet oxygen ($^3O_2$) to form singlet oxygen ($^1O_2$) and produce photooxidation reaction. Due to their high-degree unsaturation and high electron density, unsaturated fatty acids are particularly susceptible to the attack by singlet oxygen to be oxidatively degraded under high light-intensity and short-wavelength light source conditions. Oleic acid (C18:1n9c) and linoleic acid (C18:2n6c) are the unsaturated fatty acids with the highest content in dry-cured Wuchang fish. The changes in fatty acid content in different lipid groups of Wuchang fish samples under different light conditions were shown in Fig. 3(b). The overall trend of change under different light sources and different light intensities was consistent, and there was no significant change in the content of triglyceride. With the decrease in light source wavelength and the increase in light intensity, most of the phospholipids and free fatty acid contents decreased significantly, and the total fatty acid content decreased significantly. The change in unsaturated fatty acid content was greater than the change in saturated fatty acid content. The possible reason

might be that fat oxidation mostly occurs on unsaturated fatty acid, since saturated fatty acid has a stable structure and is not easy to oxidize (Kris-Etherton, Taylor, & Yu-Poth, 2000). Many fatty acids are precursors of volatile flavor substances. Fatty acids are more easily broken down under conditions of high light intensity and low-wavelength light. With the increasing light intensity, the contents of oleic acid (C18:1n9c), linoleic acid (C18:2n6c), and linolenic acid (C20:3n3) decreased significantly, indicating that high-intensity light could promote lipid oxidation. The contents of oleic acid (C18:1n9c) and linoleic acid (C18:2n6c) were the lowest in fish meat samples dried under UV-light irradiation. The content of 9,12,15-Octadecatrienoic acid, methyl ester (C18:3n6) was significantly reduced under the low-wavelength UV-light irradiation. The content of arachidonic acid (C20:4n6) in fish meat irradiated by UV-light was significantly decreased, and the oxidative degradation was intensified. The increase in linolenic acid (C20:3n3) content under UV-light may be due to the transformation of triglyceride linolenic acid and phospholipid linolenic acid into total linolenic acid under UV-light irradiation.

3.2.3. Analysis of flavor

Different light conditions have different effects on volatile organic compounds in dry-cured Wuchang fish. The flavor changes of dried Wuchang fish under different light intensities were shown in Fig. 3(c). At 25000 lx light intensity, most volatile substances (27 types) were detected from dried Wuchang fish, among which sulfide and terpenoids accounted for a large proportion. At 10000 lx light intensity, 19 types of volatile substances were detected, among which alcohols, aldehydes, and ketones had a high percentage. At 0 lx light intensity, 18 types of volatile substances were detected. Hexanal, 1-pentanol, 1-penten-3-ol were very sensitive to light intensity, and when the light intensity increased to 25000 lx, the contents of three substances were significantly increased. Among them, hexanal is the characteristic aroma substance of dry-cured Wuchang fish (Chen et al., 2023). At 25000 lx light intensity, more aroma substances were produced, indicating that 25000 lx was conducive to the formation of characteristic aroma substances in dry-cured Wuchang fish. This was consistent with the change trend of the precursor substance oleic acid. Under the condition of 25000 lx light intensity, the most terpene compounds were produced, suggesting that the aroma substances under this light intensity condition were richer, and the flavor of cured fish meat was also more intense.

Different lighting conditions have different effects on the odor of dry-cured Wuchang fish. Totally, 22 volatile compounds were detected in Wuchang fish under UV-light irradiation, 31 volatile compounds under blue light irradiation, and 21 volatile compounds under red light irradiation. Compared with Wuchang fish treated with different light sources, the dry-cured Wuchang fish treated with different light intensities under the same light source exhibited less flavor difference substances, indicating that the light source had a greater influence on the flavor of Wuchang fish than light intensity. There were significant differences in the types of aroma substances in fish meat irradiated by red light and by UV-light. At the same time, more methyl compounds were detected from the Wuchang fish treated by red light than by other two lights. The volatile components of aldehydes and alcohols mainly come from the oxidation of polyunsaturated fatty acids, and the alcohols also come from the reduction of corresponding aldehydes (Li et al., 2023). Unsaturated aldehydes and alcohols have a lower threshold and contribute more to the smell of fish meat. Aldehydes are more affected by light exposure, which is consistent with previous reports (Coppa et al., 2011). Our data showed that among alcohols, 1-Pentanol and 1-Hexanol were very sensitive to different light sources, and the short-wavelength UV-light promoted the formation of 1-Pentanol (1-Pentanol) and reduced the production of 1-Hexanol. At the same time, the short-wavelength of UV-light promoted the formation of 1-octen-3-ol, a characteristic aroma substance of dry-cured Wuchang fish. In actual production, the application of short-wavelength UV-light and high-intensity light is more conducive to the formation of the flavor of dry-cured Wuchang fish.

The volatile flavor substances of meat are produced by the interaction and degradation of flavor precursors such as proteins, sugars, fats, and amino acids, most of which are derived from lipid oxidation. These volatile flavor substances play an important role in flavor formation of dry-cured Wuchang fish. The volatile flavor compounds in dry-cured Wuchang fish are mainly fat degradation products, such as aldehydes, alcohols, and ketones. Our data showed that oleic acid (C18:1n9c) and linoleic acid (C18:2n6c) were the unsaturated fatty acids with the highest content in marinated Wuchang fish. Ding et al. (2020) have proposed a possible pathway for the oxidation of oleic acid and linoleic acid to generate volatile flavor compounds. Namely, oleic acid undergoes autooxidation, mainly generating 10- hydroperoxide and 11-hydroperoxide, and secondarily generating 8-hydroperoxide, which is further converted to aldehydes. Subsequently, linoleic acid is subjected to the enzymatic oxidation to generate 10-L(S)-hydroperoxy-*cis*-9 and *trans*-11-octadecadieuoic acid, which are converted to 1-octen-3-ol. In this study, with the increasing light intensity, the content of oleic acid was decreased, which was oxidized to produce aldehydes such as hexanal, and the content of hexanal was significantly increased. Linoleic acid was more sensitive to UV-light. Under UV-light conditions, the degree of oxidation of linoleic acid was intensified to generate 1-Octen-3-ol ($p < 0.01$). This is similar to the oxidation products obtained by Ding et al. (2020). The above results indicated that the intensity of light and the wavelength of the light source can regulate the degradation reactions of oleic acid and linoleic acid. The pathways involved in the oxidation of oleic and linoleic acids to generate volatile flavour compounds in dry-cured Wuchang fish need to be further investigated.

4. Conclusion

This study investigated the differences in multiple indicators in dry-cured Wuchang fish processed under 3 light intensities (0 lx, 10000 lx, 25000 lx), and 3 light sources (red-light, blue-light, and UV-light), mainly including the color, aroma, Mb content, primary lipid oxidation products, secondary oxidation products, fatty acid, and volatile organic compounds. UV light and 25000 lx light intensity can promote the oxidation of Wuchang fish. At the same time, the favored color was observed in UV light and light intensity of 25000 lx. The degree of Mb oxidation showed the same trend as that of fat oxidation. We found that there is a correlation between the Mb oxidation and fat oxidation and discussed the mutual promotion mechanism. The change of flavor of dry-cured Wuchang fish was significantly observed under different light conditions. Notably, under 25000 lx light intensity and UV-light irradiation, more volatile aroma substances, more sulfide and terpenes compounds were produced. Therefore, 25000 lx light intensity and UV-light source are suggested to be used in the processing of dry-cured products, which have great potential for improving the flavor of dry-cured products.

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CRediT authorship contribution statement

Lingwei Shen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation,

Conceptualization. **Fangxue Chen:** Writing – review & editing, Visualization, Project administration, Data curation. **Qi Huang:** Validation, Investigation, Conceptualization. **Hongyuan Tan:** Software, Formal analysis. **Yuzhao Ling:** Formal analysis, Data curation. **Wenxing Qiu:** Validation, Data curation. **Mingzhu Zhou:** Formal analysis, Conceptualization. **Dongyin Liu:** Software. **Yu Qiao:** Supervision, Project administration, Funding acquisition. **Lan Wang:** Supervision, Funding acquisition. **Chao Wang:** Supervision. **Wenjin Wu:** Supervision, Funding acquisition.

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

The data that has been used is confidential.

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