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Effects of selenium source and level in diet on glutathione peroxidase activity, tissue selenium distribution, and growth performance in poultry

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Review

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Abstract

Today, a few differing sources of selenium (Se), i.e. inorganic, organic, and nano forms of Se, are used as feed supplements for poultry. Published research indicates that nano-Se and organic Se possess comparable efficiency to inorganic Se in increasing GSH-Px activity of plasma and various tissues, but they deposit at higher rates in various tissues. However, there are principal differences in absorption mechanisms, metabolism, and efficiency of these three forms of Se. The aim of this review was to analyze the available literature on the effects of different Se sources and levels in the diet on glutathione peroxidase (GSH-Px) activity, tissue Se distribution and growth performance in poultry. Higher levels of Se increase GSH-Px activity in the body, but this reaches a plateau even if Se concentrations in diet increase further, while the deposition of Se in tissues increases as Se content in diet increases. In addition, many studies have shown the positive effects of adding Se to diet on growth performance in poultry. Optimal Se supplementation is necessary not only for good poultry health but also to ensure and preserve meat quality during storage and to provide human beings with this microelement.

Introduction

To achieve adequate growth and health, poultry should be provided with sufficient amounts of all necessary nutrients, including the mineral, selenium (Se). Se is essential for human and animal nutrition, as it is incorporated in at least 25 proteins that play important roles in the regulation of various functions of the body (Surai and Fisinin, 2014). One of the most important selenoproteins is the enzyme, glutathione peroxidase (GSH-Px), which is involved in the cellular defense against oxidative stress by catalyzing the reduction of reactive oxygen species to less harmful molecules (Arthur, 2000). The appropriate level of Se is important for the reproductive performance of animals, bone metabolism, immune function, and metabolism of iodine (Rayman, 2000).

Nutritional Se requirement for poultry

Although Se is essential for animal nutrition at low dietary concentrations, Se toxicosis appears when dietary concentrations are slightly over essential levels (Ohlendorf, 2003). The addition of Se at 0.15 mg kg^{-1} in the diet is recommended for broiler chickens throughout the growth period (National Research Council. Nutrient Requirements of Poultry, 1994), while the dietary Se intake of more than 0.5 mg kg^{-1} is not allowed (European Commission, 2014). However, Se is not equally distributed in soils and plants in all parts of the world, so some regions, including the Balkans, are Se-deficient areas (Oldfield, 2002). Addition of recommended quantities of Se to feed can compensate for the adverse effects of Se-deficient diets (Surai, 2002).

Selenium sources and their efficacy

The efficacy of Se in inducing Se-containing enzymes *in vivo* and *in vitro* depends on its chemical form (Ortuno *et al.*, 1996). Nowadays, a few differing sources of Se are used as feed supplements. Organic forms of Se containing selenomethionine (Se-Met) and selenocysteine (Se-Cys) perform a key role in biological processes due to the fact they are more active, less toxic (Suchý *et al.*, 2014), have higher bioavailability (Mahan *et al.*, 1999) and accumulate at higher levels in all tissues than inorganic Se salts (Payne and Southern, 2005; Suchý

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et al., 2014). The advantages of organic Se compared with inorganic Se have now been reported in numerous meat-enrichment studies in poultry (Choct *et al.*, 2004; Payne and Southern, 2005; Marković *et al.*, 2008, 2010). Organic Se is mostly used in the form of Se-enriched yeast (Briens *et al.*, 2013; Baltić *et al.*, 2015, 2016; Marković *et al.*, 2018) or in other preparations, such as Se chelate (Chadio *et al.*, 2015), proteinates (Leeson *et al.*, 2008), pure Se-Met (Wang *et al.*, 2011) or a new organic Se source, which is a selenomethionine hydroxyanalogue, 2-hydroxy-4-methylselenobutanoic acid or HMSeBA (Briens *et al.*, 2013, 2014). HMSeBA is fully converted into selenomethionine and selenocysteine and shows higher relative bioavailability through muscle Se enrichment compared with other sources of Se (Briens *et al.*, 2013, 2014). With the recent development of nanotechnology, nano-products have begun to be applied in the area of nutritional supplements and have become largely available and usable (Suchý *et al.*, 2014). Nano-materials exhibit novel properties, such as a large surface area, high surface activity, high catalytic activity, strong adsorbing ability, and low toxicity (Wang *et al.*, 2007; Zhang *et al.*, 2008). It has been reported that nano-Se possesses comparable efficiency to sodium selenite (SS) and Se-methylselenocysteine in upregulating selenoenzymes, but with dramatically decreased toxicity (Zhang *et al.*, 2008). Also, Mohapatra *et al.* (2014) indicated that the range between optimal and toxic dietary levels of nano-Se was greater than that of sodium selenite.

European Union legislation 427/2013 and 445/2013 suggested to the maximum inclusion of organic Se sources when inorganic Se is added.

Dietary selenium and glutathione peroxidase activity

An integrated antioxidant system has been described in avian tissues (Surai, 2002) and it has been suggested that the cell's first line of antioxidant defense is based on the activity of three enzymes: superoxide dismutase, GSH-Px, and catalase (Surai, 2002). GSH-Px inhibits lipid oxidation in both live tissues and post-slaughter meat (Daun and Akesson, 2004*a*; Cai *et al.*, 2012). Its activation requires small amounts of selenocysteine, which probably substitutes sulfur in the glutathione molecule and causes increases in GSH-Px activity of up to a thousand times (Burk, 2002; Suchý *et al.*, 2014). Chen *et al.* (2013) observed that oxidation resistance in broilers increased significantly along with Se level. Further, other authors found that the activity of GSH-Px in serum and tissues of broilers increased along with dietary Se content (Yoon *et al.*, 2007; Wang and Xu, 2008; Jiang *et al.*, 2009; Heindl *et al.*, 2010; Wang *et al.*, 2011; Zhou and Wang, 2011; Cai *et al.*, 2012; Chen *et al.*, 2013; Boostani *et al.*, 2015) (Table 1). Similarly, GSH-Px activity in plasma was related to the level of dietary Se supplementation (Dean and Combs, 1981), while a high positive correlation was found between GSH-Px activity and Se level in plasma of ducks (Baltić *et al.*, 2015). The linear correlation between Se concentration and GSH-Px activities of the blood and various tissues has been well documented (Pavlata *et al.*, 2001). Further, decreased GSH-Px activity was found in Se-deficient turkeys compared with Se-adequate turkey poults (Sunde and Hadley, 2010; Taylor and Sunde, 2016). In turkeys, at least 0.2 mg of Se kg^{-1} was required in their diet to achieve maximum Se concentrations in tissues and GSH-Px activity in liver and plasma (Hadley and Sunde, 1997), while other authors (Fischer *et al.*, 2008; Taylor and Sunde, 2016) determined higher dietary Se requirements for turkeys (0.3 mg kg^{-1}).

Furthermore, Hu *et al.* (2012) observed that GSH-Px produced the greatest response when 0.15 mg kg^{-1} of dietary Se was fed to broilers, plasma GSH-Px activity reached a plateau, and did not increase further with higher Se concentrations in the diet. Similarly in turkeys, increased Se supplementation (approximately 0.3 mg kg^{-1}) resulted in well-defined plateaus for all blood, liver, and gizzard GSH-Px activities, showing that these selenoprotein biomarkers could not be used as biomarkers for supernutritional-Se status (Taylor and Sunde, 2016). On the contrary, Baltić *et al.* (2015) found that a plateau for plasma GSH-Px activity was reached with 0.4 mg kg^{-1} of dietary Se in 14-days-old ducks, while at the end of the study, the highest enzymatic activity was achieved in the group with 0.6 mg kg^{-1} of Se in diet. According to these results, it seems that Se dietary requirements for ducks are higher than those of other poultry species, and that a plateau for GSH-Px could be reached with higher dietary Se content. Moreover, comparing GSH-Px activity in different species fed with similar amounts of Se, Daun and Akesson (2004*a*) found that ducks produced the highest enzymatic activity in muscles. Those authors concluded that the diversity in muscle GSH-Px activity among and within species is probably due to differing needs for antioxidant protection.

On the contrary, changing the Se level in the diet did not influence GSH-Px activity in erythrocytes (Choct *et al.*, 2004), plasma, breast muscle (Leeson *et al.*, 2008), chicken thighs (Daun and Akesson, 2004*a*; Cichoski *et al.*, 2012), or liver (Leeson *et al.*, 2008; Heindl *et al.*, 2010). This could be attributed to the fact that Se ingested by the birds is used for producing several selenoproteins besides GSH-Px (Cichoski *et al.*, 2012). Thus, Se distribution in the avian body is regulated by its metabolic needs (Daun and Akesson, 2004*b*).

With respect to the dietary Se source on GSH-Px activity, some studies indicated that the effects of organic Se were superior to those of inorganic Se in chickens (Jiang *et al.*, 2009; Yang *et al.*, 2012; Chen *et al.*, 2014), suggesting higher bioavailability of organic forms compared with inorganic forms. In turkeys, similar results were found by Mikulski *et al.* (2009), while Cantor *et al.* (1982) did not observe any differences in plasma GSH-Px activity between different dietary Se sources (SS vs. selenomethionine). However, the effect of dietary Se source had inconsistent effects on GSH-Px activity in broilers. Using organic Se resulted in a highly significant decline of GSH-Px activity in plasma, liver, pancreas, breast muscle, and in erythrocytes compared with inorganic Se (Choct *et al.*, 2004; Leeson *et al.*, 2008; Wang *et al.*, 2011). However, other authors (Kuricova *et al.*, 2003; Payne and Southern, 2005; Marković *et al.*, 2008) reported no differences in the GSH-Px activity in plasma and tissues of broilers fed Se in either an organic or inorganic form. There is some suggestion, therefore, that GSH-Px activity could be lower in certain broiler tissues when organic rather than inorganic Se is used as a feed supplement. This seems contrary to the general assumption that organic sources are more bioavailable. A more logical interpretation is that with better oxidative stability there is, in fact, less need for a synthesis of GSH-Px, so lower levels are indicative of better health status (Leeson *et al.*, 2008). Another possible explanation for lower GSH-Px activity after consuming organic Se compared with inorganic Se is due to the fact that Se, regardless of its form, must be converted to Se-Cys before it can be incorporated into the selenoprotein enzyme GSH-Px (Forstrom *et al.*, 1978). It was reported that SS was metabolized into Se-Cys more efficiently than organic Se sources containing Se-Met (Sunde and Hoekstra, 1980). Another likely possibility is that Se-Met can be

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Table 1. Selected studies that investigated the effects of different sources and levels of Se in the diet on GSH-Px activity, level of Se in tissues, and growth performance in poultry

	Reference	Poultry species	Se source	Level of selenium in diet (mg kg^{-1})	Level of Se in tissues	Activity of GSH-Px	Final body weight	Weight gain	Feed consumption	Feed conversion ratio (FCR)	Chilling loss/ Drip loss
1.	Choct *et al.* (2004)	Bartter strain broilers	Sodium selenite (SS) and Se-yeast (SY)	0.10, 0.25 with SS; 0.10, 0.25 with SY	Increasing Se supplementation rate from 0.1 to 0.25 mg kg^{-1} increased breast muscle Se concentration. SY was more efficiently deposited in the breast muscle than SS.	SS increased GSH-Px activity in red blood cells significantly more than SY.	NS	–	Broilers receiving Se at 0.1 mg kg^{-1} consumed more feed than those on 0.25 mg kg^{-1} Se. Feed intake was not influenced by the source of selenium.	Increasing the Se content in diet improved the FCR, while FCR was independent of Se source, although diets containing SY tended to be superior.	Birds receiving SY reduced drip loss, as well as birds with higher Se content in diet.
2.	Payne and Southern, (2005)	Ross broilers	Sodium selenite (SS) and Se-yeast (SY)	0; 0.3 with SS; 0.3 with SY	Dietary supplementation with SY increased ($P < 0.05$) muscle and plasma Se concentrations compared with broilers fed the control diet or the diet with SS.	Plasma GSH-Px activity was not affected by Se source or level of supplementation.	Final body weight, weight gain, feed intake, and gain to feed ratio were not affected by diet, regardless of Se supplementation or source, during any period of growth.				–
3.	Yoon *et al.* (2007)	Jumbo Cornish Cross broilers	Sodium selenite (SS) and Se-yeast (SY) A and B	0; 0.1, 0.2, 0.3 with SY-A; 0.3 with SY-B; 0.3 with SS	Blood Se and GSH-Px activities increased as the concentration of Se in diets increased. At 0.3 mg kg^{-1}, blood Se, and GSH-Px activities were higher for broilers supplemented with SY-A compared with SY-B.		NS	NS	Higher feed intake was observed in the group with 0.1 mg kg^{-1} SY-A compared with the group fed with 0.3 mg kg^{-1} SY-B.	FCR was improved in the group with 0.2 mg kg^{-1} of SY-A compared with the control group.	–
4.	Wang and Xu (2008)	Broiler chickens	Sodium selenite (SS) and Se-yeast (SY)	0; 0.2 with SS; 0.2 with SY	Supplementation of Se in diet increased Se content in tissues, while higher levels of Se in kidney, liver and pancreas were determined in SY treated group as compared with the rest.	In group with basal diet GSH-Px activity was lower compared with Se supplemented groups, where highest values of GSH-Px activity in plasma were reached after adding SY in diet.	NS	NS	–	Feed conversion ratio improved in Se supplemented broilers compared with control group.	–
5.	Perić *et al.* (2009)	Cobb broilers	Sodium selenite (SS) and Se-yeast (SY)	0.3 with SS; 0.2 SS + 0.1 SY; 0.1 SS + 0.2 SY; 0.3 SY	–	–	NS	–	–	NS	Birds fed diets containing 0.3 mg kg^{-1} of SY had the lowest value of drip loss.

6.	Jiang *et al.* (2009)	Lingnan yellow male broilers	Sodium selenite (SS) and selenomethionine (Se-Met)	0; 0.075, 0.15, 0.225 with Se-Met; 0.15 with SS	–	The addition of Se in diet elevated GSH-Px activity in plasma, where the highest enzymatic activity was determined in the group with 0.225 mg kg^{-1} of Se-Met.	Final body weight and weight gain of birds significantly increased by supplementation of Se-Met at 0.225 mg kg^{-1} level.		NS	NS	Drip loss was decreased by the addition of Se-Met.
7.	Zoidis *et al.* (2010)	Cobb broilers	Se-yeast (SY)	0; 0.15, 0.3, 3.0 with SY	Supplementation of diets with Se significantly increased Se concentration in blood and liver.	–	Final body weight and weight gain were significantly lower in control group and group with 3.0 mg kg^{-1} of added Se compared with Se adequate groups.		NS	NS	–
8.	Heindl *et al.* (2010)	Ross broilers	Sodium selenite (SS), Se-yeast (SY) and Se-enriched alga (SA)	0; 0.15, 0.3 with SS; 0.15, 0.3 with SY; 0.15, 0.3 with SA	Supplementation of Se in diet increased Se content in breast muscle reaching highest values after adding SY and SA as Se source.	Adding Se in broiler diet resulted in higher GSH-Px activity in breast and thigh muscle of Se supplemented groups compared with control group.	The highest final body weight was reached with 0.15 mg kg^{-1} of SY and 0.3 mg kg^{-1} of SA.	–	–	NS	–
9.	Wang *et al.* (2011)	Ross broilers	Sodium selenite (SS) and seleno-methionine (Se-Met)	0; 0.15 with SS; 0.15 with Se-Met	Selenium concentrations in serum, liver, kidney, pancreas, and breast muscle were higher after dietary Se supplementation, while the Se-Met group showed the highest value.	GSH-Px activity in serum and in liver, kidney, pancreas, and breast muscle was elevated by dietary Se supplementation, while SS increased GSH-Px activities in pancreas and breast muscle to a larger extent than did Se-Met.	–	–	–	–	↓ drip loss after adding Se in diet, with lowest values after adding Se-Met.
10.	Zhou *et al.* (2011)	Guangxi Yellow chickens	Nano-Se	0; 0.1, 0.3, 0.5 with nano-Se	The groups that received nano-Se showed higher liver and muscle Se contents, than that did the control group, while supplemented groups with 0.3 and 0.5 mg kg^{-1} of Se had higher Se content in muscle than group with 0.1 mg kg^{-1} of added Se.	Serum and liver GSH-Px activity was higher in Se supplemented groups compared with control group, as well as in groups with 0.3 and 0.5 mg kg^{-1} of added Se compared with group with 0.1 mg kg^{-1} of Se.	Improved final body weight, daily body weight gain, and feed conversion ratio were observed in the groups supplemented with nano-Se as compared with the control group. Groups with 0.3 and 0.5 mg kg^{-1} of added Se had higher body weight and daily body weight gain, and better feed conversion ratio compared with group supplemented with 0.1 mg kg^{-1} of Se.				(↓ drip loss after adding Se in diet)
11.	Cai *et al.* (2012)	Arbor Acres broilers	Nano-Se	0; 0.3, 0.5, 1.0, 2.0 with nano-Se	Dietary selenium increased concentration of Se in breast muscle observing highest content in groups	Increased GSH-Px activity in serum and tissue was found in groups fed nano-Se	NS	NS	NS	NS	(↓ drip loss after adding Se in diet)

(*Continued*)

Table 1. (*Continued.*)

	Reference	Poultry species	Se source	Level of selenium in diet (mg kg^{-1})	Level of Se in tissues	Activity of GSH-Px	Final body weight	Weight gain	Feed consumption	Feed conversion ratio (FCR)	Chilling loss/ Drip loss
					with 1.0 and 2.0 mg kg^{-1} of added Se.	compared with the control group.					
12.	Yang *et al.* (2012)	Arbor Acres broilers	Sodium selenite (SS) and Se-yeast (SY)	0.3 with SS; 0.3 with SY	–	In birds fed with SY serum GSH-Px activity was higher than in birds fed with SS.	–	Daily weight gain and feed intake were higher, while feed conversion was lower in SY group compared with SS group indicating that the effects of SY on broiler growth performance were better than that of SS.			–
13.	Hu *et al.* (2012)	Arbor Acres broilers	Sodium selenite (SS) and nano-Se	0; 0.15, 0.3, 0.6, 1.20 with SS; 0.15, 0.3, 0.6, 1.20 with nano-Se	Se concentrations in serum, liver, and breast muscle increased as the dietary Se level increased for either Se source, and chicks receiving nano-Se had higher Se concentrations in serum, liver, and breast muscle than did selenite treated chicks.	Se supplementation irrespective of source and level in diet increased GSH-Px activity in serum of broilers.	–	The group unsupplemented with any forms of Se showed the lowest weight gain.	NS	Group with no added Se had the lowest feed conversion ratio.	–
14.	Chen *et al.* (2013)	Arbor Acres broilers	Se-yeast (SY)	0.0; 0.3, 0.5, l.0, 2.0 with SY	Selenium contents in liver and chest muscle increased along with additive amounts of Se.	The activity of serum GSH-Px increased along with dietary selenium level.	–	NS	NS	NS	NS
15.	Briens *et al.* (2013)	Ross broilers	Sodium selenite (SS), Se-yeast (SY) and 2-hydroxy-4-methylselenobutanoic acid (SO)	*Exp 1* 0; 0.1, 0.3 with SS; 0.1, 0.3 with SY; 0.1, 0.2, 0.3 with SO	Control group induced the lowest Se concentration and all feed treatments with 0.3 mg kg^{-1} of Se resulted in higher muscle Se concentrations than feed treatments with 0.1 mg kg^{-1} of Se in diet. Regarding Se source, Se muscle content had the following order: SS < SY < SO.	–	NS	–	NS	NS	–
				Exp 2 0.3 with SS; 0.3 with SY; 0.3 with SO	Muscle Se concentrations indicated improvement with organic Se sources (SY and SO) compared with SS, with an additional increase with SO.	–	NS	–	NS	NS	–

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16.	Briens *et al.* (2014)	Ross broilers	Sodium selenite (SS), Se-yeast (SY) and 2-hydroxy-4-methylselenobutanoic acid (SO)	*Exp 1* 0; 0.3 with SS; 0.1, 0.3 with SY and 0.1, 0.3 with SO	Plasma, liver, and muscle Se concentrations were improved by all Se sources compared with the negative control group. A significant dose effect was observed from 0.1 to 0.3 mg of Se kg^{-1} of feed for each source. Muscle Se concentrations were improved such as SO>SY >SS.	–	The different treatments did not influence growth performance parameters over the overall study period.				–
				Exp 2 0; 0.3, 0.5, 5.0 with SS; 0.3, 0.5, 5.0, 10.0 with SO	–	–	Comparing growth performances of the control group and Se standard supplementation levels (SS-0.3 mg kg^{-1}, SS-0.5 mg kg^{-1}, SO-0.3 mg kg^{-1}, and SO-0.5 mg kg^{-1}), no differences were observed on growth performance parameters. The excessive dose treatments SS-5.0 mg kg^{-1} and SO-10.0 mg kg^{-1} significantly reduced body weight and feed intake, whereas excessive dose SO-5.0 mg kg^{-1} did not affect growth performances.				
17.	Chadio *et al.* (2015)	Cobb broilers	Zinc L-selenomethionine (Zn-Se-Met)	0; 0.3 with Zn-Se-Met	–	Se elevated blood plasma GSH-Px activity in Se supplemented groups at the 4th week of age	NS	NS (only a tendency for higher weight gain in Se supplemented groups compared with those fed diets with adequate Se content)	NS	NS	–
18.	Boostani *et al.* (2015)	Cobb broilers	Sodium selenite (SS), Se-yeast (SY) and nano-Se	0; 0.3 nano-Se; 0.3 SS; 0.3 SY	–	Different sources of Se increased blood GSH-Px activity and a greater increase was in group with nano-Se.	–	NS	NS	NS	–
19.	Baltić *et al.* (2015)	Cherry Valley ducks	Se-yeast (SY)	0; 0.2, 0.4, 0.6 with SY	Se supplementation increased significantly Se levels in plasma, liver, muscles, and feces. Se content was markedly improved as dietary Se level increased.	Higher enzymatic activity in plasma was determined in groups with 0.4 mg kg^{-1} and 0.6 mg kg^{-1} added Se compared with groups with lower levels of Se in their diets (0 mg kg^{-1} and 0.2 mg kg^{-1}).	Animals fed high Se diets (0.4 mg kg^{-1}) had higher live weight compared with those fed diets with inadequate (0 mg kg^{-1}) or with supranutritional (0.6 mg kg^{-1}) Se levels.	–	–	–	–
20.	Baltić *et al.* (2016)	Cherry Valley ducks	Se-yeast (SY)	0; 0.2, 0.4, 0.6 with SY	–	–	On days 14, 21, and 35 higher bodyweight was found in group with 0.2 mg kg^{-1} of added Se than in group with 0.6 mg kg^{-1} of added Se. Animals fed with 0.4 mg kg^{-1} had higher final bodyweight and daily weight gain compared with those fed diets with 0 mg kg^{-1} or with 0.6 mg kg^{-1} of Se. Ducks fed only with basal diet showed a higher feed conversion ratio compared with those supplemented with Se at 0.4 mg kg^{-1} and 0.6 mg kg^{-1}.				–

(*Continued*)

Table 1. (*Continued.*)

	Reference	Poultry species	Se source	Level of selenium in diet (mg kg^{-1})	Level of Se in tissues	Activity of GSH-Px	Final body weight	Weight gain	Feed consumption	Feed conversion ratio (FCR)	Chilling loss/ Drip loss
21.	Fischer *et al.* (2008)	BUT BIG 6 turkeys	Sodium selenate (SS)	0; 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4 with SS	Increasing selenium supplementation elevated selenium concentrations in organs and plasma. Plateaus of selenium concentration were reached at 0.15 mg Se kg^{-1} diet (thigh muscle) and 0.30 mg Se /kg^{-1} diet (liver, plasma, gizzard, breast muscle).	High correlation was observed between the activities of liver and plasma GSH-Px and the selenium supplementation. GSH-Px activity in liver reached plateau at 0.20 mg Se kg^{-1}, while in plasma at 0.30 mg Se kg^{-1} of diet.	Reduced weight gain could be observed in the Se deficient group and this led to a reduced live weight of the Se deficient animals compared with the others.		Feed consumption was reduced in the group receiving the Se-deficient diet. No differences were observed between the groups for the feed conversion ratio		–
22.	Mikulski *et al.* (2009)	BUT 9 turkeys	Sodium selenite (SS) and Se-yeast (SY)	0; 0.3 with SS; 0.3 with SY	–	GSH-Px activity was higher in turkeys fed the diet with SY than in SS group and control group, while addition of 0.3 mg kg^{-1} SS to diets for turkeys had no effect on the activity of GSH-Px.	NS	–	NS	NS	(a tendency for ↓ drip loss after adding SY compared with SS)
23.	Taylor, and Sunde (2016)	Nicholas white-derived turkeys	Sodium selenite (SS)	0; 0.025, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.75 with SS	–	Se deficiency decreased plasma GSH-Px 3, liver GSH-Px 1, and liver GSH-Px 4 activities to 2, 3, and 7%, respectively, of Se-adequate levels.	Se supplementation did not have any significant effect on final body weight, although Se-deficient birds (0 mg kg^{-1}) averaged 70% of the weight of poults fed 0.4 mg kg^{-1}. Groups with 0 mg kg^{-1} and 0.025 mg kg^{-1} had lower rate of growth as compared with all other groups.		–	–	–

NS, no significant differences were found among compared groups.

incorporated into a wide spectrum of cellular proteins in place of methionine and is only later incorporated into GSH-Px, whereas Se from SS was rapidly incorporated into GSH-Px (White and Hoekstra, 1979).

In many studies, increased GSH-Px activity in serum and tissues was found in groups fed nano-Se compared with the control group (Zhou and Wang, 2011; Cai *et al*., 2012; Hu *et al*., 2012; Boostani *et al*., 2015). The results of some authors (Zhou and Wang, 2011; Cai *et al*., 2012; Boostani *et al*., 2015) indicate that elevation of GSH-Px activities in serum, liver, and muscle can be optimized by supplementation with 0.3 mg kg^{-1} of nano-Se, while the maximum supplementation of nano-Se should not be more than 1.0 mg kg^{-1}.

Dietary selenium and its content in tissues and feces

Se is a semi-metallic element that is physiologically required by birds, but at increased levels, it can be toxic and cause deleterious effects (Hoffman, 2002; Yoon *et al*., 2007). It is clear that Se accumulation in tissues is related to dietary Se supplementation, but this accumulation depends on type of tissue, and can vary according to animal species, the source, and level of Se supplementation (Vignola *et al*., 2009). Regarding differences in species, the highest average total Se content was found in duck, followed by lamb >chicken >ostrich >turkey (Daun and Akesson, 2004*a*). Combs and Combs (1986) indicated that Se concentrations are usually highest in kidney, intermediate in the liver, and lowest in skeletal muscle. Pan *et al*. (2007) found a similar order of Se distribution: liver >kidney >spleen >cardiac muscle >egg >blood >breast muscle, irrespective of the Se level or source. Moreover, deposition of Se in tissues increases as Se content in diet increases (Choct *et al*., 2004; Zhou and Wang, 2011; Chen *et al*., 2013; Briens *et al*., 2014; Baltić *et al*., 2015). A consistent improvement in Se accumulation was observed from organic Se sources compared with SS or control diet (Briens *et al*., 2013). Thus, higher Se concentrations in plasma and various tissues were found by many authors after organic Se was incorporated into diets compared with inorganic Se (Kuricova *et al*., 2003; Choct *et al*., 2004; Payne and Southern, 2005; Pan *et al*., 2007; Leeson *et al*., 2008; Marković *et al*., 2008, 2018; Perić *et al*., 2009; Heindl *et al*., 2010; Wang *et al*., 2011; Briens *et al*., 2013, 2014; Chen *et al*., 2014). The effects of different Se levels and sources in the diet on the accumulation of Se in tissues are summarized in Table 1. Furthermore, by replacing inorganic Se with organic Se in diets, the concentration of Se in excreta was decreased and a higher level of Se retention was observed (Choct *et al*., 2004; Yoon *et al*., 2007; Briens *et al*., 2013). Some studies also proved that turkeys receiving inorganic Se retained less Se in tissues than those receiving organic Se (Cantor *et al*., 1982; Mikulski *et al*., 2009). This is probably due to the different absorption mechanisms for organic and inorganic forms of Se. Inorganic Se is passively absorbed from the intestine by a simple diffusion process, competing with a number of mineral elements for the same absorption route, whereas organic Se is actively absorbed through the amino acid transport mechanisms (Wolfram *et al*., 1989). Further, the different concentrations of Se in tissues from inorganic and organic Se sources might also be explained by differences in metabolic routes. As mentioned above, Se in both forms can be incorporated into GSH-Px, but Se-methionine is also incorporated non-specifically into other body proteins too, in substitution for methionine (Schrauzer, 2000; Kim and Mahan, 2003). Enriching muscle with Se-methionine does not affect protein structure or properties and produces an endogenous Se pool available in challenging conditions due to environmental or physiological stress (Schrauzer, 2003). Accordingly, Se-methionine-supplemented animals maintain higher activities of selenoenzymes during Se depletion for longer periods than selenite-supplemented animals (Schrauzer, 2000). Thus, Se-yeast contains predominantly Se-methionine which is accumulated mostly in proteins as evidenced by greater contents of Se in breast muscle (Leeson *et al*., 2008). On the other hand, inorganic Se is less efficiently retained and usually excreted via the urine (Kim and Mahan, 2003). The amount of Se assimilated into tissues depends on the Se source, but the dietary Se concentration also plays a role. In some studies Se retention decreased as the level of Se increased in the diets (Choct *et al*., 2004; Yoon *et al*., 2007). This was also observed in 14-day-old-ducks, but in 49-day-old-ducks, the highest retention was found in animals fed diets with the highest Se level (Baltić *et al*., 2015). A possible explanation of the discrepancy between those studies could be due to the fact that different sources of Se were used; inorganic Se (Choct *et al*., 2004) or organic Se (Baltić *et al*., 2015).

Due to the many advantages of nano-materials, nano-Se has been recently introduced as a Se supplement in animal diet. Accumulation of Se in serum, liver, and breast muscle increased as dietary nano-Se levels increased (Zhou and Wang, 2011; Cai *et al*., 2012; Hu *et al*., 2012; Selim *et al*., 2014). Supplementing diets with 0.30 mg kg^{-1} of nano-Se effectively increased Se in tissues (Zhou and Wang, 2011; Cai *et al*., 2012). Some authors indicated that nano-Se was accumulated to a greater extent in liver and muscle than SS (Hu *et al*., 2012; Selim *et al*., 2014). Moreover, the transfer of nano-Se from the intestinal lumen to the body was higher than that of selenite, while the intestinal retention of nano-Se was lower than that of selenite (Hu *et al*., 2012). The different retentions of nano-Se and SS are probably related to the different absorption process and metabolic pathways. Chithrani and Chan (2007) suggested that the superior performance of nanoparticles is attributed to their smaller particle size and larger surface area, increased mucosal permeability, and improved intestinal absorption due to the formation of nano-emulsion droplets. In addition, nano-Se upregulates selenoenzymes more efficiently and exhibits less toxicity than inorganic Se (Zhang *et al*., 2005; Wang *et al*., 2007) (Table 1).

Selenium and growth performance

Although Se supplementation in broilers did not have any effect on growth performance or feed conversion (Payne and Southern, 2005; Perić *et al*., 2009; Cai *et al*., 2012; Briens *et al*., 2014; Boostani *et al*., 2015; Chadio, *et al*., 2015), many authors found an increase in live weight in broilers (Ševčíková *et al*., 2006; Upton *et al*., 2008; Zhou and Wang, 2011; Marković *et al*., 2014), turkeys (Hadley and Sunde, 1997; Taylor and Sunde, 2016) or ducks (Dean and Combs, 1981; Baltić *et al*., 2016) due to higher dietary contents of Se. It seems that dietary intake of 0.15 mg kg^{-1} of Se (National Research Council. Nutrient Requirements of Poultry, 1994) does not meet the growth requirements for faster growing and higher yielding poultry, and additional quantities of Se might be used in poultry nutrition (Upton *et al*., 2008). However, high concentrations of selenium in diet (exceeding 1 mg kg^{-1}) could impair animal growth (Kirchgessner *et al*., 1997; Zoidis *et al*., 2010; Briens *et al*., 2014), or lead to development of Se toxicosis, seen after adding 6 mg kg^{-1} to feed for broilers (Echevarria *et al*., 1988) or 4 mg kg^{-1} of Se to diet for ducks (Hoffman and Heinz, 1998).

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Moreover, it was observed that adding Se to diet improved feed conversion of poultry (Choct *et al.*, 2004; Mahmoud and Edens, 2005; Zhou and Wang, 2011; Baltić *et al.*, 2016), which could be a result of lower feed intake while maintaining the same weight gain (Choct *et al.*, 2004). Since Se is a part of iodothyronine deiodinases, which are involved in the metabolism of thyroid hormones necessary for normal growth and development (Arthur, 1992), better activation of thyroid hormones by increased selenium content may explain the improved feed efficiency (Choct *et al.*, 2004). Moreover, increased yields of leg, thigh, breast, and neck were measured in Se treated broilers (Choct *et al.*, 2004; Upton *et al.*, 2008; Marković *et al.*, 2014), while other authors did not observe any effect of selenium on carcass cut yields (Payne and Southern, 2005; Ševčíková *et al.*, 2006; Baltić *et al.*, 2016).

Regarding the effect of Se source on growth performance results in poultry, it was found that organic forms of Se improved final body weight, daily weight gain, feed consumption or feed conversion ratio compared with inorganic forms (Choct *et al.*, 2004; Wang and Xu, 2008; Jiang *et al.*, 2009; Heindl *et al.*, 2010; Yang *et al.*, 2012), while other authors did not find any difference between those two forms of Se (Payne and Southern, 2005; Yoon *et al.*, 2007; Mikulski *et al.*, 2009; Perić *et al.*, 2009; Briens *et al.*, 2013, 2014). Table 1 reports the major effects of adding different levels and sources of Se to diet on growth performance parameters in poultry.

In addition, dietary Se reduced chilling loss and drip loss in pigs (Mahan *et al.*, 1999) and poultry (Choct *et al.*, 2004; Jiang *et al.*, 2009; Perić *et al.*, 2009; Zhou and Wang, 2011; Cai *et al.*, 2012) by protection from cell damage caused by free radicals, indicating better meat quality.

Conclusion

Based on the brief data presented, it can be concluded that Se plays an important role in broiler nutrition. The appropriate level of Se is important for broiler growth, antioxidant protection, reproductive performance, bone metabolism, immune function, and metabolism of iodine. The minimal dietary requirement for Se for broiler chickens is 0.15 mg of Se kg^{-1} of diet, while the dietary selenium intake of more than 0.5 mg kg^{-1} is not allowed. Nano-Se and organic Se possess at least comparable (and sometimes improved) efficiency to inorganic Se in upregulating selenoenzymes, and have higher bioavailability and lower toxity. Moreover, higher levels of Se increase GSH-Px activity in the body, but this plateaus with higher Se concentrations in the diet, while the accumulation of Se in animal tissues is dose-dependent. In addition, many studies have shown positive effects of adding Se to diet on growth performance in poultry and yields of carcass cuts. Optimal Se supplementation is necessary not only for good poultry health but also to ensure and preserve meat quality during storage and to provide people with this microelement.

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