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ORIGINAL PAPER

Impact of far-infrared radiation-assisted heat pump drying on chemical compositions and physical properties of squid (*Illex illecebrosus*) fillets

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Abstract Squid fillets were dried in a heat pump (HP) dryer alone or combining with far-infrared radiation (FIR) with the power of 500, 1,000, and 2,000 W at 50 °C and air flow rate of 0.8 m s^{-1}. Proximate composition, total volatile basic nitrogen (TVBN), fatty acid composition, trimethylamine-N-oxide demethylase (TMAOase), dimethylamine (DMA), trimethylamine (TMA), color, and microbial changes of squid were recorded. Results showed that FIR in combination with HP decreased TMAOase, TMA, TVBN, polyunsaturated fatty acids (PUFA), and total aerobic bacterial counts, but increased both saturated (SFA) and monounsaturated (MUFA) fatty acid content, compared with HP alone. Dried squids had higher values of redness and yellowness, but lower values of lightness (L) than raw ones. No significant differences were found in protein, DMA, or L values among all dried samples. The inhibitory effects of FIR on TMAOase, TMA production, and microbial growth were more obvious with increase in the power supplied to the FIR rods. The present data suggest that FIR in combination with HP technology has the potential to retard the quality deterioration of squid.

Keywords Heat pump drying · Far-infrared radiation · Trimethylamine-N-oxide demethylase · Chemical composition · Quality · Squid

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Introduction

Squid is an abundant source of marine protein and has become a popular seafood in the world [1]. Fresh squid has a short shelf life due to its high-moisture content (more than 80%). Therefore, squid has to be preserved in order to increase its shelf life. Drying, such as smoking, hot air drying, or solar drying, is one of the preservation methods that can extend shelf life of the products. In addition, the growing popularity of dried squid consumption has created the need of this process. However, the traditional drying processes have some disadvantages such as long drying time, more nutrient loss, and physical characteristics degradation of the dried products [2]. Therefore, it is imperative to optimize processing conditions to produce high-quality dried products.

Heat pump drying is an alternative drying technique which can improve energy efficiency and independently control the operation parameters [3]. Especially, it allows drying at low and medium temperatures and is suitable for temperature sensitive products [4]. Some works have been done about the effect of this technique on fish [5], shrimps [6], squids [2], and vegetables and fruits [7]. However, there is an inherent problem of uniform drying [2, 3].

The use of infrared radiation technology for dehydrating foods could reduce drying time, maintain uniform temperature in the product, increase energy efficiency, kill microorganism, inhibit enzymatic reaction, and produce better-quality finished products [8, 9]. A few reports have suggested that combing far-infrared radiation (FIR) with other dehydration techniques could shorten drying time, improve nutritional, sensorial, and functional properties of dried products, such as longan [10], banana slices [11],potato, and pineapple [12]. FIR has also been proved to be more effective in products containing higher moisture content [10, 12]. Therefore, far-infrared radiation-assisted heat pump drying was seemed to be suitable for heat-sensitive squids with high-moisture content. However, no work has been reported on the combination of FIR and heat pump systems for drying squids and other aquatic products as yet.

Our previous work has characterized drying kinetics, shrinkage, rehydration rate, and texture of squid fillets under heat pump combined with far-infrared radiation drying system (submitted to Boiosystems Engineering). Thus, the objective of the present study was to explore the effect of far-infrared radiation-assisted heat pump drying on dried squid fillet qualities, including main chemical compositions, trimethylamine-N-oxide demethylase (TMAOase), dimethylamine (DMA), trimethylamine (TMA), physical properties, and microbial changes.

Materials and methods

Materials

Commercial frozen Argentina squids (*Illex illecebrosus*) were procured in August 2010 from the local fishery market in Shanghai, China. The samples were brought to the laboratory and first defrosted in a refrigerator at 4 °C overnight. The average weight of the squid block before filleting was approximately 7.5 kg. Then, all samples were sliced by an electric food slicer into rectangular sheets with an average length of 8.0 ± 0.5 cm, width of 4.0 ± 0.5 cm, and thickness of 3.0 ± 0.5 cm.

Salting

After filleting, the squid pieces were immersed at 4 °C in 3% (w/w) sodium chloride solutions for 14 h at a ratio of 4 L/kg of samples. After salting, the samples were removed from the solution, quickly rinsed with distilled water (ca. 30 s) to remove the excessive solutions, and then gently blotted with tissue paper to remove excess water.

Drying

The squid samples were dried in a heat pump dryer. Three infrared heaters with the power of 500 W, 1,000 W, and 2,000 W were installed inside the dryer. All heat pump drying experiments were conducted at the temperature of 50 °C as recommended by Ren [2] and ~0.8 m/s air velocity. Pretreated samples (~2,000.0 ± 10 g) were spread as a single layer on a mesh tray and dried at 50 °C (HP), HP + 500 W (HP + 5FIR), HP + 1,000 W (HP + 10FIR), and HP + 2,000 W (HP + 20FIR). Samples were dried until reached the final moisture content (<20% dry solids). The dried squids were allowed to cool down at room temperature for ca.10 min and then packed immediately into polyethylene bags for further analysis. Drying experiments were carried out in triplicate.

Proximate composition

Moisture, ash, crude fat, and crude protein content were determined according to the AOAC methods [13]. All measurements were done in triplicate.

Fatty acid compositions

Fat extraction and fatty acid compositions were determined as described by Wu and Mao [14]. Fatty acid compositions of the squids were analyzed with an Agilent 6890 Gas Chromatograph (GC) with 5973 MSD system (Palo Alto, CA, USA) in EI mode (70 eV). Full-scan mass spectra were recorded for analysis identification. Separation was achieved with a fused-silica capillary column with 5% diphenyl poly (~30 m length, 0.2 mm i.d., 0.33 m film thickness). The sample splitting ratio was 20:1. The injector temperature was 250 °C. The heat process of GC oven was as follows: the oven was held at 100 °C for 3 min, ramped to 190 °C at 20 °C min^{-1}, kept for 10 min, then raised to 205 °C at 5 °C min^{-1}, kept for 6 min, then raised to 230 °C at 10 °C min^{-1}, and hold for 5 min. Helium was used as a carrier gas at a constant flow of 1.0 mL min^{-1}. Fatty acid peak in the squid samples were identified by comparing the retention times with that of the standard methyl esters (Sigma, St. Louis, MO). The amounts of each fatty acid and its isomers present were expressed as percentages of the total fatty acid content. All measurements were made in triplicate.

Trimethylamine-N-oxide demethylase (TMAOase) extraction and determination

TMAOase crude extract and assay were performed according to the methods of Gou et al. [15], with some modifications. Finely minced squid samples were mixed

with 20 mM Tris–acetate buffer (pH, 7.0) containing 0.1 M NaCl and 0.1% Triton X-100 at a ratio of 1: 2 (w/v) and stirred continuously at 4 °C for 30 min. The homogenate was centrifuged at 38,500×*g* at 4 °C for 30 min (GL-22 M, Shanghai Luxiangyi Centrifuge Instrument Co., Ltd., China). The supernatant was collected as an extract of the enzyme for determination of TMAOase activity. The TMAOase activity was determined using TMAO as a substrate in the presence of selected cofactors. The reaction medium contained 0.5 mL of enzyme extract and 2.5 mL of 24 mM Tris–acetate containing 24 mM TMAO, 2.4 mM cysteine, 2.4 mM ascorbate, and 0.24 mM $FeCl_2$ (pH 7.0). The reaction mixture was incubated at 25 °C for precisely 20 min, and 1 mL of 30% trichloroacetic acid (TCA) was added to terminate the reaction. The reaction mixture was then centrifuged at 8,000 ×*g* for 15 min, and the supernatant was subjected to DMA determination. One unit of TMAOase activity was expressed as 1 nmol DMA production under the incubation with an enzyme for 1 s (nkat). The 'katal' is defined as the amount of catalysis that releases 1 mol of DMA per second [15]. All measurements were done in triplicate. All measurements were made in triplicate.

Dimethylamine (DMA) and Trimethylamine (TMA) determination

A sample of 10 g was mixed with 50 mL of 7.5% cold trichloroacetic acid (TCA) solution and incubated at 25 °C for 24 h. The swelling squid samples were homogenized with a homogenizer for 3 min and centrifuged at 3,000×*g* for 15 min in a GL-22 M high-speed refrigerated centrifuge (Shanghai Luxiangyi Centrifuge Instrument Co., Ltd., China). The supernatant neutralized with 1 M NaOH was used for the determinations of DMA and TMA. The DMA and TMA were determined by the copper-dithiocarbamate method and the colorimetric method, respectively, as described by Gou et al. [15]. All measurements were done in triplicate.

Total volatile basic nitrogen

Total volatile basic nitrogen in term of mg N per 100 g squids was determined by the method of Antonacopoulos and Vyncke [16]. All measurements were done in triplicate.

Color

Color of dried samples was measured using a Color Difference Meter (WSC-S, Shanghai Precise Scientific Apparatus, Shanghai, China). CIE-Lab coordinates were obtained from the reflection spectra of the samples using a D65 illuminant and the observer at 10. Color parameters range from L = 0 (black) to L = 100 (white); −a (greenness) to +a (redness), and −b (blueness) to +b (yellowness). The hue angle h (h = arctg (b/a)) and the chroma C ($C = (a^2 + b^2)^{0.5}$) were also calculated. Twenty individual samples were tested for each treatment.

Microbial analysis

Aerobic mesophilic bacteria were determined on plate count agar following the pour plate method. A 25 g of the sample was aseptically taken and mixed with 225 mL sterile saline solution and then homogenized for about 2 min. Tenfold dilution series were prepared in peptone saline solution as needed for plating. One milliliter of the mixture or the solution diluted to 10^{-3} to 10^{-6} was brought on pouring plates of plate count agar to determine the total aerobic plate count. After an incubation period of 48 h at 36 °C, colony forming units (CFU) were counted. Each treatment has been repeated four times.

Data analysis

The data were analyzed using ANOVA ($p < 0.05$). Mean differences were established by the Duncan's multiple range tests. The data were analyzed using SAS 8.0 statistical data analytical software.

Results and discussion

Proximate composition

The crude protein, lipid, ash, and moisture of raw squids were 13.38 ± 1.85, 0.34 ± 0.01, 1.05 ± 0.02, and 83.73 ± 0.39%, based on fresh weight, respectively. These values were within the general range of 13.0–19.2% for protein, 0.29–2.0% for fat, and 74.0–84.18% for moisture content in squid [2, 17]. These differences in proximate compositions of squids are associated with species, age, sex, reproductive status, etc. The proximate compositions of all dried squid were given in Table 1. Compared with the initial proximate compositions, the reduction in the moisture content was the most prominent change in squid fillets after drying. In addition, the contents of protein and ash increased significantly in all dried samples. The increase in protein after drying is due to water elimination, agreeing with previous reports [14]. No significant difference in protein is a consequence of protein nitrogen was not lost during drying. An increase of ash levels was associated with salting and dehydration processes. However, no significant differences were found in protein or ash contents among all the drying treatments ($p < 0.05$).

Table 1 Proximate compositions of squid samples (g/100 g dry product)

Drying methods	Moisture	Protein	Fat	Ash
Raw		68.33 ± 0.80[b]	5.22 ± 0.44[a]	6.24 ± 0.16[b]
HP	17.61 ± 0.78[a]	70.45 ± 0.99[a]	3.31 ± 0.03[b]	14.80 ± 0.08[a]
HP + 5FIR	17.60 ± 0.94[a]	70.02 ± 1.66[a]	3.23 ± 0.02[b]	14.67 ± 0.20[a]
HP + 10FIR	17.44 ± 1.01[a]	69.05 ± 1.37[a]	3.10 ± 0.05[b]	14.26 ± 0.01[a]
HP + 20FIR	16.96 ± 0.86[a]	71.08 ± 0.72[a]	1.49 ± 0.50[c]	14.21 ± 0.07[a]

Each value is expressed as an average ± standard deviation ($n = 3$). Means in same column with same lowercase letters are not significantly different ($p < 0.05$)

HP heat pump drying, *HP + 5FIR* heat pump drying combining with far-infrared radiation with the power of 500 W, *HP + 10FIR* heat pump drying combining with far-infrared radiation with the power of 1,000 W, and *HP + 20FIR* heat pump drying combining with far-infrared radiation with the power of 2,000 W

Drying led to a sensible decrease in fat levels based on dry weight in all dried squids. Moreover, the fat contents of squids dried by FIR + 20HP were lower than those of samples dried by other treatments. The fat loss during drying was due to exuding with the moisture evaporation [14] and FIR at 2,000 W made this phenomenon worse.

Fatty acid compositions

Table 2 showed the percentage composition of fatty acids of squid fillets under different drying types together with the raw squid. Among saturated fatty acids (SFA) in the squid fillets, palmitic acid (C16:0) was the most abundant (39.9%) and followed by stearic acid (C18:0) (13.9%) as shown in Table 2. It was also observed that the levels of C16:0, C18:0, and C17:0 in all dried products were statistically significantly lower than those in raw ones ($p < 0.05$). However, the relative contents of C14:0 and C19:0 exhibited a slight increase after drying except for HP drying. Furthermore, squids dried by HP + FIR had 1.5-fold higher C16:0 content in comparison with the sample dried only by HP (Table 2). HP + 10FIR-dried samples showed the smallest loss of the total content of SFA (11.4%), followed by HP + 5FIR- and HP + 20FIR-dried samples (13.6 and 13.8%, respectively), while HP alone led to the greatest loss (35.1%).

The major monounsaturated fatty acids (MUFA) accumulated in the squid were eicosanoic acid (C20:1) (11.34%), oleic acid (C18:1) (6.82%), and erucic acid (C22:1) (3.99%). After drying, the sum of MUFAs decreased significantly ($p < 0.05$), ranging from 22.15% in raw fillets to 12.89% in HP-dried samples, 13.91% in HP + 5FIR-treated samples, 15.21% in HP + 10FIR-dried samples, and 14.93% in HP + 20FIR-dried ones (Table 2). However, the use of FIR did not influence the content change of C20:1. And, there were no significant differences in C18:1 or C22:1 between HP and HP + 5FIR ($p < 0.05$).

Two principal polyunsaturated fatty acids (PUFA) were identified in squid fillets, they were EPA (C20:5) (6.13%) and DHA (C22:6) (13.84%), respectively. The two PUFA contents increased significantly after drying processes compared with the raw squids ($p < 0.05$) (Table 2). The highest levels of C20:5 and C22:6 were found in the samples dried by HP + 5FIR and HP drying, respectively. FIR at 500 W resulted in more obvious increasing of EPA or DHA than at 1,000 W and 2,000 W, while no significant differences were observed for EPA or DHA level between HP + 10FIR and HP + 20FIR. The total level of PUFA increased from 19.97% in raw fillets to 49.05% in HP-dried samples and 33.39-38.05% in HP + FIR-dried ones.

In a word, drying processes resulted in an increase of PUFA but a declination of MUFA and SFA, in agreement with previous reports [14]. However, more research should be done on how the uses of FIR impact the contents and structures of fatty acids.

Trimethylamine-N-oxide demethylase (TMAOase), dimethylamine (DMA), and trimethylamine (TMA)

As shown in Table 3, TMAOase activity was 0.64 nkat/g in frozen Argentina squid. Gou et al. [15] reported that the initial TMAOase activity in raw squid (*T. pacificus*) was 9.96 nkat/g. The activity of TMAOase depended on species, different organs and tissues, age, process condition, etc. After drying, there were significant decreases in TMAOase activities ($p < 0.05$), which suggested that drying treatments effectively inactivated the TMAOase. Previous works showed that FIR can be effectively used to inactivate enzymes such as lipase, α-amylase, etc. [9]. HP + FIR gave lower TMAOase activity than HP alone due to the inhibiting effect of FIR on TMAOase. The activity of TMAOase in HP + 5FIR-dried fillets was about twice higher than that in HP + 10FIR or HP + 20FIR-treated samples; however, there were no statistically significant differences between HP + 10FIR and HP + 20FIR treatment ($p < 0.05$) (Table 3). TMAOase can catalyze the decomposition of trimethylamine-N-oxide (TMAO) to form formaldehyde (FA) and dimethylamine (DMA) in equimolar amounts. The rate of catalytic reaction is closely related to temperature,

Table 2 Main fatty acids profile of squid fillets (g/100 g fatty acids)

Fatty acids	Raw	HP	HP + 5FIR	HP + 10FIR	HP + 20FIR
Saturated acids					
C12:0	0.09 ± 0.03^{a}	0.07 ± 0.00^{a}	0.07 ± 0.01^{a}	0.08 ± 0.02^{a}	0.05 ± 0.01^{b}
C14:0	1.37 ± 0.05^{b}	0.93 ± 0.01^{c}	1.45 ± 0.11^{a}	1.44 ± 0.04^{a}	1.46 ± 0.07^{a}
C15:0	0.53 ± 0.01^{a}	ND	0.50 ± 0.01^{a}	0.46 ± 0.06^{a}	0.49 ± 0.03^{a}
C16:0	39.90 ± 0.22^{a}	23.76 ± 0.03^{c}	33.80 ± 0.10^{b}	34.70 ± 0.08^{b}	34.75 ± 0.09^{b}
C17:0	2.99 ± 0.03^{a}	1.26 ± 0.05^{c}	1.47 ± 0.01^{b}	1.52 ± 0.02^{b}	1.49 ± 0.02^{b}
C18:0	13.90 ± 0.07^{a}	12.08 ± 0.11^{c}	12.06 ± 0.04^{c}	12.75 ± 0.01^{b}	12.03 ± 0.03^{c}
C19:0	0.25 ± 0.01^{c}	0.21 ± 0.06^{c}	0.58 ± 0.03^{b}	1.34 ± 0.00^{a}	0.60 ± 0.01^{b}
$\sum$ SFAs	59.03	38.31	49.93	52.29	50.87
Monounsaturated acids					
C18:1	6.82 ± 0.16^{a}	2.20 ± 0.09^{d}	2.30 ± 0.03^{d}	3.18 ± 0.02^{c}	3.83 ± 0.02^{b}
C20:1	11.34 ± 0.06^{a}	7.72 ± 0.08^{c}	8.52 ± 0.03^{b}	8.87 ± 0.02^{b}	8.47 ± 0.04^{b}
C22:1	3.99 ± 0.03^{a}	2.97 ± 0.13^{d}	3.09 ± 0.09^{d}	3.16 ± 0.01^{b}	2.63 ± 0.05^{c}
$\sum$MUFs	22.15	12.89	13.91	15.21	14.93
Polyunsaturated acid					
C20:5	6.13 ± 0.09^{c}	13.96 ± 0.17^{b}	14.06 ± 0.04^{a}	13.33 ± 0.03^{b}	11.11 ± 0.08^{b}
C22:6	13.84 ± 0.04^{d}	35.09 ± 0.03^{a}	23.99 ± 0.03^{b}	20.06 ± 0.07^{c}	19.94 ± 0.20^{c}
$\sum$ PUFs	19.97	49.05	38.05	33.39	33.9

Each value is expressed as an average ± standard deviation ($n = 3$). Means in same row with same lowercase letters are not significantly different ($p < 0.05$)

ND not detected

HP heat pump drying, *HP + 5FIR* heat pump drying combining with far-infrared radiation with the power of 500 W, *HP + 10FIR* heat pump drying combining with far-infrared radiation with the power of 1,000 W, and *HP + 20FIR* heat pump drying combining with far-infrared radiation with the power of 2,000 W

reducing conditions, species, and muscle integrity of samples [18]. The formation of FA contributes to the denaturation and/or aggregation of protein and the loss of texture and functionality, which in turn cause quality deterioration and decrease their storage life of the products [19]. FA is not easily extracted due to its tissue-binding property [14]. Therefore, the level of FA was estimated by that of DMA in this work. DMA content has been used as the most useful chemical index of frozen fish quality [20]. Results from Table 3 showed that DMA increased considerably during drying, and the DMA in all dried fillets was about 5 times higher than that in the raw samples ($p < 0.05$). Similar results were reported by Ryu et al. [21], who found that DMA in cuttlefish during drying increased 16 times compared with the fresh product, and that the level of DMA in roasted mackerel appeared to be 6 times higher than the fresh product, but was 8 times higher on canning. However, Spinelli and Koury [22] stated that no DMA and only small amounts of TMA were formed during the drum- or freeze-drying cycle. These different results indicated that the pathway(s) of TMAO degradation in the muscle may not be completely understood. There were no statistically

Table 3 TMAOase activity, DMA, TMA, and TVBN contents of squid samples

	TMAOase activity (nkat/g)	DMA content (μmol/g)	TMA content (μmol/g)	TVBN (mg/100 g sample)
Raw	0.64 ± 0.01^{a}	0.88 ± 0.03^{b}	2.36 ± 0.09^{d}	17.34 ± 1.91^{d}
HP	0.35 ± 0.12^{b}	4.09 ± 0.21^{a}	2.75 ± 0.05^{a}	55.49 ± 2.36^{a}
HP + 5FIR	0.25 ± 0.09^{c}	4.46 ± 0.15^{a}	2.52 ± 0.01^{b}	47.36 ± 2.17^{b}
HP + 10FIR	0.12 ± 0.05^{d}	4.54 ± 0.14^{a}	2.50 ± 0.06^{b}	36.10 ± 2.39^{c}
HP + 20FIR	0.11 ± 0.02^{d}	4.62 ± 0.12^{a}	2.43 ± 0.15^{c}	34.33 ± 0.93^{c}

Each value is expressed as an average ± standard deviation ($n = 3$). Means in same column with same lowercase letters are not significantly different ($p < 0.05$)

HP heat pump drying, *HP + 5FIR* heat pump drying combining with far-infrared radiation with the power of 500 W, *HP + 10FIR* heat pump drying combining with far-infrared radiation with the power of 1,000 W, and *HP + 20FIR* heat pump drying combining with far-infrared radiation with the power of 2,000 W

TMAOase Trimethylamine-N-oxide demethylase, *DMA* dimethylamine, *TMA* trimethylamine, *TVBN* total volatile basic nitrogen

significant differences ($p < 0.05$) in the DMA values among all drying methods.

Trimethylamine (TMA) in seafood is produced from trimethylamine oxide (TMAO) possibly partly by the action of intrinsic enzymes but certainly through bacterial action [14, 23], which can be also used as an indicator for assessing fish quality. Table 3 showed that TMA content of the raw squid was about 2.36 μmol/g, which was higher than that of the raw squid (*T. pacificus*) (0.12 μmol/g) [15]. The difference in TMA content was associated with process, specie, age, time of year, muscle type, and diet of fish [20, 23]. From Table 3, all dried fillets had a higher level of TMA than raw ones ($p < 0.05$). This may be attributed to two factors: (a) dehydration provoked an increase in concentrations of all the metabolites including TMA and (b) much larger amounts of TMA could be formed during long storage in chilled water and in the case of processes such as salting prior to drying [20]. When FIR was combined with HP drying, the TMA level decreased with increased power supplied to FIR heater. This was ascribed to the fact that FIR treatment could lead to potentially lethal damage of microorganism and enzymatic inactivation [8, 9].

Total volatile basic nitrogen

Total volatile basic nitrogen (TVBN) is an important characteristic for the assessment of quality in seafood products and appears as the most common chemical indicators of marine fish spoilage [20]. TVBN values for squids were presented in Table 3. The initial TVBN value of raw squid was 17.34 mg/100 g sample. Comparable result was reported on jumbo squid (*Dosidicus gigas*) of 14.67 ± 0.10 mg/100 g sample [24]. However, the TVBN values of all dried fillets were higher than those of raw squids ($p < 0.05$). The TVBN content was the highest in the fillets dried by HP, followed by HP + 5FIR, HP + 10FIR, and HP + 20FIR, and exceeded the legal limit of 30 mg/100 g, which is set by the China Seafood Sanitation Standards. Vega-Gálvez et al. [24] also found that the process temperatures of 80 and 90 °C led to TVBN values greater than the Chilean Food Sanitation limit of 60 mg/100 g. In fact, the acceptable limit of squid TVBN depends on the species, size, environmental and physiological conditions, processing and storage conditions [20, 24, 25, 27]. This increase phenomenon in TVBN content may be attributed to high levels of ammonium chloride (NH_4Cl) in the cellular medium in the squid, which changed into ammonium hydroxide and then ammonia during the period of assay of TVBN [24, 27]. Thus, the finally quantified compound included the products of microbial protein decomposition and NH_4Cl decomposition in alkaline media.

Color

Color changes of muscles are associated with browning reactions, the degree of structural changes of protein as well as its derivatives, and concentration of myoglobin [24, 25]. The color parameters of dried squids were shown in Table 4. The lightness (L) values of dried fillets (79.40–81.85) decreased significantly compared with those of raw squids (94.29), and all dried squid fillets presented higher values of redness (a) and yellowness (b) than raw ones ($p < 0.05$). These results were in agreement with previous reports on osmosed jumbo squid fillets during convective dehydration at 50, 60, 70, 80, and 90 °C [24]. There were no statistically differences in L values among all drying methods. Combined of FIR and HP drying increased the redness (a) values compared with HP alone; however, the FIR intensity did not affect a values significantly ($p < 0.05$). There were no significant differences in b values among HP-, HP + 5FIR- and HP + 10FIR-dried samples ($p < 0.05$), but HP + 20FIR-dried samples had significantly high b values. Similar results were reports by Nathakaranakule et al. [10] who found that FIR-assisted HP drying processes increased the values of redness and yellowness and lowered the values of lightness of the dried logan. The decrease in L value and increase in a and b values indicated the increase of browning discoloration in the dried squid fillets. Vega-Gálvez et al. [24] also

Table 4 Changes in color of squid samples

	L	a	b	C	h
Raw	94.29 ± 1.43^{a}	-2.35 ± 1.11^{c}	2.76 ± 1.41^{c}	3.62 ± 1.01^{c}	310.39 ± 6.79^{a}
HP	80.48 ± 0.97^{b}	1.10 ± 1.42^{b}	23.75 ± 3.89^{b}	23.77 ± 3.12^{b}	87.39 ± 3.07^{b}
HP + 5FIR	81.85 ± 1.23^{b}	2.81 ± 1.13^{a}	23.32 ± 1.44^{b}	23.49 ± 2.33^{b}	83.17 ± 2.56^{c}
HP + 10FIR	80.45 ± 1.82^{b}	3.14 ± 1.46^{a}	25.53 ± 2.58^{b}	25.72 ± 2.05^{b}	83.03 ± 1.99^{c}
HP + 20FIR	79.40 ± 1.83^{b}	4.06 ± 1.96^{a}	28.69 ± 3.37^{a}	28.96 ± 2.31^{a}	81.99 ± 4.24^{c}

Each value is expressed as an average ± standard deviation ($n = 12$). Means in same column with same lowercase letters are not significantly different ($p < 0.05$)

HP heat pump drying, *HP + 5FIR* heat pump drying combining with far-infrared radiation with the power of 500 W, *HP + 10FIR* heat pump drying combining with far-infrared radiation with the power of 1,000 W, and *HP + 20FIR* heat pump drying combining with far-infrared radiation with the power of 2,000 W

observed that the color changes of dried jumbo squid were related to non-enzymatic browning reactions. Maillard non-enzymatic browning reactions should involve a condensation between a carbonyl compound and a free amino group. Squid is rich in proteins and free amino acids; therefore, browning is a serious problem in squid processing and storage, depending on squid species and treatment conditions [2, 25]. Compared with other three dried samples, the HP + 20FIR-dried ones had a darker and more yellow color (Table 4), which could be due to the acceleration of Maillard reaction at the power of 2,000 W. The chroma (C) value indicates the degree of saturation of color. The C values of dried squid fillets were higher than those of raw ones ($p < 0.05$) (Table 4). The effects of drying treatments on C values closely followed the b values. The hue angle (h) has been used to indicate the color stability of fresh and processed meats. Compared with raw squid, the hue angle significantly decreased when samples were dried ($p < 0.05$), showing that color became more stable. No significant differences were found in h values among HP + FIR-dried samples ($p < 0.05$) (Table 4).

Total aerobic plate count

Figure 1 showed the effects of drying methods on the aerobic mesophilic count of squid fillets. The initial number of aerobic mesophilic for the raw squids was 5. 56 log cfu/g. The drying process resulted in a significant microbial load decrease ($p < 0.05$) in the dried samples. The effects of FIR on total plate counts were more obvious with increase in the power supplied to the FIR heaters. After drying, the counts in HP + 5FIR-dried samples were about 2.5-fold higher than in HP + 20FIR-dried ones. These results revealed that FIR irradiation-assisted heat pump drying was more effective for killing bacterial cells and bacterial spores. FIR (3–1,000 μm wavelength) radiation is easily absorbed by water and organic materials. There are some reports on the application of FIR heating to inactivate microorganisms from the surface of food [8, 26]. However, the counts (Fig. 1) did not exactly reflect the amount of TMA produced (Table 3). This phenomenon also confirmed that the TMA production can only be used as an index of bacteria spoilage for only certain species such as *Photobacterium, Shewanella, Vibrio, Rhodobacter,* and enterobacteria and not as an index of freshness of seafood [15, 20].

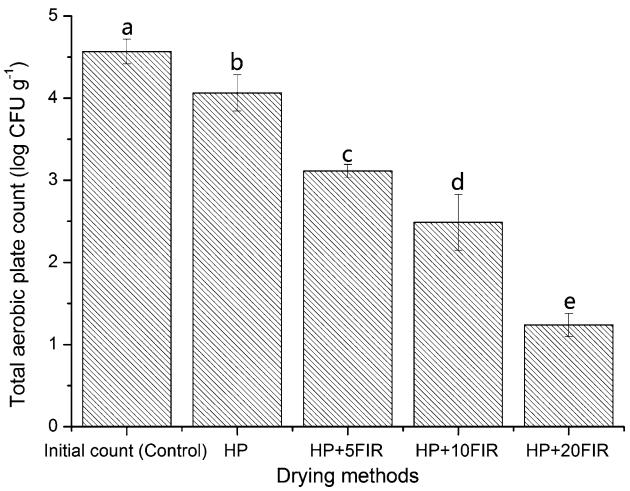

Fig. 1 Total aerobic mesophilic count of squid fillets

Conclusions

The present results showed that drying led to a significant increase of protein, DMA, TMA, TVBN, redness (a) and yellowness (b) values, but a reduction in fat, TMAOase, and lightness (L). Combination of FIR with HP processes gave lower TMAOase activity, TMA, TVBN, PUFA, and aerobic bacterial number, but higher SFA and MUFA content than HP alone. All dried squid fillets showed lower values of lightness (L), but higher values of redness and yellowness than raw ones. All drying treatments did not led to statistically significant variations in protein, DMA, or L values of the squid fillets. When FIR was combined with HP drying, the products showed less TMAOase activity, TMA production, and total microbial counts along with the increase in the power supplied to FIR. It can be seen that drying process increased considerably the amount of TVBN and exceeded the legal limit. Therefore, it is necessary to choose more suitable TVBN determination method, processing and storage environments, species, etc., in order to reduce its content until reaching the legal limit. The present study provides a possible application of FIR combined with HP drying as an efficient drying process for squid fillets, and optimization of squid quality during drying process requires more investigations in order to overcome the constraints related to structural and functional dried squid behavior.

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