Effects of selenium feed supplements on functional properties of eggs

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Abstract The aim of the present study was to assess the effects of selenium feed supplements on the functional properties of eggs. The hens in experimental groups were fed diets supplemented with 0.2 mg/kg selenium from sodium selenite (Group 1), selenium-enriched yeast (Group 2), synthetic L-selenomethionine (Group 3), or hydroxy analog of selenomethionine (Group 4). The Control Group (Group C) was fed with basal feed without supplementation. The highest values of albumen gel firmness were shown in Group C eggs; differences with all experimental groups were significant ($p < 0.001$ to $p = 0.009$). It was ascertained that albumen gel firmness correlated with albumen pH ($r_s = 0.490$; $p < 0.001$), which was highest in eggs from non-supplemented hens. Group 1 eggs and Group C eggs showed lower albumen foaming capacity ($p < 0.001$)

compared to eggs from other groups. Both albumen foaming capacity and albumen foam stability were higher in Group 2 eggs than in Group C eggs ($p < 0.001$). The highest yolk foaming capacity was found in Group 2 eggs ($p < 0.001$). Sponge cakes baked with Group C eggs had a smaller volume than those baked with eggs from Group 2 ($p = 0.005$), Group 3 ($p = 0.004$) and Group 4 ($p = 0.024$). The results of the study confirmed that selenium added to the laying hen feed significantly affected the monitored functional properties of both albumen and yolk. The most distinctive effect of selenium was shown in eggs from the group supplemented with selenium-enriched yeast, for which the results of albumen foam capacity and stability and yolk foaming capacity were the best.

Keywords Eggs · Organic selenium · Inorganic selenium · Functional properties · Storage

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Introduction

The past decade has seen increasing interest in the use of selenium feed supplements in laying hen nutrition. Selenium received by hens in feed has not only shown positive effects on their health status and the zootechnical aspects of their breeding, but also has positive effects on the quality parameters of eggs (Cobanova et al. 2011). Interest in the use of inorganic selenium in animal nutrition, especially in the form of sodium selenite, dates back to 1960 (Heindl et al. 2010). Although inorganic selenium such as sodium selenite became the most widely used selenium feed additive (Heindl et al. 2010), no selenium reserves can be built up after intake of this selenium form and unused selenium is excreted from the body. Selenium in the organic form, which forms an integral part of amino acids

such as selenocysteine and selenomethionine, demonstrates higher bioavailability (Pavlovic et al. 2009). Selenium-enriched yeast is obtained by cultivation of a specific *Saccharomyces cerevisiae* strain on a medium enriched with sodium selenite (SS). During the growth of the yeast, SS is transformed to hydrogen selenide (H_2Se). H_2Se is an intermediate metabolite used by the yeast to synthesize different organic selenocompounds such as selenomethionine (SeMet) and selenocysteine (SeCys), but also many other seleno-active components (Dobrzanski and Jamroz 2003). Selenomethionine, as an organic source of selenium, is absorbed by active transport through epithelial cells (Pan et al. 2007). In addition, the methionine-like chemical structure of selenomethionine allows for the mutual substitution of these two amino acids in the processes of protein synthesis, and thus for the non-specific incorporation of selenomethionine into tissues instead of methionine (Pavlovic et al. 2009). The selenomethionine that is not used for the immediate synthesis of proteins is subsequently deposited as a reserve of the organism in the tissues, eggs and milk (Cobanova et al. 2011; Jing et al. 2015).

Several studies in the last 20 years (Jing et al. 2015; Kieliszek et al. 2015; Han et al. 2017) have confirmed that the selenium level in eggs can be increased by supplementation of laying hen feed. An increased level of selenium increases the stability of egg lipids and proteins in the egg due to its antioxidative function (Pappas et al. 2005; Sevcikova et al. 2006; Wang et al. 2010).

The effect of selenium on the stability of egg lipids and proteins is probably reflected in the functional properties of selenium-enriched eggs. However, no study reporting results of the observation of functional properties of eggs after selenium supplementation of hens' diet has been published so far.

The aim of the present study was to evaluate the effects of four forms of selenium feed supplements on the functional properties of eggs.

Materials and methods

The experiment involved 1740 Bovans Brown laying hens laying hens brought in at the age of 133 days. They were divided into four experimental groups ($n = 420$ in each group) and 1 Control Group ($n = 60$). The Control Group was fed basal feed, while the feeds of Groups 1–4 were supplemented with 0.2 mg/kg selenium from four different sources, i.e. sodium selenite (Group 1), selenium-enriched yeast (Group 2), synthetic L-selenomethionine (Group 3) and hydroxy analog of selenomethionine (Group 4). The basal feed contained 0.26 mg of selenium per kg of feed. Experimental diets were fed to the hens for 8 months

divided in 9 experimental periods of 28 days each. The detailed chemical composition of the basal feed is shown in Table 1.

The laying hens were reared in a three-tier furnished cage system with 750 cm² of floor area per bird. The cage system used in the experiment met the requirements for furnished cage systems set out in Decree 464/2009 Sb., amending Decree 208/2004 Sb. on minimum standards for the protection of farm animals as amended by Decree 425/2005 Sb. The cage batteries were placed in a climate-controlled windowless hall with an ambient temperature of 19 ± 1 °C and a relative humidity of $65 \pm 5\%$. The temperature control system consisted of vacuum fans and suction valves. A gas-fired heating unit was used during cold periods. Automatic ventilation provided air exchange at a rate of at least 3 m³ per hour per 1 kg live weight in

Table 1 Chemical composition of the basal feed

Ingredients	Content
Wheat (%)	18.954
Maize (%)	40.000
Soybean meal (%)	18.200
Wheat bran (%)	7.000
Fish meal (%)	2.000
Soybean oil (%)	1.900
Lysine-HCl (%)	0.030
DL-methionine (%)	0.160
Arbocell Cell Fibre (%)	1.700
Salt (%)	0.310
Limestone (%)	2.950
Limestone-roughly ground (%)	6.000
MCP-monocalciumphosphate (%)	0.570
Vitamin and mineral supplementation (%)	0.226
Crude protein (g/kg)	172.66
Fat (g/kg)	46.39
Linoleic acid (g/kg)	23.01
Crude fiber (g/kg)	45.92
ME (MJ/kg)	11.52
Lysine (g/kg)	8.46
Methionine (g/kg)	4.25
Methionine + cysteine (g/kg)	7.29
Threonine (g/kg)	6.12
Tryptophan (g/kg)	2.07
Ca (g/kg)	38.21
P (g/kg)	5.82
P (digestible) (g/kg)	4.00
Na (g/kg)	1.61
Vitamin A (UI/kg)	12,948.03
Vitamin D3 (UI/kg)	2496.00

winter and 5 m³ per hour per 1 kg live weight in summer. The laying hens were fed ad libitum twice a day. The experiment was approved by the Ethics Committee of the Central Commission for Animal Welfare of the Ministry of Agriculture of the Czech Republic.

A total of 85 eggs were collected in each period for 8 months in Groups 1, 2, 3, 4 and C. These eggs were analyzed for the selenium content and for albumen pH, as well as for egg functional parameters such as albumen firmness, albumen and yolk foam characteristics and the volume of defined bakery products made from sponge cake batter. Furthermore, some selected parameters were monitored within the storage experiment in fresh eggs on the day on which they were laid (D0) and on storage day 35 (D35). The eggs were stored at 16 ± 2 °C in a dry and dark place.

Determination of selenium content of feed and eggs

The feed and fresh egg albumen and yolk samples were mineralised in a closed system using a microwave digestion technique in the presence of nitric acid and 30% hydrogen peroxide in the Milestone Ethos TC apparatus (Milestone, Sorisole BG, Italy). The dried mineralised product was dissolved in water and reduced by addition of 20% hydrochloric acid. The processed samples were measured by the atomic absorption spectroscopy (AAS Solaar M6, Unicam, UK). The values of selenium concentration in feed and egg albumen samples are given in µg/g of samples.

Albumen pH determination

Albumen pH was determined in fresh eggs and 35-day-old eggs. The analysis was performed using a 340i pH meter (WTW GmbH, Weilheim, Germany) with a piercing-tip electrode (SenTIX SP, WTW GmbH, Weilheim, Germany).

Instrumental determination of albumen gel firmness

Albumen gel firmness was determined in fresh and 35-day-old eggs according to the modified method of Chang and Chen (2000). For the preparation of albumen gel, we used a mixture of homogenized liquid albumen heat-treated in a cellulose casing (Viscofan, caliber 20 ± 0.5 mm) at 90 °C for 30 min. The albumen gel prepared in this way was cooled to 21 ± 2 °C and shaped into 2-cm-long rolls. Firmness measurements were performed using an Instron Universal Testing Machine (Model 5544) (Instron Corporation, High Wycombe, UK) set to 50 mm/min speed, 70% deformation and 2 kN load. Merlin Series IX software was used for data acquisition (Merlin; Merlin, Richardson,

USA). The firmness was expressed as the compressive force (N) needed to deform and disrupt the coherence of the sample.

Albumen foaming capacity and foam stability

The albumen foaming capacity was determined in fresh and 35-day-old eggs. Albumen foam was prepared by manual homogenization of a mixture of liquid egg albumen and subsequent whipping for 60 s (ETA 0042, speed 1400 rpm). The foaming index was calculated according to the following formula:

$$FC = (V2/V1) \times 100$$

FC—albumen foaming capacity (%), V1—volume of the initial liquid phase (ml), V2—volume of albumen foam (ml).

The albumen foam stability was determined in fresh and 35-day-old eggs by monitoring the foams for 30 min, after which the volume of liquefied albumen was substituted into the following formula:

$$FS = [(V1 - V3)/V1] \times 100$$

FS—albumen foam stability (%), V1—volume of the initial liquid phase (ml), V3—volume of drainage (ml).

Yolk foaming capacity

Yolk foaming capacity was determined in fresh and 35-day eggs according to the method of Sheikh et al. (2009). Yolk foam was prepared by manual homogenization and subsequent whipping for 60 s (Braun Multiquick 5600-W blender). Yolk foaming capacity was calculated according to the formula:

$$FC = (V1/m1) - (V2/m2)$$

FC—yolk foaming capacity (%), V1—volume of the initial liquid phase m1—weight of the initial liquid phase (g), V2—volume of yolk foam (ml), m2—weight of yolk foam (g).

Sponge cake volume test

In the sponge cake volume test carried out with fresh eggs, we determined the total volume (ml) of defined bakery products made from sponge cake batter. The methodology was optimized and applied according to the procedure of Norris and Cotterill (1986). Sponge cake batter was prepared by homogenizing whole eggs with crystal sugar for 4 min (ETA 0042, speed 1400 rpm). During homogenization, the cake flour was gradually added in four portions. The blended cake batter was then baked in a preheated oven at 177 °C for 14 min.

Ingredients used for sponge cake were: 138 g homogenized whole egg, 89.4 g granulated sugar and 51.4 g cake flour.

Statistical analyses

Mean values and standard deviations of selenium content, pH and all functional properties of eggs were calculated for each egg group, day of storage and period—laying hens age.

Factorial ANOVA was used to analyze effect of egg group, i.e. dietary selenium supplementation, period—laying hens age and day of storage on functional properties of eggs. Tuckey post hoc test for unequal N was used when ANOVA revealed significant result. One-way ANOVA followed with Tuckey HSD test was used to assess differences in sponge cake volume between groups.

The relationship between functional properties of eggs and egg albumen pH or selenium content in albumen was assessed by the non-parametric Spearman-rank correlation. As these characteristics were measured on different eggs, data had to be aggregated for defined group/period/day of storage before performing the correlation test. This operation resulted in small number of observations and usage of nonparametric correlation coefficient.

$p < 0.05$ was regarded as significant in all tests. Statistical analyses were performed with IBM SPSS Statistics, version 22 (IBM Corp., Armonk, NY) and Statistica, version 12 (StatSoft, Tulsa, OK).

Results

Albumen gel firmness

Albumen gel firmness was significantly affected by selenium supplementation of the feed of laying hens (factorial ANOVA for the albumen gel firmness, effect of group: $p < 0.001$). Eggs from Group C (Control Group) showed the highest average values of albumen gel firmness (Fig. 1a). Group C values were significantly higher than those of the other groups (post hoc test: $p < 0.009$). The lowest average albumen gel firmness was recorded in Group 4, followed by Groups 2, 3, and 1. The difference between eggs from organic selenium supplemented groups (Groups 2, 3 and 4) and eggs from inorganic selenium supplemented group (Group 1) was significantly higher (post hoc test: $p < 0.001$), in all cases. However, there was no difference between the eggs from organic selenium groups.

By monitoring the effects of the selenium level on albumen gel parameters, we found a negative correlation between the parameters (Spearman's correlation

coefficient: $r_s = -0.579$; $p = 0.002$). The higher the level of selenium in the egg albumen, the lower the albumen gel firmness. The relationship between these two parameters monitored separately for each group was not, however, significant. Both albumen pH values and albumen gel firmness were highest in Group C, but a significant effect of the selenium supplementation of feed on the pH value of albumen was statistically confirmed only in the complex model (factorial ANOVA for egg albumen pH, effect of group: $p = 0.001$), and a subsequent detailed analysis failed to confirm any statistically significant differences between the groups (post hoc test, differences between groups non-significant). The overall evaluation (Spearman's correlation coefficient: $r_s = 0.490$; $p < 0.001$) as well as individual evaluations in Group 2 ($r_s = 0.685$; $p = 0.029$) and in the Control Group ($r_s = 0.661$; $p = 0.038$) confirmed a correlation between albumen gel firmness and albumen pH (Fig. 1b): albumen gel firmness increased significantly with increasing albumen pH (Fig. 1b). Albumen pH was significantly higher in 35-day eggs than in fresh eggs (factorial ANOVA for egg albumen pH, effect of day of storage: $p < 0.001$). Albumen gel firmness of the older eggs was also higher (factorial ANOVA for albumen gel firmness, effect of day of storage: $p < 0.001$).

Albumen foaming capacity and foam stability

Selenium supplementation of laying hen feed significantly influenced albumen foaming capacity and foam stability (factorial ANOVA for albumen foaming capacity, effect of group: $p < 0.001$, factorial ANOVA for albumen foam stability, effect of group: $p < 0.001$). Eggs from Groups 1 and C showed, on average, lower albumen foaming capacity values than eggs from groups fed diets enriched with organic selenium (Fig. 2a), i.e. lower ability to produce high volumes of foam (post hoc test: $p < 0.001$, Groups 1 and C vs. Groups 2, 3 and 4). There was no difference between the eggs from organic selenium supplemented groups (no difference between yeast and selenomethionine supplementation).

When comparing the stability of albumen foam between the groups, the lowest values of albumen foam stability of all the groups were found in Group C eggs (post hoc test: $p < 0.001$ in all comparisons of all experimental groups vs. Control Group, Fig. 2b). The highest foam stability values were found in Group 2 eggs, though these values were statistically significantly different only when compared with Group C eggs ($p < 0.001$). There were no differences between the eggs from selenium supplemented groups (no difference between the organic selenium sources).

The correlation analysis confirmed the significant effect of the selenium level in egg albumen on the albumen

Fig. 1 Albumen gel firmness (a) and relationship between albumen gel firmness and egg albumen pH (b). Group 1—supplementation with sodium selenite, Group 2—supplementation with selenium-enriched yeast, Group 3—supplementation with synthetic

L-selenomethionine, Group 4—supplementation with hydroxy analog of selenomethionine, group C—Control Group. Significant differences between groups are marked with different letters. Vertical bars: 95% confidence

Fig. 2 Albumen foaming capacity (a) and albumen foam stability (b) in eggs. Group 1—supplementation with sodium selenite, Group 2—supplementation with selenium-enriched yeast, Group 3—supplementation with synthetic L-selenomethionine, Group 4—

supplementation with hydroxy analog of selenomethionine, group C—Control Group. Significant differences between groups are marked with different letters. Vertical bars: 95% confidence interval

foaming capacity (Spearman's correlation coefficient, $r_s = 0.423$, $p = 0.035$). A positive correlation was, however, demonstrated only in the overall assessment regardless of groups. No dependence was statistically confirmed when correlations were analyzed for each group individually. In the overall assessment of dependence, a positive correlation—although not statistically significant—was also confirmed between albumen foam stability and the content of selenium in egg albumen (Spearman's correlation coefficient, $r_s = 0.357$; $p = 0.080$). The correlation

analysis performed for each group showed the dependence of albumen foam stability on the selenium content in eggs albumen from Group 3 (Spearman's correlation coefficient, $r_s = 0.900$, $p = 0.037$) and Group 4 ($r_s = 0.900$, $p = 0.037$).

The albumen foaming capacity significantly increased with increasing albumen pH both in the aggregate (Spearman's correlation coefficient, $r_s = 0.541$; $p < 0.001$) and also individually in eggs from Group 2 ($r_s = 0.806$; $p = 0.005$), Group 4 ($r_s = 0.782$; $p = 0.008$) and Group C ($r_s = 0.758$; $p = 0.011$; Fig. 3a). Albumen foam stability

Fig. 3 Relationship between albumen foaming capacity and egg albumen pH (a) and relationship between albumen foam stability and egg albumen pH (b). Group 1—supplementation with sodium selenite, Group 2—supplementation with selenium-enriched yeast,

Group 3—supplementation with synthetic L-selenomethionine, Group 4—supplementation with hydroxy analog of selenomethionine, group C—Control Group

decreased, on the other hand, with increasing albumen pH, both in aggregate ($r_s = -0.792$; $p < 0.001$) and also individually in the eggs from Group 1 ($r_s = -0.879$; $p = 0.001$), Group 2 ($r_s = -0.830$; $p = 0.003$), Group 3 ($r_s = -0.806$; $p = 0.005$), Group 4 ($r_s = -0.794$; $p = 0.006$) and Group C ($r_s = -0.782$; $p < 0.008$; Fig. 3b).

In the storage experiment, a significantly higher foaming capacity was found in older eggs in all the groups in the experiment (factorial ANOVA for albumen foaming capacity, effect of day of storage: $p < 0.001$). Albumen foam stability, in contrast, was significantly higher in all groups in fresh eggs than in eggs after storage (factorial ANOVA for albumen foam stability, effect of storage day: $p < 0.001$).

Yolk foaming capacity

A statistically significant difference between groups was confirmed in the values of yolk foaming capacity (factorial ANOVA for yolk foaming capacity, effect of group: $p < 0.001$). Significantly, the largest volumes of yolk foam were found in eggs from Group 2 supplemented with selenium-enriched yeast compared to the other groups (Fig. 4a). The eggs from Group 2 differed significantly from the eggs from all the other groups (post hoc test: $p < 0.001$ in all cases). The lowest volumes of whipped yolk foam were produced from eggs from Group 1 (supplementation with sodium selenite) and Group C (Control Group).

The dependence of yolk foaming capacity on selenium levels in the yolk was not statistically significant (Spearman's correlation coefficient, $r_s = 0.320$, $p = 0.112$).

The storage experiment showed increasing foaming capacity of yolk during egg storage. After 35 days of storage, foaming capacity values of eggs in all the groups (i.e. Groups 1–4 and C) were significantly higher than those of fresh eggs (factorial ANOVA for yolk foaming capacity, effect of day of storage: $p < 0.001$).

Sponge cake volume

The determination of the total volume of model bakery products from sponge batter showed that their volume was significantly influenced by selenium supplementation of laying hen feed (one-way ANOVA, effect of group: $p = 0.002$). The lowest sponge cake volumes were recorded in eggs from Group 1 (sodium selenium supplementation) and Group C eggs (Control Group; Fig. 4b). The difference between the volume values of defined bakery products made from Group C eggs and eggs from Groups 2 (post hoc test: $p = 0.005$), 3 ($p = 0.004$) and 4 ($p = 0.024$) was statistically confirmed. There was no difference between the eggs from organic selenium supplemented groups.

An evaluation of the relationship between sponge cake volume and albumen selenium content confirmed a positive correlation, which was not, however, statistically significant (Spearman's correlation coefficient, $r_s = 0.800$, $p = 0.104$). The higher the level of selenium in egg albumen, the higher the volume of sponge cakes. Correlations were also investigated between sponge cake volume and albumen foaming capacity ($r_s = 0.000$, $p = 1.000$), and between sponge cake volume and albumen foam stability ($r_s = 0.400$, $p = 0.505$). No correlation was, however, confirmed in these cases.

Fig. 4 Yolk foaming capacity (**a**) and sponge cake volume (**b**). Group 1—supplementation with sodium selenite, Group 2—supplementation with selenium-enriched yeast, Group 3—supplementation with synthetic L-selenomethionine, Group 4—supplementation with

hydroxy analog of selenomethionine, group C—Control Group. Significant differences between groups are marked with different letters. Vertical bars: 95% confidence interval

Discussion

Albumen gel firmness can be utilized as an indicator of the freshness and quality of eggs. The albumen gel properties change in dependence on albumen pH values that change as the result of aging of the eggs. Hermansson (1982) states that a high-firmness gel can be made from egg albumen with a high pH value. According to a study by Beveridge et al. (1980), the explanation lies in the formation of disulfide bridges from sulfhydryl groups, which is accelerated by increasing the pH to 9.0, because the firmness of albumen gel increases with the content of -SH groups. The reason for the increased firmness of albumen gel produced by heat treatment is probably related to the formation of a gel network consisting of disulfide bonds and other protein molecules (Zayas 1997). Moreover, egg albumen, whose pH is less than 7, forms a coagulant with a high carbon dioxide content which makes for the bubbly structure and reduced firmness of the formed gel (Chang and Chen 2000).

The above facts account for the results of the storage experiment in our study, which confirmed that albumen from older eggs with a higher albumen pH formed firmer gels compared to those from fresh eggs. Figure 1b shows that there is a positive correlation between values of albumen gel firmness and albumen pH, which is in agreement with the results of the experiment by Houska et al. (2004). A positive correlation between albumen pH and albumen gel firmness is also reported by Chang and Chen (2000). Houska et al. (2004) further explain that the dry matter content, whose proportion increases during storage

as a result of the transfer of water from the albumen to the yolk during storage, also has a positive effect on gel firmness. Alleoni (2006) points out that albumen gel properties are influenced by the presence of s-ovalbumin; s-ovalbumin, which results from the conversion of native ovalbumin, especially at higher pH, increases albumen gel firmness. The proportion of s-ovalbumin increases at a pH of 9.0, but remains low at a pH in a range of 7.0–8.0, and the albumen gel therefore exhibits lower firmness (Alleoni 2006).

It follows from the results obtained that selenium in supplemented eggs acts as a retarder of proteolytic changes associated with carbon dioxide diffusion thereby selenium slows down an increase in albumen pH and negatively influences gel firmness. Figure 1a demonstrates that albumen gel in eggs from Groups 1 (sodium selenium supplementation) and C (Control Group) had a firmer structure with fewer air bubbles in comparison with the eggs from groups supplemented with organic selenium (eggs from Groups 2, 3 and 4). The rate of CO₂ diffusion associated with protein degradation was higher in eggs from Groups C and 1. In contrast, Franchini et al. (2002), who monitored the effects of antioxidants on the functional properties of eggs in their study, did not confirm any statistically significant differences in their results regarding albumen gel firmness between enriched and non-enriched eggs.

Since higher albumen pH values have a positive effect on whipped foam volumes, it could have been expected that eggs in the Group C, whose albumen pH values were the highest, will also produce the largest volumes of albumen foam. Our results, however, disprove this

assumption. Findings on albumen foaming capacity are in agreement with results obtained by Franchini et al. (2002). These authors analyzed the functional properties of eggs to verify the effects of antioxidants and found that the largest volumes of foam were attained in groups supplemented with vitamin C and vitamin E, whose antioxidant activity is similar to that of selenium. However, the results of this experiment were not statistically confirmed.

The results of our study further confirmed a negative correlation between foam stability and albumen pH value (Fig. 3b). According to this finding, also corroborated by Alleoni and Antunes (2004), it is clear that selenium, which retards the increase in albumen pH, improves albumen foam stability. In our experiment, significantly higher levels of foam stability were found in eggs from supplemented groups (Groups 1–4, Fig. 2b). According to Franchini et al. (2002), the addition of feed supplements in the form of vitamins E and C promoted egg production with a significantly higher ability of albumen to form stable foam. Increased albumen foam stability after the addition of vitamin E to the diet of laying hens was also confirmed by Kirunda and McKee (2000).

Our storage experiment also confirmed the better foaming capacity of albumen from older eggs. This finding is corroborated by the results of the studies by Silversides and Budgell (2004), Biladeau and Keener (2009) and Sheikh et al. (2009). Silversides and Budgell (2004) reported that increases in albumen pH during storage increased the capacity to form large volumes of foam, which was corroborated by the correlation between foam volume and albumen pH ascertained in our study. A positive correlation between albumen pH values and albumen foam volumes was also corroborated by Chang and Chen (2000). According to Biladeau and Keener (2009), the largest volumes of foam are produced when albumen pH ranges from 8.3 to 9.5. Our storage experiment also demonstrated that egg aging has the opposite effect on albumen ability to form foams of high stability. In all the groups (Groups 1–4 and C), albumen foam stability was significantly better in fresh eggs than in eggs after storage. The reason is that, as a result of changes in albumen pH, native ovalbumin is transformed into more hydrophilic ovalbumin in older eggs, which increases albumen drainage from whipped foam (Alleoni and Antunes 2004). Moreover, the mucilage-lysozyme complex breaks up during storage, which causes a reduction in the albumen thick and its viscosity. The reduction of albumen viscosity results in a reduction in the durability of whipped foam (Alleoni 2006).

Our study presents the first data on the foaming capacity of selenium-supplemented egg yolk. Due to its antioxidant activity, selenium slows down the oxidation of the yolk proteins that are necessary for the formation of yolk foam

and thereby has an indirect effect on the properties of yolk foam. The results obtained by analyzing eggs from groups enriched with selenium in organic form (Groups 2–4) corroborate this assumption (Fig. 4a).

According to the results of our sponge cake volume test, the ability to produce large volumes of foam of great firmness was demonstrated by the volume of model bakery sponge cake items made with eggs from the groups supplemented with the organic form of selenium. Since no study reporting results of the evaluation of bakery products made from selenium-supplemented eggs had been published prior to 2019, the present study provides the first data on the matter. Some data, however, have been published on sponge cake volume analysis after vitamin E supplementation (Kirunda and McKee 2000). Kirunda and McKee (2000) found that the products of the largest volume were those made from eggs from hens fed a diet supplemented with vitamin E. The authors further stated that sponge cake volumes increased with the increasing levels of vitamin E. Our results confirmed that selenium, which affects proteins responsible for the formation and stability of egg foam, has secondary impacts on the volume of sponge cake items (Fig. 4b).

Conclusion

The results of the study confirmed that selenium added to the laying hen feed significantly affected the monitored functional properties of both albumen and yolk. Eggs from non-enriched groups showed, on average, the highest values of albumen gel firmness, which is due to their high albumen pH values. On the other hand, selenium supplementation of laying hen diets can be expected to improve the foaming capacity of both albumen and yolk. Organic selenium supplemented in the form of selenium-enriched yeast and selenomethionine proved to have a particularly positive effect on albumen foam stability and foaming capacity. The organic form of selenium slows down the oxidation of proteins responsible for the foaming capacity of both albumen and yolk more effectively than its inorganic form. The high efficacy of the organic form of selenium was also positively demonstrated in the bakery experiment, in which the volume of sponge cake products was highest when eggs from the groups supplemented with selenium-enriched yeast and selenomethionine were used. Differences between the organic selenium sources were not confirmed in all observed parameters except yolk foaming capacity where the selenium-enriched yeast showed the best results.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Animal handling followed the European Union Directive 86/609/EEC on the protection of animals used for scientific purposes, European Convention for the protection of vertebrate animals used for experimental and other scientific purposes, Act Number 246/1992 Coll. of Laws of the Czech Republic on the protection of animals against cruelty as amended and with the agreement of the Branch Commission for Animal Welfare of the Ministry of Agriculture of the Czech Republic (Permission No. MZe.17214).

References

- Alleoni ACC (2006) Albumen protein and functional properties of gelation and foaming. *Sci Agric (Piracicaba, Braz.)* 63:291–298
- Alleoni ACC, Antunes AJ (2004) Albumen foam stability and s-ovalbumin contents in eggs coated with whey protein concentrate. *Rev Bras Cienc Avic* 6:105–110
- Beveridge T, Arntfield S, Ko S, Chung JKL (1980) Firmness of heat induced albumen coagulum. *Poult Sci* 59:1229–1236
- Biladeau AM, Keener KM (2009) The effects of edible coatings on chicken egg quality under refrigerated storage. *Poult Sci* 88:1266–1274
- Chang YI, Chen TC (2000) Functional and gel characteristics of liquid whole egg as affected by pH alteration. *J Food Eng* 45:237–241
- Cobanova K, Petrovic V, Mellen M, Arpasova H, Gresakova L, Faix S (2011) Effects of dietary form of selenium on its distribution in eggs. *Biol Trace Elem Res* 144:736–746
- Dobrzanski Z, Jamroz D (2003) Bioavailability of selenium and zinc supplied to the feed for laying hens in organic and inorganic form. *EJPAU* [online] 6: #03 <http://www.ejpau.media.pl/volume6/issue2/animal/art-03.html> Accessed 15 May 2017
- Franchini A, Sirri F, Tallarico N, Minelli G, Iaffaldano N, Meluzzi A (2002) Oxidative stability and sensory and functional properties of eggs from laying hens fed supranutritional doses of vitamins E and C. *Poult Sci* 81:1744–1750
- Han XJ, Qin P, Li WX, Ma QG, Ji C, Zhang JY, Zhao LH (2017) Effect of sodium selenite and selenium yeast on performance, egg quality, antioxidant capacity, and selenium deposition of laying hens. *Poult Sci* 96:3973–3980
- Heindl J, Ledvinka Z, Tumova E, Zita L (2010) The importance, utilization and sources of selenium for poultry: a review. *SAB* 41:55–64
- Hermansson AM (1982) Gel characteristics-structure as related to texture and water binding of blood plasma gels. *J Food Sci* 47:1965–1972
- Houska M, Hyhos K, Novotna P, Landfeld A, Strohalm J (2004) Gel strength of the native egg white. *Czech J Food Sci* 22:58–66
- Jing CL, Dong XF, Wang ZM, Liu S, Tong JM (2015) Comparative study of DL-selenomethionine vs sodium selenite and seleno-yeast on antioxidant activity and selenium status in laying hens. *Poult Sci* 94:965–975
- Kieliszek M, Blazejak S, Gientka I (2015) Accumulation and metabolism of selenium by yeast cells. *Appl Microbiol Biotechnol* 99:5373–5382
- Kirunda DFK, McKee SR (2000) Relating quality characteristics of aged eggs and fresh eggs to vitelline membranes strength as determined by a texture analyzer. *Poult Sci* 79:1189–1193
- Norris ME, Cotterill OJ (1986) Sponge cake preparation. Appendix II. Recommended Methods for Analysis of Eggs and Poultry Meat. North Central Regional Research Publication 307
- Pan C, Huang K, Zhao Y, Qin S, Chen F, Hu Q (2007) Effect of selenium source and level in hen's diet on tissue selenium deposition and egg selenium concentrations. *J Agric Food Chem* 55:1027–1032
- Pappas AC, Acamovic T, Sparks NHC, Surai PF, Mcdevitt RM (2005) Effects of supplementing broiler breeder diets with organic selenium and polyunsaturated fatty acids on egg quality during storage. *Poult Sci* 84:865–874
- Pavlovic Z, Miletic I, Jokic Z, Sobajic S (2009) The effect of dietary selenium source and level on hen production and egg selenium concentration. *Biol Trace Elem Res* 131:263–270
- Sevcikova S, Skrivan M, Dlouha G, Koucky M (2006) The effect of selenium source on the performance and meat quality of broiler chickens. *Czech J Food Sci* 51:449–457
- Sheikh H, Pasha A, Katiya G (2009) Factors affecting whipping ability of fresh and stale eggs. *Pak J of Food Sci* 19:1–6
- Silversides FG, Budgell K (2004) The relationships among measures of egg albumen height, pH, and whipping volume. *Poult Sci* 83:1619–1623
- Wang ZG, Pan XJ, Zhang WQ, Peng ZQ, Zhao RQ, Zhou GH (2010) Methionine and selenium yeast supplementation of the maternal diets affects antioxidant activity of breeding eggs. *Poult Sci* 89:931–937
- Zayas JF (1997) Foaming properties of proteins. In: Zayas JF (ed) *Functionality of proteins in food*. Springer, Berlin, pp 260–309

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