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Quality Changes of N-3 PUFAs Enriched and Conventional Eggs under Different Home Storage Conditions with Wireless Sensor Network

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Abstract: Omega-3 polyunsaturated fatty acids (n-3 PUFAs) enriched eggs are popular for their enrichment of PUFAs, but their freshness and quality are prone to decline with time, particularly if storage conditions are not well maintained. Home storage is the last but a neglected important tach in eggs supply chain, but few studies are available on the egg storage in the home stage. This study aimed to evaluate the internal quality change of both n-3 PUFAs enriched and conventional eggs by simulating eggs stored at consumers' home in refrigeration and under room temperature. The egg quality indices (Haugh unit, yolk index, weight, and albumen pH) were adopted and analyzed for both storage conditions. Wireless sensor network (WSN) was used for real-time monitoring of the temperature and humidity during storage. The results showed that temperature, humidity and time of storage all have an influence on the freshness of both n-3 PUFAs enriched and conventional eggs and there is no significant difference happened to n-3 PUFAs enriched eggs and conventional eggs. Refrigeration can decelerate the quality deterioration of both n-3 PUFAs enriched and conventional eggs and consumers should be educated about how to maintain the internal quality of eggs during home storage.

Keywords: egg quality; Omega-3 polyunsaturated fatty acids (n-3 PUFAs) enriched eggs; Wireless sensor network (WSN); temperature; humidity

1. Introduction

As one of the most essential polyunsaturated fatty acids (PUFAs), omega-3 (n-3) PUFAs play an important role in the development of human beings' nervous systems and protection against cardiovascular disease, as well as the prevention of breast and colorectal cancers [1–3]. With consumer's increasing awareness about health benefits of PUFAs [4], a variety of functional foods fortified with PUFAs have been developed, among which n-3 PUFAs enriched egg is becoming more and more popular. The egg is not only an important source of nutrients for the human being [5] but is also considered as an ideal delivery system for n-3 PUFAs, as its composition can be modified to more functions through the manipulation of laying hen diets [5,6]. Hens fed with n-3 PUFAs enriched diets, such as fish oil, seaweed, and flaxseed can produce eggs enriched with n-3 PUFAs [3,7] and provide a new way for the human being to enhance the intake of n-3 PUFAs in diets.

Like conventional eggs, n-3 PUFAs enriched eggs are also highly perishable, whose freshness and quality start to decline as soon as laid by hens [8–10] and through the whole supply chain from poultry farm to consumers' dining table. Egg quality is further influenced by both extrinsic (such as environmental conditions) and intrinsic factors (such as nutrients and water activity). The main environmental factors affecting these processes are the storage temperature and humidity [11–14] as well as storage time [15] during commercial circulation after laying until consumption.

Home storage is the last but not the least important stage in the eggs supply chain [16–18]. Refrigeration is believed to be the most commonly used method to preserve internal egg quality [19] at home, hence the eggs are recommended to be kept under refrigeration at home in the European Union (EU) countries [20] and Egg regulations of United States Department of Agriculture (USDA) [21] required the cooler should be capable of maintaining an ambient air temperature of 7.2 °C or lower and a relative humidity of 40 to 70 percent for a long time storage of eggs. However, there are no regulations or suggestions to tell consumers how to keep eggs at home in China yet. Data on the effects of storage conditions on n-3 PUFAs enriched eggs quality are very limited and even few studies have covered the time-temperature history of eggs after shopping until consumption during home storage.

As an advanced technology, wireless sensor network (WSN) is a combination of sensor technology, embedded networking, wireless communication technology and the distributed processing [22]. It can sense and transmit the information of environments to the client-sides via the wireless network. WSN has many merits over a traditional data monitoring system [23] for its higher accuracy and speed on data acquisition, wireless and real-time transmission, better flexibility and lower costs, and has been widely used in many application areas including medical field [24,25], food safety [26–28], environmental monitoring [29], and etc. Therefore, WSN is considered as a good choice to monitor the changes of environment for home storage of eggs.

The objective of the present study is three-fold, (a) to quantify the effects of different home storage conditions (room temperatures vs. refrigeration) on shell eggs quality; (b) to compare the quality change between n-3 PUFAs enriched and conventional eggs; (c) to identify the optimum duration (days) to store shell eggs in a home refrigerator and under room temperature. The remainder of the paper is organized as follows: Section 2 describes the experimental design and the WSN based environment-monitoring scheme, Section 3 presents the temperature and humidity fluctuation monitored during the experiment and the quality changes of n-3 and conventional eggs during storage. The conclusions are provided in Section 4.

2. Materials and Methods

2.1. Materials

Eggs for this research were collected from Shuangyin Poultry Farm located in Pinggu, Beijing, China and produced by Hy-line Brown (Hy-Line International, West Des Moines, IA, USA) laying hens of 30 weeks of age. Two groups of laying hens were fed with two kinds of different diets: one with n-3 PUFAs enriched diet for n-3 PUFAs enriched eggs (72% corn, 26% soybean, and 2% seaweed powder), and the other with standard diet for conventional eggs (74% corn and 26% soybean). Sample eggs were collected, packaged and delivered by SF Express (Beijing, China) immediately on the same day they were laid, arriving at the laboratory on the following day.

As soon as the eggs arrived at the lab, eggs were candled to take out defects (cracked, broken, and stained) and weighted. A total of 200 n-3 PUFAs enriched eggs and 200 conventional eggs were selected respectively for the experiment.

2.2. Experiment Design

Two scenarios, room temperature (scenario 1) and refrigeration (scenario 2) conditions were designed to simulate home egg storage in June 2017 in the Laboratory of Food Quality and Safety at China Agriculture University, (Beijing, China). Eggs in scenario 2 were put in a refrigerator (BCD-251WDPV, Haier, Qingdao, China) set to 4 °C for the duration of the study.

Both n-3 PUFAs enriched and conventional eggs were randomly divided into two groups (100 eggs per group) for two scenarios respectively. In each scenario, the eggs were numbered and put into egg trays. To evaluate the change of egg quality during storage, 5 conventional eggs and 5 n-3 PUFAs enriched eggs from each scenario were taken out separately and measured orderly at intervals of three days during the experiment period.

2.3. Monitoring Scheme

The WSN were utilized for real-time monitoring of temperature and humidity during eggs' storage in two scenarios. The WSN architecture was composed of two sensor nodes, a network coordinator and the wireless network (Figure 1).

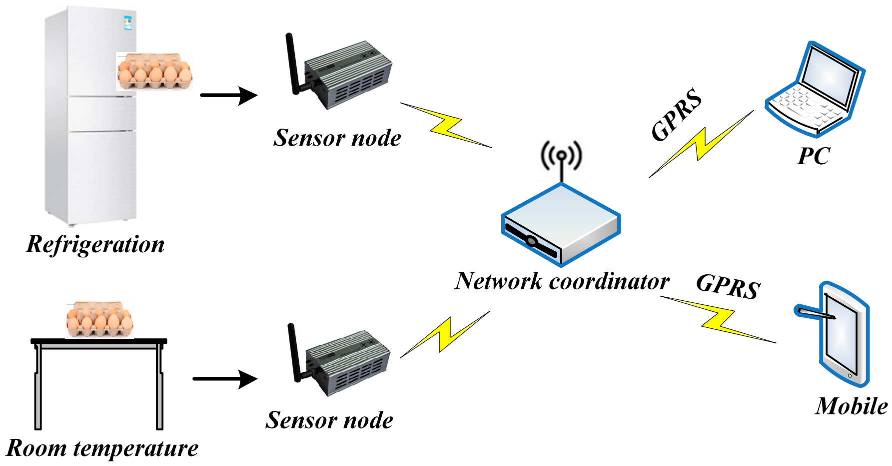


Figure 1. Architecture diagram of the Wireless sensor network (WSN). GPRS, General Packet Radio Service. PC, personal computer.

The sensor node is an integration of a microcontroller, an antenna with a 433 RF module, storage and clock chips, temperature and humidity sensors and power supply (Figure 2a). The microcontroller (STC12LE5A60S2, STCTM, Shanghai, China) were used to interconnect the slave modules and realize the functionality of sensor nodes by improving processing speed and the capacity of interference resistance. The antenna with a 433 RF module was designed to communicate with the coordinator, which performed low power consumption and high mobility performance. The clock chip can offer the time when data was collected, and the storage chip was used to save the sensor and time information. Six lithium batteries (LR6-4B/1.5 V, Nanfu, Nanping, China) were used to supply voltage for the sensors.

Temperature and humidity data were monitored by the digital sensors AM2302 (AOSONG, Guangzhou, China), whose data accuracy for temperature and humidity was 0.1 °C and 1% respectively. The working parameters of AM2302 are as follows: temperature ranges from −55 to +125 °C, relative humidity from 0% to 99%, operating voltage between 3.0 and 6.0 V.

The network coordinator was constructed of a wireless microcontroller, the General Packet Radio Service (GPRS) transmission module (WG 8010-485, Comway, Lewes, MD, USA), the crystal oscillator, and the antenna with an amplifier and power supply (Figure 2b). The environmental data were transferred to the network coordinator for grouping and then sent to the client side by the GPRS module. The CC2530 module (TI, Dallas, TX, USA) was chosen as the wireless microcontroller to integrate the slave modules and optimize their performance.

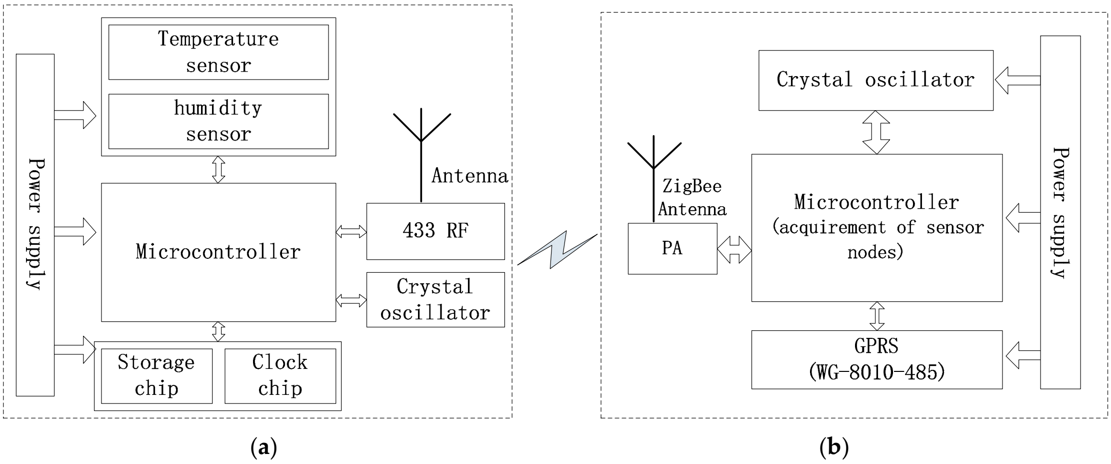


Figure 2. Block diagram of the WSN nodes. (**a**) Block diagram of the sensor node; (**b**) Block diagram of the network coordinator. PA, power amplifier.

2.4. Egg Quality Parameters

Haugh unit (HU), yolk index (YI) and albumin pH are commonly used parameters indicating egg quality [8,30,31] and are adopted in this experiment to evaluate the freshness change of eggs during storage.

The whole egg weight was measured by a digital weighing scale (DL-X01, Donlim, Foshan, China) with precision of 0.01 g. After being weighed, the egg was broken onto a white flat plate. The HU value was calculated using the formula $HU = 100 \lg(H - 1.7W^{0.37} + 7.57)$ [32], where H is the thick albumen height (mm) and W is the weight (g) of a whole egg. The thick albumen height was measured by averaging three measurements taken at different points of the thick albumen at a distance of 10 mm from the yolk by a sliding caliper (YB5002B, OK-TOOLS, Hangzhou, China). The yolk index is obtained by dividing the height by the diameter of the yolk [33], and the yolk height and diameter were measured by the same sliding caliper. Albumin pH was measured by the pH meter (testo 206, lenzkirch, Fort Baden, Germany).

The experiment was ended when the HU decreased to 55 or YI down to 0.15 according to USDA's egg regulation [21] when eggs are inedible.

2.5. Statistical Analysis

One-way analysis of variance (ANOVA) and Least Significant Difference (LSD) were used to analyze significant difference among the eggs under two scenarios by IBM SPSS statistics 20 (IBM, Chicago, IL, USA, 2011). All statements of significance are based on $p < 0.05$ unless otherwise specified. The data regression, fitting and processing were performed by using MATLAB 2013b software (Math Works, Natick, MA, USA, 2013).

3. Results and Discussion

3.1. Performance Evaluation of the WSN

Based on the monitoring scheme shown in Figure 2, the WSN for the experiment is constructed with external sensors, antennas and batteries integrated with the sensor nodes by the ports respectively (Figure 3).

The performance of the WSN in this experiment was evaluated in terms of frequency, accuracy and duration time. The sensors' data accuracy, response time, battery life and packet losses rate are key factors for WSN nodes [28,34] and the performance of WSN nodes as demonstrated in Table 1.

The battery charge conditions varied from 90% to 99% after about one day. The packet losses rate was lower than 0.2% in both room and refrigeration storage in the measurement number of 3000.

The results show that the WSN nodes could accurately monitor the environmental parameters fluctuation with low error rate and is reliable to monitor the environment change of eggs stored in this experiment.

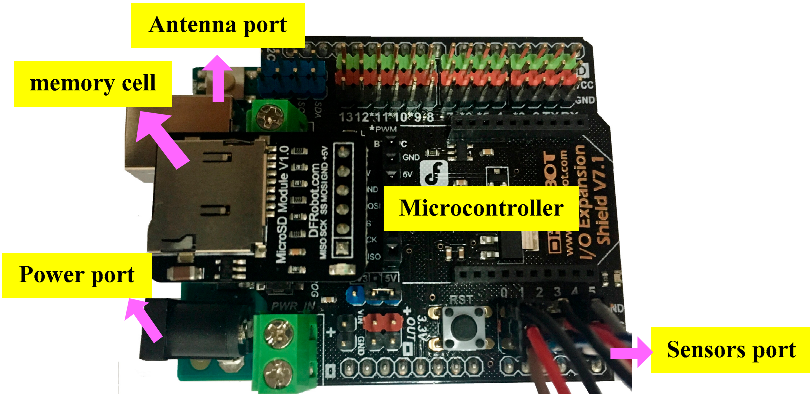


Figure 3. Physical implementation of the sensor node hardware.

Table 1. Performance parameters of the wireless sensor network (WSN).

Parameters	Temperature Sensor	Humidity Sensor
Sensor range	−55–125 °C	0–99%
Data accuracy	0.1 °C	1%
Response time	5 s	5 s
Sampling interval	1.5 s	1.5 s
Voltage range	3.0–5.5 V	3.0–6.0 V
Power consumption	<0.1 mW	<0.1 mW
Battery charge	90–99% (1 day)	
Packet losses rate	<0.5% (3000 *)	

* Number of measurements.

3.2. Fluctuation of Environment Factors

3.2.1. Time-Temperature Fluctuation

The experiment lasted 18 days for eggs stored in scenario 1 under room temperature and 30 days for those in scenario 2 in refrigeration when the HU decreased to 55 or YI down to 0.15.

The ambient temperature was not stable during the experiment period under both room temperature and refrigeration (Figure 4). The room temperature was around 25 °C with the lowest temperature down to 22 °C and the highest up to 31 °C. The room temperature fluctuated mainly because of the changes of weather in June 2017, and other factors, such as the refrigeration equipment and people's activities in the room.

The temperature of the refrigerator was set to 4 °C in this experiment. Although the lowest temperature was kept at 4 °C, the temperature in the refrigerator was sometimes higher than 7 °C during the experiment, as lots of refrigerators are in reality running at higher temperature than set [35]. In our experiment, the temperature fluctuation did happen (Figure 4) when the refrigerator was opened for taking out sample eggs and fluctuated with the cooling system running.

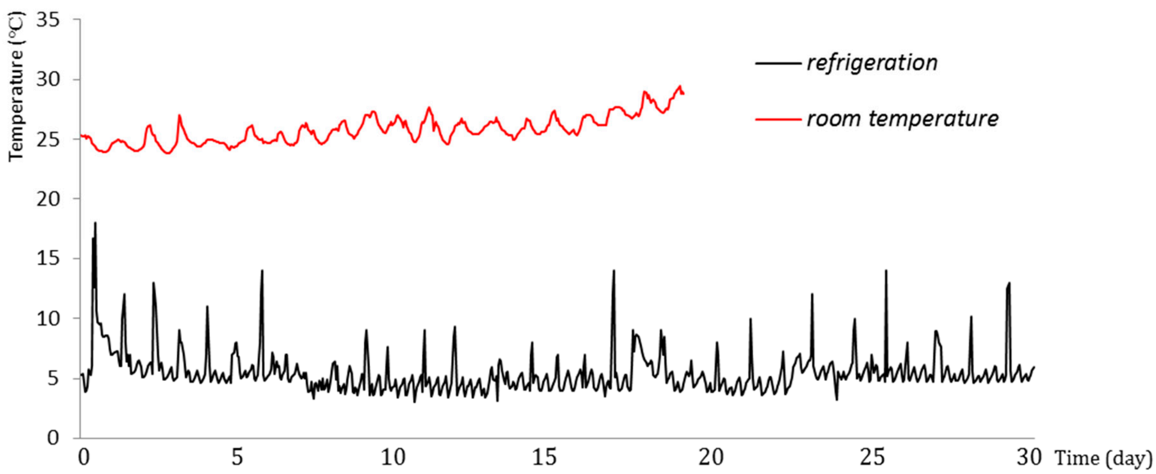


Figure 4. Time-temperature fluctuation under different storage conditions.

3.2.2. Time-Humidity Fluctuation

The ambient humidity floated along with the fluctuation of temperature under both room temperature and refrigeration storage (Figure 5). During the refrigeration, the relative humidity fluctuated regularly around 40 percent with the cooling system running and the opening times of the refrigerator door. The relative humidity for eggs kept under room temperature was about 50 percent, which was obviously higher than those in refrigeration.

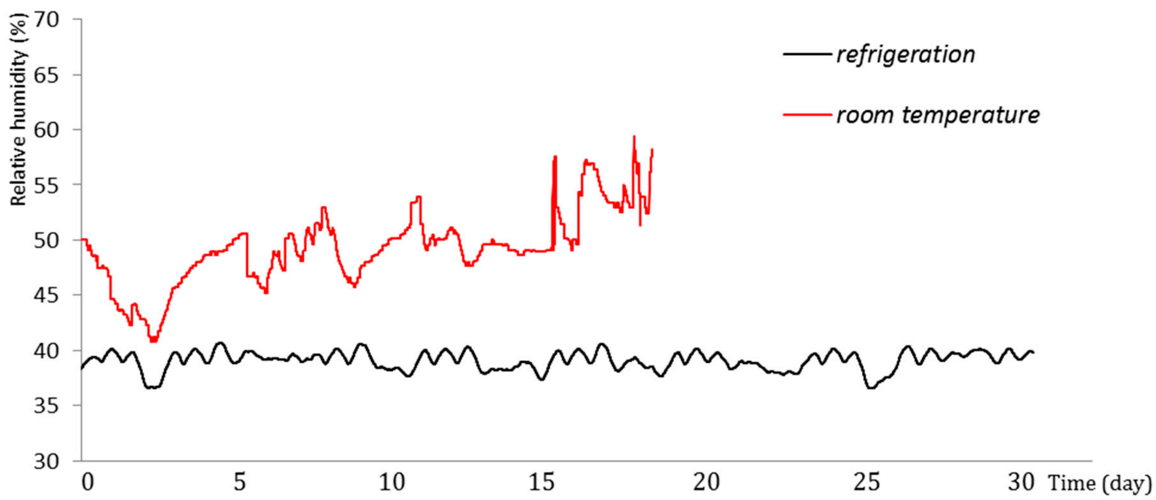


Figure 5. Time-humidity fluctuation of different storage conditions.

3.3. *Eggs Quality Changes*

3.3.1. Changes of Haugh Unit (HU)

According to USDA's egg regulations [30], the HU values of AA eggs (According to USDA's egg regulation, eggs were classed into three grades: AA, A and B, among which grade AA is the highest quality) are above 72. In this study, the initial HU values of the eggs were 95.66 for n-3 PUFAs enriched eggs and 90.56 for conventional eggs (Tables 2 and 3) when measured two days after being laid and as soon as transported to the lab.

Table 2. The quality * changes of Omega-3 polyunsaturated fatty acids (n-3 PUFAs) enriched and conventional eggs under room temperature.

Sample	Parameters	Initial Value	6 Days	12 Days	18 Days
n-3 PUFAs enriched eggs	Weight	61.31 ± 4.82^{a}	$59.67 \pm 4.91^{a,b}$	$59.04 \pm 4.68^{b,c}$	57.53 ± 4.32^{c}
	HU ①	95.66 ± 1.41^{a}	78.98 ± 3.73^{b}	67.35 ± 2.17^{c}	51.42 ± 1.84^{d}
	YI ②	0.46 ± 0.03^{a}	0.28 ± 0.02^{c}	0.21 ± 0.02^{c}	0.18 ± 0.03^{c}
	Albumen pH	8.40 ± 0.12^{a}	9.18 ± 0.11^{b}	$9.35 \pm 0.37^{b,c}$	9.42 ± 0.14^{c}
Conventional eggs	Weight	64.33 ± 3.13^{a}	$63.04 \pm 3.11^{a,b}$	61.01 ± 2.67^{b}	58.59 ± 3.37^{c}
	HU ①	90.56 ± 0.39^{a}	75.66 ± 4.14^{b}	63.63 ± 1.51^{c}	48.25 ± 3.73^{d}
	YI ②	0.45 ± 0.01^{a}	0.30 ± 0.02^{b}	0.23 ± 0.01^{c}	0.19 ± 0.03^{c}
	Albumen pH	8.24 ± 0.18^{a}	$8.98 \pm 0.37^{a,b}$	$9.28 \pm 0.17^{b,c}$	9.51 ± 0.12^{c}

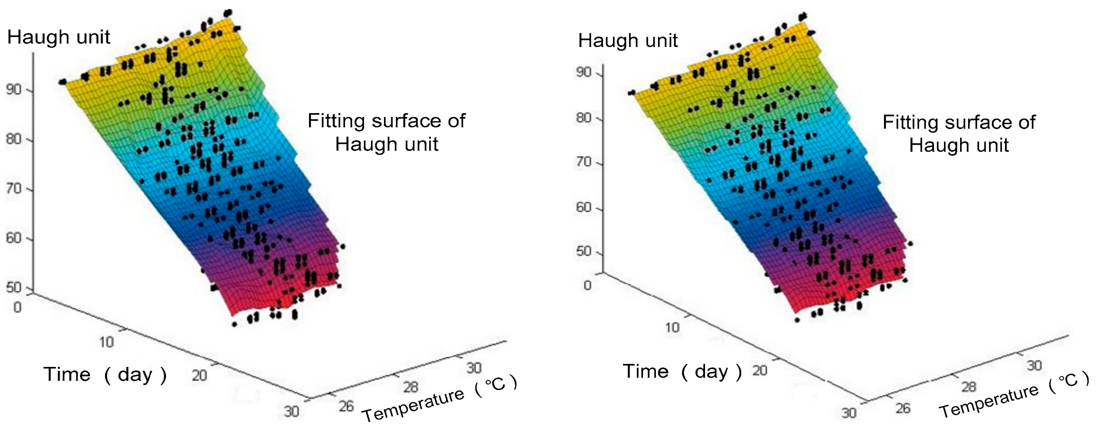
* Means ± SD of 5 measurements; ① Haugh unit; ② yolk index; Values with different letters ($^{a-c}$) within the same row are significantly different ($p < 0.05$).

Table 3. The quality * changes of n-3 PUFAs enriched and conventional eggs in refrigeration.

Sample	Parameter	Initial Value	9 Days	18 Days	30 Days
n-3 PUFAs enriched eggs	Weight	59.34 ± 2.81^{a}	$59.03 \pm 2.13^{a,b}$	58.18 ± 2.31^{b}	56.75 ± 2.05^{c}
	HU *	95.66 ± 1.44^{a}	$88.97 \pm 3.68^{a,b}$	76.62 ± 6.33^{c}	54.89 ± 4.03^{d}
	YI *	0.46 ± 0.01^{a}	0.43 ± 0.01^{b}	0.38 ± 0.03^{b}	0.30 ± 0.01^{c}
	albumen pH	8.40 ± 0.14^{a}	8.67 ± 0.73^{a}	$9.04 \pm 0.15^{b,c}$	9.36 ± 0.12^{c}
Conventional eggs	Weight	66.45 ± 3.71^{a}	66.43 ± 3.87^{a}	65.32 ± 3.25^{b}	64.18 ± 3.43^{c}
	HU *	90.56 ± 0.43^{a}	$86.93 \pm 1.52^{a,b}$	$72.69 \pm 2.31^{b,c}$	52.14 ± 2.37^{d}
	YI *	0.45 ± 0.02^{a}	$0.42 \pm 0.01^{a,b}$	$0.36 \pm 0.02^{b,c}$	0.27 ± 0.03^{c}
	albumen pH	8.24 ± 0.13^{a}	8.38 ± 0.08^{a}	$8.99 \pm 0.23^{b,c}$	9.41 ± 0.29^{c}

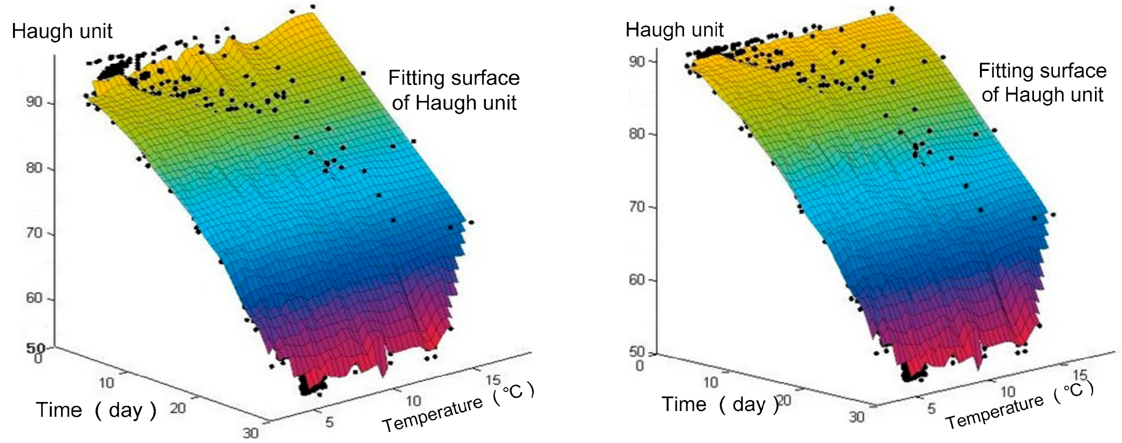
Values with different letters ($^{a-c}$) within the same row are significantly different ($p < 0.05$); * See Table 2 for details.

There was a 40–50% decrease in HU values of n-3 PUFAs enriched and conventional eggs after 30 days of refrigeration (Figure 6a,b). However, for eggs under room temperature, the same level of decline happened after 18 days' storage (Figure 6c,d). The reduction of HU values was mainly due to the breakdown of carbonic acid in eggs albumen, which caused elasticity loss and structure change of mucin fibers. So the albumen became watery and albumen height reduced, which directly resulted in the decrease of HU values [36]. The data shows that the rate of HU decline varies significantly in different temperature and the higher temperature, the faster the HU decreased, which was in agreement with earlier studies [36–38].



(**a**) (**b**)

Figure 6. *Cont.*



(**c**) (**d**)

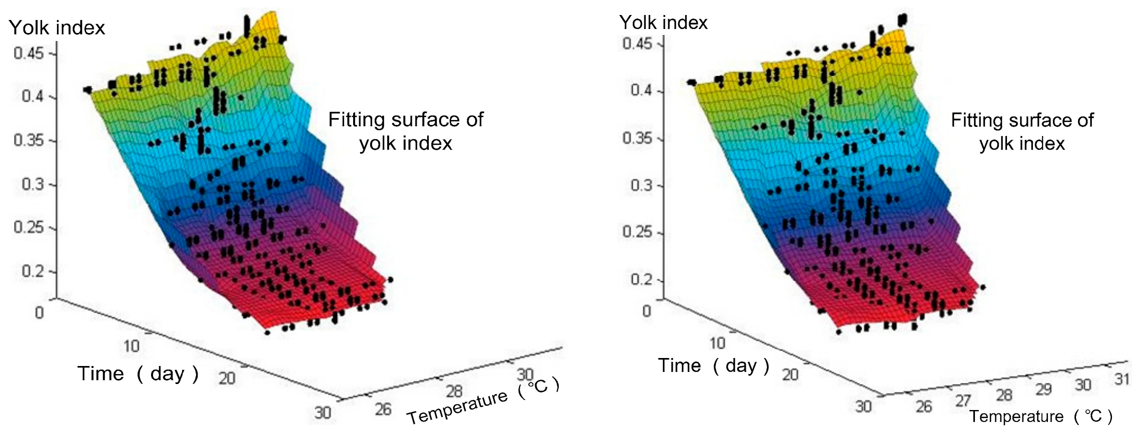
Figure 6. Haugh unit changes of Omega-3 polyunsaturated fatty acids (n-3 PUFAs) enriched and conventional eggs under different conditions. (**a**) Haugh unit changes of n-3 PUFAs enriched eggs under room temperature; (**b**) Haugh unit changes of conventional eggs under room temperature; (**c**) Haugh unit changes of n-3 PUFAs enriched eggs in refrigeration; (**d**) Haugh unit changes of conventional eggs in refrigeration.

3.3.2. Changes of YI

YI indicates yolk quality and eggs' freshness [39]. The YI of fresh eggs varies from 0.3 to 0.5 according to Yannakopoulos [40] and the initial YI of the fresh eggs in our experiment was 0.5 for both types of eggs (Tables 2 and 3).

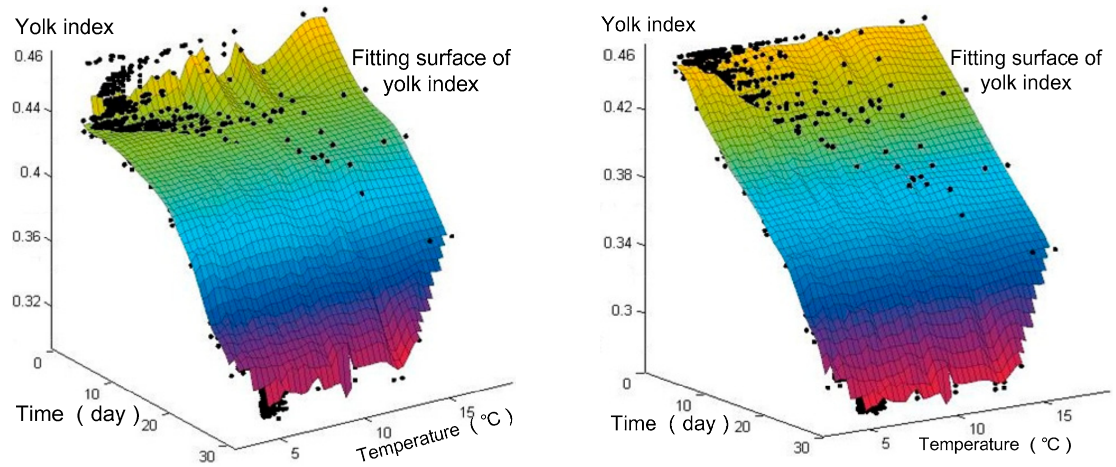
The experiment shows a significant reduction of YI values during storage ($p < 0.05$) irrespective of the storage conditions and egg types (Figure 7). As the storage goes on, the egg yolk gradually expanded and led to the weakening of the strength of vitelline membrane [41], which happened because water gradually permeated from the albumen through the vitelline membrane to yolk. The process finally changed the yolk shape from a spheroid to an oblateness [36].

The result also shows that temperature had significant effects ($p < 0.05$) on the YI values for both n-3 PUFAs enriched and conventional eggs during home storage, and refrigeration can reduce the speed of YI reduction as the eggs stored in refrigerator obviously kept higher YI values than those under room temperature.



(**a**) (**b**)

Figure 7. *Cont.*

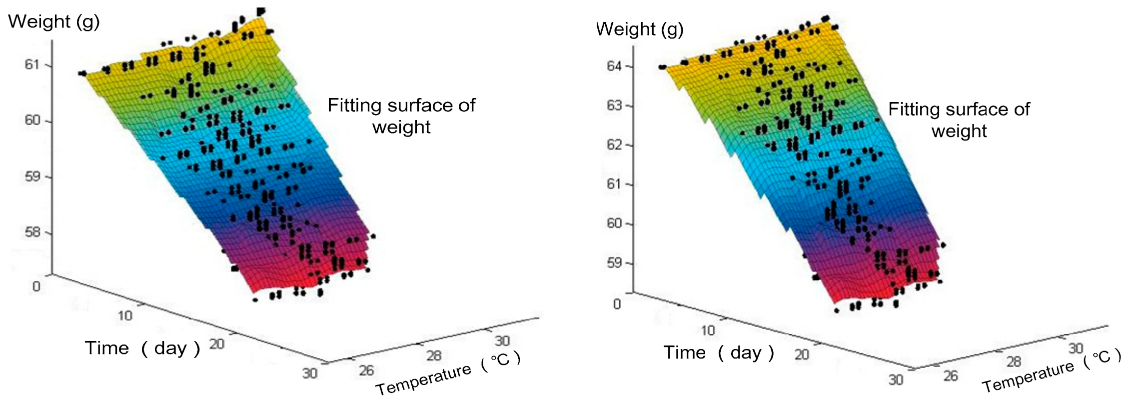


(**c**) (**d**)

Figure 7. Yolk index changes of n-3 PUFAs enriched and conventional eggs under different conditions. (**a**) Yolk index changes of n-3 PUFAs enriched eggs under room temperature; (**b**) Yolk index changes of conventional eggs under room temperature; (**c**) Yolk index changes of n-3 PUFAs enriched eggs in refrigeration; (**d**) Yolk index changes of conventional eggs in refrigeration.

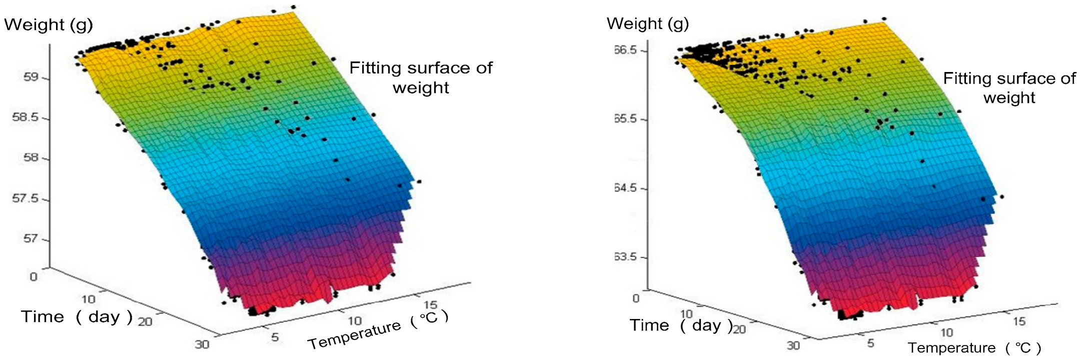
3.3.3. Changes of Weight

Significant differences of eggs weight were observed during storage periods (Tables 2 and 3). The loss of weight obviously happened to both n-3 PUFAs enriched and conventional eggs along with the storage especially for eggs stored under room temperature (Figure 8), which is in accordance with earlier study [42]. Significant weight loss of eggs was mainly because of the escape of the moisture and CO_2 from eggs. During the storage, the breakdown of carbonic acid in eggs' albumen produced CO_2 and water, and the enlargement of shell spores makes it easier for moisture and CO_2 to escape [36]. It can also be found that the higher the environment temperature, the higher loss rate of eggs weight, which can be explained as the high temperature accelerated the breakdown of carbonic acid in eggs albumen [36].



(**a**) (**b**)

Figure 8. *Cont.*

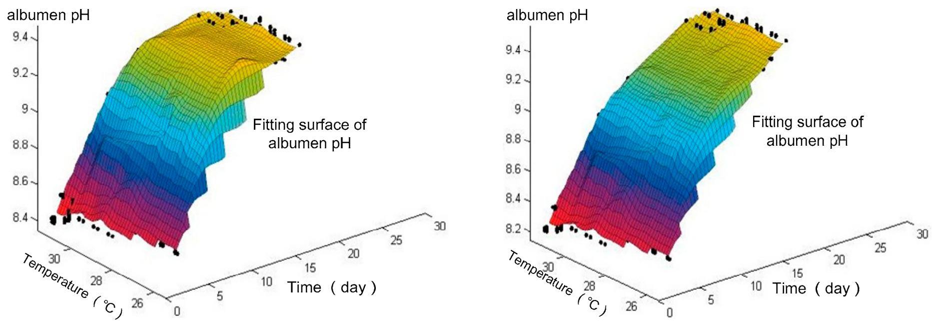


(**c**) (**d**)

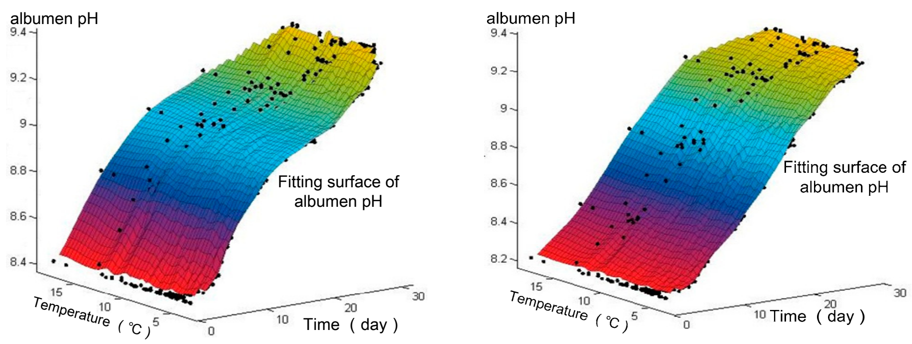
Figure 8. Weight changes of n-3 PUFAs enriched and conventional eggs under different conditions. (**a**) Weight changes of n-3 PUFAs enriched eggs under room temperature; (**b**) Weight changes of conventional eggs under room temperature; (**c**) Weight changes of n-3 PUFAs enriched eggs in refrigeration; (**d**) Weight changes of conventional eggs in refrigeration.

3.3.4. Changes of Albumen pH

The observed albumen pH increased during the storage period independently of the storage conditions and egg types, but the rate of albumen pH increase varies significantly at different storage conditions. The changes of albumen pH were slower for eggs stored in refrigeration than those under room temperature (Figure 9). Take n-3 PUFAs enriched eggs as an example, Albumen pH went up to 9.36 from 8.40, 11.4% increase after 30 days storage in refrigeration, while those under room temperature, it just took 18 days for albumen pH to increase 12.1%, from 8.4 to 9.42. It is believed that the escape of CO_2 and water leads to the rise of albumen pH during storage [23,36].



(**a**) (**b**)



(**c**) (**d**)

Figure 9. Albumen pH changes of n-3 PUFAs enriched and conventional eggs under different conditions. (**a**) Albumen pH changes of n-3 PUFAs enriched eggs under room temperature; (**b**) Albumen pH changes of conventional eggs under room temperature; (**c**) Albumen pH changes of n-3 PUFAs enriched eggs in refrigeration; (**d**) Albumen pH changes of conventional eggs in refrigeration.

3.3.5. Comparison of Quality Changes of N-3 PUFAs Enriched and Conventional Eggs

There was no significant difference ($p > 0.05$) of weight loss between n-3 PUFAs enriched and conventional eggs. The weight loss was 3.87% and 3.4% respectively for n-3 PUFAs enriched and conventional eggs in refrigeration, 6.1% and 7.8% for eggs stored under room temperature (Table 4).

Table 4. The quality ① changes of n-3 PUFAs enriched and conventional eggs under different conditions.

Sample	Weight Loss	Loss Rate	HU * Decline	HU * Decline Rate	YI * Decline	YI * Decline Rate	Albumen pH Increase	pH Increase Rate
n-3 ref ②	2.5 [a]	4.2%	40.8 [a]	42.6%	0.2 [a]	34.7%	0.9 [a]	11.4%
con ref ③	2.3 [a]	3.4%	38.4 [a]	42.4%	0.2 [a]	40.0%	1.2 [a]	14.2%
n-3 room ④	3.8 [b]	6.2%	44.2 [b]	46.2%	0.3 [b]	60.9%	1.0 [a,b]	12.1%
con room ⑤	5.7 [b]	8.9%	42.2 [a,b]	46.6%	0.3 [b]	57.8%	1.3 [b]	13.4%

① Means of 5 measurements; ② The n-3 PUFAs enriched egg samples stored in refrigeration; ③ The conventional egg samples stored in refrigeration; ④ The n-3 PUFAs enriched egg samples stored under room temperature; ⑤ The conventional egg samples stored under room temperature; Values with different letters ([a,b]) within the same column are significantly different ($p < 0.05$); * See Table 2 for details.

The decline of HU and YI values of n-3 PUFAs enriched and conventional eggs were on the same level both in refrigeration and under room temperature, which is consistent with the studies of Cedro and Mazalli. [23,43] who reported that no significant differences ($p > 0.05$) were observed between n-3 PUFAs enriched and conventional eggs in terms to HU and YI. But in this experiment, the YI of n-3 PUFAs enriched eggs decreased to 0.3 after 9 days' storage in the early period, faster than conventional eggs whose YI did not go down to the same level after 15 days' storage under room temperature (Figure 7).

In refrigeration, albumen pH of n-3 PUFAs enriched and conventional eggs increased 11.4% and 14.7% respectively by the end of the experiment, and for eggs under room temperature, the rate was 12.1% and 15.4% after 18 days' storage. Egg types presented similar change ($p > 0.05$) of the albumen pH both in refrigeration and under room temperature, which is consistent with the result of Pappas, A.C. [23,44] who observed that the albumen pH increased as the time extended irrespective of the egg types.

4. Conclusions and Implications

According to the results of the conducted experiment and above analysis, the WSN adopted in this study is a convenient and useful tool to monitor the real-time environment conditions including temperature and humidity for eggs at consumers' home storage. Temperature, humidity and time of storage all have an influence on the freshness of eggs and there was no significant difference between n-3 PUFAs enriched eggs and conventional eggs. N-3 PUFAs enriched and conventional eggs stored under refrigeration may be kept for as long as approximately one month whereas stored at room temperature only 18 days. It can be concluded that to maintain the internal quality of eggs, refrigeration is strongly recommended for home storage and consumers in China should be educated about it.

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