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Abstract

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Keywords

shell egg, irradiation, color, physicochemical property, functional

Disciplines

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Effect of Irradiating Shell Eggs on Quality Attributes and Functional Properties of Yolk and White

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ABSTRACT Shell eggs were irradiated and the physicochemical, and functional properties of egg yolk and white were determined. The color of egg yolk was not affected, but the viscosity of egg white was dramatically lowered and became watery by irradiation. The foam capacity and foam stability of egg white were significantly decreased due to protein oxidation by irradiation. However, the texture characteristics of egg white were not changed by irradiation, indicating that irradiation may not alter the thermal characteristics of egg white proteins. Sulfur volatiles were generated by irradiation but disappeared during storage under aerobic conditions. Because egg white became watery, irradiation may not be advisable for table eggs but may be useful for pasteurizing liquid egg white or liquid whole egg without significant deterioration of their quality and functionality. In particular, the dramatic decrease in the viscosity of egg white by irradiation will improve flow of liquid egg white or liquid whole egg, which could be highly useful for egg processing.

(*Key words*: shell egg, irradiation, color, physicochemical property, functional)

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INTRODUCTION

Salmonellosis in humans caused by *Salmonella enteritidis* (SE) has steadily increased throughout the past decades in the United States. The rate of SE infections has increased from 2.38 per 100,000 populations in 1985 to 3.9 per 100,000 in 1995. Although the rate has declined to 1.98 per 100,000 in 1999, no further reduction in the rate of infection has been observed since 2001 (Centers for Disease Control, 2003). From 1985 to 1999, a total of 841 cases of salmonellosis outbreaks accounted for 29,763 illness and 79 deaths, and 80% of outbreaks with a confirmed food vehicle (298 out of the 371) were associated with shell eggs and egg-containing products (Patrick et al., 2004). Investigations of SE sporadic infections and outbreaks have indicated that undercooked and raw shell eggs are a major cause of SE infections in humans (Centers for Disease Control, 2003; Patrick et al., 2004).

Eggs usually become infected in the upper oviduct of SE-infected laying hens. The SE not only contaminates the surface of the eggshell but also exists in egg yolk and white (Gast and Beard, 1990). Therefore, a process is needed before pasteurization that can eliminate SE in egg yolk and white. Irradiation is the only nonthermal method that can efficiently eliminate foodborne pathogens such as *Salmonella*, *Escherichai coli*, and *Listeria* inside shell eggs. Narvaiz et al. (1992) reported that *Salmonella* and other pathogens in egg yolks can be controlled by an irradiation dose above 2 kGy, and Serrano et al. (1997) suggested that SE in shell eggs and liquid whole eggs could be effectively reduced (approximately 4 $\log_{10}$) by 1.5 kGy of irradiation.

The Food and Drug Administration approved irradiation of shell eggs with doses up to 3 kGy (USDA-Food Safety and Inspection Service, 2000). Irradiation produces free radicals that can cause significant changes in quality and functional properties of egg and egg products (Branka et al., 1992). Irradiation increases the oxidation of polyunsaturated fatty acids and cholesterol, changes color, and destroys carotenoids in dehydrated egg products (Katusin-Razem et al., 1992; Lebovics et al., 1992; Du and Ahn, 2000). Irradiation of shell eggs substantially deteriorates the internal and sensory quality of eggs, decreases the viscosity of egg white, and partially degrades egg proteins (Ma et al., 1990). However, Huang et al. (1997) reported that 2.5 kGy of irradiation does not cause substantial changes in physical, chemical, and functional properties, such as color, protein degradation, protein solubility, or emulsion capacity of frozen liquid egg yolk. An irradiation dose of 1.5 kGy did not affect color and thermal characteristics of shell eggs and liquid whole eggs

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Abbreviation Key: SE = *Salmonella enteritidis*; b* = CIELAB yellowness value; IRCF = improved Roche color fan; TPA = texture profile analysis.

(Serrano et al. (1997). Some (Ma et al., 1993; Huang et al., 1997) have even suggested that important functional properties such as whipping, emulsion, and thermal gelation properties of shell eggs and egg products could be improved by low-dose irradiation (1 to 3 kGy). Wong et al. (1996) indicated that irradiated liquid egg white has greater foaming stability and more stable viscosity than thermally pasteurized egg white.

Irradiation is considered the most effective decontamination technique for shell eggs and egg products. However, the effects of irradiation on the physicochemical and functional properties of shell eggs and liquid egg yolk and white are still controversial. The objective of this study was to determine the effects of irradiation on the quality attributes of egg yolk and white in shell eggs.

MATERIALS AND METHODS

Sample Preparation

The eggs were processed (washed, graded, and packaged) online on the same day and stored in a 4°C cooler before shipping. Upon receipt, the eggs were stored in a 4°C cooler until irradiated. Eggs were placed on pulp cartons and irradiated at 1 or 2 kGy using a linear accelerator (Circe IIIR, Thomsom CSF Linac, St-Aubin, France) with 10 MeV of energy, 5.6 kW of power level, and 61.3 kGy/min of average dose rate. Because of the height of eggs, all eggs were irradiated twice; after the first irradiation, eggs were turned upside down for the second irradiation. Alanine dosimeters were attached on the top and bottom of an egg per each cart, and the absorbed doses were measured by 104 Electron Paramagnetic Resonance Instrument (Bruker Instruments Inc., Billerica, MA). The ranges of absorbed doses were 1.286 to 1.301 kGy for 1 kGy and 2.110 to 2.182 kGy for 2 kGy, respectively. Nonirradiated control samples were brought into the irradiation facility to expose to the same environment as the irradiated ones. After irradiation, all eggs were broken, and the yolk and white were separated and stored at 4°C until used.

Color Determination of Egg Yolk

Color of egg yolk was determined using objective and subjective methods. For the objective color measurement, separated egg yolk was placed into zipper bags (polyethylene, 4 × 6 in., 2 mil), and CIELAB color values were read on the surface of the zipper bags containing egg yolk (LabScan colorimeter, Hunter Associate Labs, Inc., Reston, VA). Calibration was conducted with black and white reference tiles covered with the same zipper bag as used for samples. An illuminant A was used as a light source to determine the CIELAB color values of lightness (L*), redness (a*), and yellowness (b*). Two random readings from both sides of the zipper bags were measured, and the average values were used. For the subjective method, the color of unbroken egg yolk was measured using a 10-point improved Roche color fan (IRCF, Hoffman LaRoche, Nutley, NJ). The number of the closest matching color in the IRCF was used as the designated color score of the yolk.

pH and Viscosity of Egg White

The pH of separated egg white was determined using a pH meter (model 420Aplus, Themo Orion, Beverly, MA) after diluting the samples with 9 volumes of distilled water. A viscometer (model DV-II+, Brookfield Engineering Labs Inc., Stoughton, MA) with a no. 1 RV spindle rotating at 100 rpm was used to measure the viscosity of egg white, 400 mL of which was placed in a 600-mL beaker at room temperature.

Protein Oxidation in Egg White

The concentration of protein carbonyls in egg white was measured for the estimation of protein oxidation using the modified method of Mercier et al. (2001). One milliliter of egg white was diluted with 19 mL of deionized distilled water (DDW) and then homogenized using a polytron (type PT 10/35, Brinkman Instruments, Inc., Westbury, NY) for 5 s at high speed. One milliliter of diluted egg white was divided into 2 aliquots of 0.5 mL. Proteins in both aliquots were precipitated with 0.5 mL of 20% tricholoroacetic acid (TCA). Both aliquots were centrifuged at 3,000 × *g* for 10 min, and then supernatants were discarded. The pellet of one aliquot was treated with 1 mL of 2 *N* HCl and the other with 1 mL of 0.2% 2,4-dinitrophenylhydrazine in 2 *N* HCl (wt/vol). The samples were placed at room temperature for 1 h with regular stirring, precipitated with 1 mL of 20% TCA, and then centrifuged at 3000 × *g* for 10 min. The pellets were collected and washed twice with ethanol/ethyl acetate (1:1), dissolved in 2 mL of 6 *M* guanidine-HCl in 20 m*M* sodium phosphate buffer (pH 6.5), and then centrifuged at 3,000 × *g* for 10 min to remove insoluble debris. The absorbance of supernatants from HCl-treated and 2,4-dinitrophenylhydrazine-treated samples were taken to obtain protein carbonyl content using the molar extinction coefficient of 21,000 m/cm for protein hydrazone. Protein concentration was determined at 280 nm with HCl-treated samples, using BSA in the 6 *M* guanidine solution as a standard.

Foaming Properties of Egg White

Foam density and foam stability of egg white were measured using the modified method of Wong et al. (1996). Fifty grams of egg white was weighed and mixed in a mixer (model ono. KSM5PPWH, KitchenAid, St. Joseph, MI) at maximum speed for 3 min. To determine specific density, the foam formed was transferred into a weighing dish, whose volume was previously measured, and then weighed. Foam stability was determined by measuring drainage after 30 min of holding the foam at room temperature. Drainage was collected in a 100-mL graduated volumetric cylinder, and the volume was read.

Texture Profiling and Sensory Analysis of Hard-cooked Egg White

One hundred milliliters of egg white was poured into a 25-mm diameter cellulose casing to produce sausage-like cylindrical sticks. The products were heated in boiling water for 18 min and then cooled down to room temperature. After the casing was peeled away, the products were cut into pieces that were 2.0 cm long and then used for texture profile analysis (TPA) (Bourne, 1982). Texture was measured using a Texture Analyzer (model TA-XT2i, Texture Technologies, Scarsdale, NY) with a 25-kg loading cell and a cylinder probe (TA-4, 38-mm diameter) attached to a converter (TA-71). The samples were compressed by 2 repeated cycles with 70% compression of the height at 1 mm/s crosshead speed. Three pieces from each stick were taken and measured, and then the data from these 3 pieces were averaged. Hardness, springiness, cohesiveness, chewiness, and gumminess obtained from the TPA curve were reported.

A 14-member trained sensory panel evaluated the texture characteristics of hard-cooked egg white. Training sessions were conducted to familiarize panelists with terms for texture characteristics [i.e., hardness, cohesiveness, and elasticity (springiness)] determined in this study. The definition of each term for texture profiles was as follows: 1) hardness is the force required to bring teeth together at first bite, 2) cohesiveness is the extent to which a material can be deformed before rupturing during first bite, and 3) elasticity is the amount of recovery of the sample from a deformed state to its undeformed conditions when the deforming force is removed (Brennan, 1988). Hard-cooked egg white pieces with the same size and shape as described in TPA were served to each panelist in isolated booths. Samples were served to the panelists in random order after the sample was adjusted to room temperature. The panelists marked the intensity of each texture characteristic on a 15-cm unstructured line anchored from very soft to very hard for hardness, from none to extremely cohesive for cohesiveness, from weak to extremely strong for elasticity, and from not acceptable to highly acceptable for overall acceptance of texture.

Volatile Analysis of Egg White

Volatiles from egg white were analyzed using a dynamic headspace gas chromatography-mass spectrometery method (Nam et al., 2004). Three grams of egg white was placed in a 40-mL sample vial, flushed with helium gas (40 psi) for 3 s, and then tightly capped with a Teflon-fluorocarbon resin-silicone septum. The vial was placed onto the temperature-controlled loading tray (4°C) of an autosampler (Tekmar-Dorham, Cincinnati, OH). The waiting time of samples on the loading tray was less than 2 h to minimize any changes during waiting. The sample was purged with helium gas (40 mL/min) for 15 min at 40°C. Volatiles were collected and trapped in a Tenax-charcoal-silica column (Tekmar-Dorham). After being trapped, the volatiles were desorbed for 2 min at 225°C, focused into a cryofocusing module (–80°C, Tekmar-Dorham), and then injected into a gas chromatography column for 60 s at 225°C. The column used in this study was a combined column (Hewlett-Packard Co., Wilmington, DE) and consisted of 3 different columns connected by zero dead-volume column connectors, an HP-624 column (7.5 m × 0.25 mm, 0.25-μm film thickness), an HP-1 column (52.5 m × 0.25 mm, 0.25-μm film thickness), and an HP-wax column (7.5 m × 0.25 mm, 0.25-μm film thickness). Ramped oven temperature conditions (initially held for 1.5 min at 0°C then increased to 15°C at 2.5°C/min, immediately increased to 45°C at 5°C/min, increased to 110°C at 20°C/min, and increased to 210°C at 10°C/min then held for 2.25 min) was used to improve the separation and reduce running time. Constant column pressure at 22.5 psi was applied. Helium gas as a carrier gas, and a constant flow rate (1.7 mL/min) was used. The volatiles separated by the gas chromatograph were identified using the mass spectrometry detector. The ionization potential of the mass spectrometer was 70 eV, and the scan range was 29.1 to 350 m/z. The identification of volatiles was performed by using the Wiley Library (Hewlett-Packard Co.). The area of each peak was integrated using the ChemStation software (Hewlett-Packard Co.). The peak area (total ion counts × 10^4) for each volatile was reported as the amount of the volatile generated from egg white.

Table 1. The CIELAB color values and improved Roche color fan values of egg yolk irradiated with different doses

Color values[1]	Nonirradiated control	Irradiated 1 kGy	Irradiated 2 kGy	SEM
L*	54.89	55.57	56.95	0.82
a*	10.74[a]	10.04[ab]	9.81[b]	0.18
b*	75.00[a]	71.95[b]	71.83[b]	1.11
IRCF value	8.83	8.33	7.88	0.44

[a,b]Means with different letters within the same row are significantly different ($P \leq 0.05$); n = 4.

[1]L* = lightness; a* redness; b* = yellowness; IRCF value = improved Roche Color Fan value on a 10-point scale.

Statistical Analysis

This study was conducted using a completely randomized design with 4 replications except for volatile analysis (3 replications), and the data were analyzed using a JMP software (version 5.1.1) provided by SAS Institute Inc. Data were reported as means and standard error of the means. Tukey's method ($P \leq 0.05$) was used to compare the means of each treatment (Kuehl, 2000).

RESULTS AND DISCUSSION

The b* values were significantly decreased with the increase of irradiation dose, but IRCF values for egg yolks were not significantly changed by irradiation (Table 1). The changes in yellowness of egg yolks could have been caused by the breakdown of carotenoids in egg yolks

Table 2. pH and protein carbonyl content of liquid egg white irradiated with different doses

Measurement	Nonirradiated control	Irradiated 1 kGy	Irradiated 2 kGy	SEM
pH	9.05	8.98	8.99	0.99
Protein oxidation[1]	4.40[b]	5.04[ab]	5.57[a]	0.19

[a,b]Means with different letters within the same row are significantly different ($P \leq 0.05$); n = 4.

[1]Unit of protein carbonyl content: nanomoles of 2,4-dinitrophenylhydrazine per milligram of protein.

during irradiation (Katusin-Razem et al., 1989). Serrano et al. (1997) reported that up to 1.5 kGy of irradiation did not induce detectable changes of Hunter color values in egg yolks. On the other hand, Ma et al. (1993) found that eggs irradiated at 2.37 kGy or higher doses had lower Roche yellow color fan values than those that were not irradiated. Our results indicated that the b* values between nonirradiated and irradiated egg yolk were significantly different, but humans could not recognize the differences. There might be certain threshold values for the organoleptic sensitivity of humans, which differs from that of instruments. Therefore, we suggest that irradiation dose up to 2 kGy does not cause significant color changes in egg yolks.

Irradiation did not change the pH of egg white (Table 2). The pH of egg white (pH = ~9) measured in this study was higher than that (pH = 7.6 ~ 8.5) of newly laid eggs. Li-Chan et al. (1995) reported that the pH of egg white during storage of shell eggs increases to a maximum value of pH ~9.7 because of the evacuation of CO_2 gas through pores in the shell. This indicated that irradiation did not affect the pore structure of the eggshell. Total carbonyl contents in egg white proteins increased with the increase of irradiation dose. Carbonyl contents can be considered as a marker for protein oxidation because amino acid residues of proteins, such as histidine, arginine, methionine, lysine, and cysteine, can be oxidized to carbonyl derivatives by oxidative stresses (Butterfield et al., 1998). The free radicals produced by irradiation can cause protein oxidation, which can affect the structural and functional properties of proteins in egg white. Therefore, these changes in proteins may influence the physicochemical and functional properties of egg white.

The viscosity and foaming properties of liquid egg white from nonirradiated and irradiated shell eggs are shown in Table 3. The viscosity of egg white decreased dramatically by irradiation regardless of irradiation doses used. All egg white became watery even after irradiating shell eggs at 1.0 kGy, but the changes in the viscosity of egg white were independent to irradiation dose. Li-Chan et al. (1995) reported that ovomucin, one of the major proteins in egg white, plays an important role in the gel-like structure of egg white. It has been suggested that irradiation causes changes in carbohydrate and protein moieties involved in formation of ovomucin complex, resulting in a loss of gel-like structure (Ma et al., 1990). The dramatic decrease in the viscosity of egg white is an important physical change in egg by irradiation, which can be used in egg processing. Watery egg white will facilitate the separation of egg white and yolk, and low viscosity can improve the flow of liquid egg white or liquid whole egg in plant facilities that break eggs.

Table 3. Viscosity and foaming properties of liquid egg white irradiated with different doses

Measurement	Nonirradiated control	Irradiated 1 kGy	Irradiated 2 kGy	SEM
Viscosity (cP)	45.0[a]	25.4[b]	23.3[b]	0.63
Foam density (g/mL)	0.11[c]	0.14[b]	0.21[a]	0.01
Foam stability (mL)[1]	7.83[c]	11.70[b]	20.15[a]	0.87

[a–c]Means with different letters within the same row are significantly different ($P \leq 0.05$); n = 4.

[1]Foam stability = volume of drainage.

Table 4. Texture profile analysis of hard-cooked egg white made from liquid egg white irradiated with different doses[1]

Characteristic[2]	Nonirradiated control	Irradiated 1 kGy	Irradiated 2 kGy	SEM
Hardness (N)	4.30	4.78	4.36	0.19
Springiness	0.88	0.88	0.86	0.01
Cohesiveness	0.23	0.25	0.18	0.02
Gumminess	1.05	1.26	0.84	0.12
Chewiness	0.92	1.10	0.73	0.10

[1]n = 4.

[2]Hardness = the peak force during the first compression cycle; springiness = the ratio of length between the first compression (L_1) and second compression (L_2): L_2/L_1); cohesiveness = the ratio of the area of work during the second (A_2) compression divided by the area of work during the first (A_1) compression: A_2/A_1); chewiness = hardness × cohesiveness × springiness.

Egg white is an excellent foaming agent. Both specific density and drainage of the foam formed from egg white significantly increased with the increase of irradiation dose (Table 3). The method for measuring specific density of foam is an indirect method for determining foam capacity. The foam stability was determined by measuring the volume of drain released from the foam in a given time. Thus, the data in Table 3 indicate that the foaming capability and foam stability of egg white decreased with the increase of irradiation dose, which agree with the results of Ball and Gardner (1968) who indicated that irradiated liquid egg white showed an increase in beating time and a decrease in foam stability. The formation of foam depends on the surface activity and film formation properties of protein components present in a food system. Yang and Baldwin (1995) suggested that the mixture of various proteins such as egg white can be a good foaming agent because each protein achieves a different function during foaming (e.g., globulins contribute to the formation of foam and ovomucin and lysozyme to foam stability). They also indicated that the viscosity of liquid egg white is positively related to foam properties. Therefore, the oxidative changes of proteins by irradiation, especially globulins, ovomucin, and lysozyme, would result in deterioration of foam properties in egg white. In contrast, Ma et al. (1990) reported that the whipping ability and foaming

Table 5. Sensory analysis of hard-cooked egg white made from liquid egg white irradiated with different doses[1]

Characteristic[2]	Nonirradiated control	Irradiated 1 kGy	Irradiated 2 kGy	SEM
Hardness (N)	5.8	6.3	7.3	0.7
Cohesiveness	7.8	8.0	6.8	1.0
Elasticity	8.9	8.3	6.7	1.3
Overall acceptance	8.0	9.5	8.3	1.0

[1]n = 4.

[2]Hardness = the peak force during the first compression cycle; springiness = the ratio of length between the first compression (L_1) and second compression (L_2): $L_2/L1$); cohesiveness = the ratio of the area of work during the second (A_2) compression divided by the area of work during the first (A_1) compression: A_2/A_1); chewiness = hardness × cohesiveness × springiness); resilience (the ratio of the area during the withdrawal of the first compression divided by the area of the first compression).

stability of egg white was improved after 2.37 and 2.98 kGy irradiation due to conformational changes of proteins in egg white, which increased surface hydrophobicity and lowered viscosity. The formation of foam from egg white could be affected by various factors such as methods of beating, pretreatments, and addition of ingredients (Yang and Baldwin, 1995). Therefore, more studies are needed to determine the effect of irradiation on the functional properties of liquid egg white.

Several studies have suggested that irradiation at <3.5 kGy did not affect the gelation properties of liquid egg white significantly (Ma et al.; 1990, Serrano et al., 1997). The TPA showed that hardness, springiness (elasticity), cohesiveness, gumminess, and chewiness of irradiated cooked egg white were not different from that of whites that were not irradiated (Table 4). Sensory analysis also could not detect any texture differences between irradiated and nonirradiated hard-cooked egg whites (Table 5). Therefore, we suggest that irradiation of shell eggs at <2.0 kGy does not alter the thermal characteristics of egg white proteins.

Volatiles of egg white from nonirradiated and irradiated shell eggs were compared in Table 6. The amounts of several volatiles in nonirradiated egg white increased with the increase of irradiation dose, and several new volatiles were generated after irradiation. The amount of total volatiles generated from egg white irradiated at 2 kGy was significantly higher than that from nonirradiated and eggs irradiated at 1.0 kGy. Sulfur-containing compounds such as S-methyl thioacetate and dimethyl disulfide were newly generated by irradiation. Ahn and Lee (2002) indicated that sulfur-containing compounds are highly irradiation-dependent and generated by the radiolysis of sulfur-containing amino acids. Many other volatiles can be formed from egg proteins and lipids by irradiation via the radiolytic degradation of amino acid side chain and the secondary reaction between products of the primary degradation. Ahn et al. (2000) indicated that sulfur compounds are responsible for off-odor in irradiated meat. However, the sulfur compounds produced by irradiation disappeared during storage under aerobic conditions because of their high volatility. Therefore, irradiation-dependent odor, which potentially exists in irradiated liquid egg white soon after irradiation, may be eliminated during processing under aerobic conditions.

In conclusion, irradiation of shell eggs does not cause significant deterioration in functional properties, color, or odor of egg yolk and white. However, irradiation is not recommended for pasteurizing table eggs because it liquefies egg white, which lowers the Haugh units of egg dramatically. If used for pasteurizing liquid eggs, however, irradiation can improve the flow of liquid egg, which will improve the efficiency of egg processing steps such as adding or mixing for removal of sugars and for spray-drying. Therefore, further studies on egg irradiation should be focused on liquid eggs rather than table eggs.

Table 6. Volatile profiles of liquid egg white influenced by irradiation at different doses

Volatiles	Nonirradiated control	Irradiated 1 kGy	Irradiated 2 kGy	SEM
	(total ion counts × 10^4)			
Acetaldehyde	399^{c}	2,273^{b}	3,510^{a}	47
Propanal	0^{b}	0^{b}	101^{a}	7
2-Propanone	721^{c}	1,532^{b}	2,214^{a}	109
2-Methly propanal	0^{c}	493^{b}	895^{a}	39
Ethanol	6,433^{b}	9,985^{b}	24,662^{a}	2,781
2-Propanol	616^{b}	847^{ab}	1,237^{a}	110
Hexane	115	141	142	18
2-Butanone	119^{c}	540^{b}	1,007^{a}	50
3-Methyl butanal	0^{c}	579^{b}	1,187^{a}	87
2-Methyl butanal	0^{c}	347^{b}	708^{a}	47
Benzene	0^{b}	0^{b}	88^{a}	0
2-Butanol	321	432	532	60
Pentanal	0^{b}	94^{ab}	185^{a}	23
S-Methyl thioacetate	0^{b}	0^{b}	103^{a}	6
Dimethyl disulfide	0^{b}	321^{b}	1,610^{a}	136
Toluene	0^{b}	253^{b}	834^{a}	64
1-Octene	53^{b}	63^{ab}	82^{a}	6
Octane	0^{b}	0^{b}	43^{a}	5
Hexanal	175^{b}	432^{b}	925^{a}	98
Heptanal	0^{b}	155^{ab}	287^{a}	63
Total	8,952^{b}	18,487^{b}	40,424^{a}	2,932

[a–c]Means with different letters within the same row are significantly different ($P \leq 0.05$); n = 3.

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