

Effect of dietary selenium supplementation (organic and inorganic) on carcass characteristics and meat quality of ruminants: a meta-analysis

T. Wahyono^{1,*}, R. Wahyuningsih¹, A.I. Setiyawan¹, D. Pratiwi¹, T. Kurniawan¹, S. Hariyadi¹, M.M. Sholikin^{2,3}, A. Jayanegara^{3,4}, E. Triyannanto⁵ and A. Febrisiantosa¹

¹ National Research and Innovation Agency of Indonesia, Research Center for Food Technology and Processing, 55861 Gunungkidul, Indonesia

² National Research and Innovation Agency of Indonesia, Research Center for Animal Husbandry, 16915 Bogor, Indonesia

³ IPB University, Faculty of Animal Science, Animal Feed and Nutrition Modeling (AFENUE) Research Group, 16680 Bogor, Indonesia

⁴ IPB University, Faculty of Animal Science, Department of Animal Nutrition and Feed Technology, 16680 Bogor, Indonesia

⁵ Universitas Gadjah Mada, Faculty of Animal Science, Department of Animal Products Technology, 55281 Sleman, Indonesia

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* Corresponding author:
e-mail: tegu021@brin.go.id

ABSTRACT. The objective of this study was to evaluate the effects of dietary selenium supplementation (organic and inorganic) on carcass characteristics and meat quality in ruminants. The data sources for this meta-analysis originated from several databased (Scopus, PubMed, and Google Scholar), searched for the keywords: “selenium”, “supplementation”, “meat”, “cattle”, “goat” and/or “sheep”. The results of meta-analysis were statistically analysed using mixed model methodology. After assessing compliance with the objectives of the work and research topic, a total of 19 articles (out of 26 studies) were selected and included in the database. Individual studies were treated as random effects, whereas Se levels were considered fixed effects. The results showed that Se supplementation increased hot carcass weight and rib eye area ($P < 0.01$). The weight of the fore shank and testicles was also increased due to Se supplementation ($P < 0.05$); however, dietary Se addition decreased rib and lung weight ($P < 0.05$). With regard to meat quality, Se addition increased total Se level in meat ($P < 0.01$), decreased the concentration of thiobarbituric acid reactive substances and cooking loss percentage ($P < 0.05$). However, the addition of Se did not affect the majority of carcass cuts (saddle, breast, loin, legs, and rack), which had similar proximate parameter values and cholesterol levels. It can be concluded that Se supplementation can improve carcass and meat quality in ruminants.

Introduction

Healthy farm animal products have recently become a major focus of the livestock industry in many countries. As humans currently live in a nutritional environment that differs from the one that selected our genetic constitution, functional foods

aim to bridge the nutritional gap between the Western diet and genetically determined requirements (Matics et al., 2017). In recent years, many studies have been published concerning selenium supplementation and functional meat production. Supplementing bull rations during the finishing period is a promising strategy to increase the concentration of

essential nutrients in meat to the levels required for specific health claims and classification as healthy food and a significant source of these compounds (Haug et al., 2018). A good bioavailable source of Se from food is required for the full expression of selenoproteins with antioxidant function, especially in diseases associated with oxidative stress (Jarzyńska and Falandysz, 2011). Se plays an important role in the immune system, however, the true extent of Se's immunomodulatory capacity remains unknown (Pecoraro et al., 2022). Glutathione peroxidases are antioxidant enzymes that contain selenium and catalyse the reduction of lipid and hydrogen peroxides to less harmful products, providing protection against oxidative stress (Cozzi et al., 2011; Ripoll et al., 2011; Zhang et al., 2020a).

Selenium both improves animal health and provides high-quality meat for humans (Joksimovic-Todorovic et al., 2012). In addition to being useful for product fortification, Se supplementation has also been reported to improve livestock performance. Adding appropriate Se levels to the diet can promote the growth and development of animals (Zhang et al., 2020a). Zepeda-Velazquez et al. (2020) reported that Se supplementation improved the antioxidant status and productive performance of broilers under heat stress. Oral Se supplementation in dairy cattle was shown to improve Se milk levels (Ceballos et al., 2009). Two forms of Se can be considered in the livestock industry, i.e. inorganic (sodium selenite or selenate), or organic (selenium yeast and selenomethionine). Sodium selenite and selenium yeast have been commonly used as Se supplementation sources to improve performance, immune function, and meat quality in animals (Zhang et al., 2020b). Sodium selenite is commonly used as an additive for dairy cows since it is less expensive than organic selenium (Azorin et al., 2020). However, the rate of ruminal microbial uptake of inorganic selenium is lower compared to its organic counterpart. Moreover, powdered inorganic salts are very sensitive to the dissolution and formation of elemental Se in the rumen environment (Niwińska and Andrzejewski, 2017). Previous studies have demonstrated that selenium yeast, the most commonly used organic Se feed supplement, has a greater bioavailability (Yoshida et al., 1999; Wei et al., 2019). Approximately 63% of the total Se content in selenium yeast is Se-methionine incorporated in *Saccharomyces cerevisiae* proteins (Czauderna et al., 2009; Rozbicka-Wieczorek et al., 2016).

To our knowledge, no studies to date have attempted to quantitatively summarise the effect of Se supplementation on carcass and meat quality of sheep, goats, and cattle. It is necessary to provide an overview of the effect of Se supplementation on meat quality and livestock performance. Therefore, this study aimed to conduct a meta-analysis of published experiments regarding the effects of Se supplementation (organic and inorganic) on carcass characteristics and meat quality in ruminants. Other related parameters such as average daily gain (ADG), dry matter intake (DMI), and gain to feed ratio were also analysed to comprehensively assess the effect of Se in ruminants.

Material and methods

Literature search and database development

Keywords included “selenium”, “supplementation”, “meat”, “cattle”, “goat” and/or “sheep” searched against the Scopus, Google Scholar and Science Direct databases. Meta-data were compiled from published trial reports evaluating the effect of Se supplementation on carcass characteristics and meat quality. The criteria for registering articles in the database were as follows: (1) article was submitted in English; (2) experiments were performed in ruminants (beef cattle, sheep, and goat); (3) study was performed *in vivo*; (4) Se sources, types and dietary levels were reported; (5) carcass characteristics and meat quality parameters were reported. When a published article described more than one experiment, each individual examination was coded separately. A total

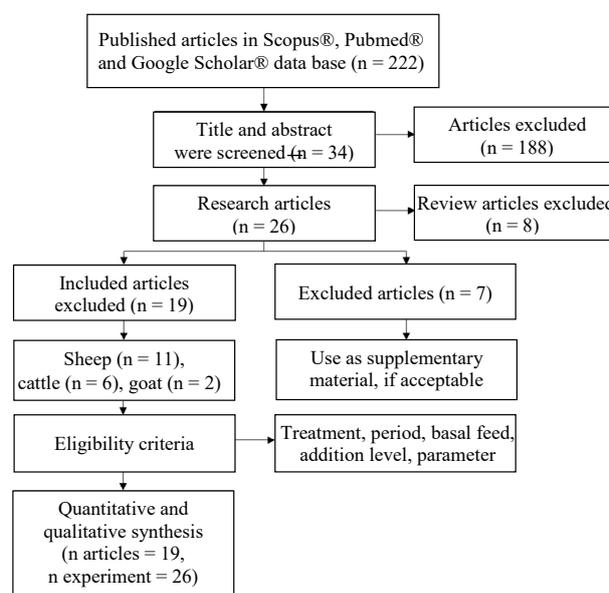


Figure 1. Flowchart of literature selection for meta-analysis

of 26 experiments from 19 studies were registered in the database (Vignola et al., 2009; Liao et al., 2011; Liu et al., 2011; Hernandez-Calva et al., 2013; Netto et al., 2014; Sushma et al., 2015; Aghwan et al., 2016; Jaworska et al., 2016; Przybylski et al., 2017; Haug et al., 2018; Mahmood et al., 2018; Maraba et al., 2018; Bezerra et al., 2020; Silva et al., 2020; Grossi et al., 2021; Shin et al., 2021; Jia et al., 2022; Mariezcurrena-Berasain et al., 2022; Tian et al., 2022). Details of the studies included in the meta-analysis are listed in Table 1. Among the ruminant species, sheep, beef cattle, and goats were

included. The analysed sheep breeds included Italian Apennine, Dorper × Santa Ines, Pelibuey, Karadi, Nellore, Corriedale, Dohne Merino, and Merino. Beef cattle breeds were Nelore, Hanwoo, Norwegian Reed, Angus, Charolais, and Brangus. Goat Breeds included Kacang and Qianbei-pockmarked. Most of the described diets were total mixed ration diets with a small proportion of high-concentrate rations. Se levels in the diets varied from 0 to 4.8 mg/kg dry matter intake (DMI). Se sources were derived from both organic and inorganic species. Since the authors often did not report Se supplementation

Table 1. Studies included in the meta-analysis of the effect of selenium (Se) supplementation on carcass characteristics and meat quality of ruminants

No.	Reference	Se source	Se type	Basal feed	Animal	Se level, mg/kg
1	Vignola et al., 2009	Sodium selenite and SeY	Inorganic and organic	TMR (2:5 hay/concentrate ratios)	Sheep	0; 0.3; and 0.45
2	Liao et al., 2011	Sodium selenite and Sel-Plex®	Inorganic and organic	TMR (cottonseed hulls/soybean hulls/cracked corn/soybean meal)	Heifer cattle	0; and 0.76
3	Liu et al., 2011	Sodium selenite	Inorganic	Pellet (hay/lupin/barley)	Sheep	0; and 2.5
4	Hernandez-Calva et al., 2013	Sodium selenite	Inorganic	TMR (hay/grain/fish meal/molasses cane)	Sheep	0; and 0.3
5	Netto et al., 2014	Sodium selenite	Inorganic	High concentrate diet (2.5:7.5 corn silage/concentrate ratios)	Bull	0; and 2
6	Sushma et al., 2015	Sodium selenite	Inorganic	Fodder and concentrate	Sheep	0; 0.1; 0.2; and 0.4
7	Aghwan et al., 2016	Not described	Inorganic	Concentrate and ad libitum fresh guinea grass	Goat	0; and 0.6
8	Jaworska et al., 2016	SeY and selenate	Organic and inorganic	TMR (hay, soybean meal, barley meal, and wheat starch)	Sheep	0; and 0.35
9	Przybylski et al., 2017	SeY and selenate	Organic and inorganic	Concentrate and hay	Sheep	0; and 0.35
10	Haug et al., 2018	SeY	Organic	Concentrate and <i>ad libitum</i> silage (grass and clover)	Bull	0; and 0.5
11	Mahmood et al., 2018	Sodium selenite	Inorganic	TMR (barley, wheat bran, soybean meal, yellow corn)	Sheep	0; 0.15; and 0.25
12	Maraba et al., 2018	Selenium premix	Inorganic	TMR	Sheep	0; and 0.2
13	Silva et al., 2020	SeY and sodium selenite	Organic and inorganic	TMR (corn silage, corn grain, and soybean)	Bull	0; 0.3; 0.9; and 2.7
14	Bezerra et al., 2020	Hydroxy-selenomethionine	Organic	High concentrate diet (0.6:9.4 hay/concentrate ratios)	Sheep	0; and 0.5
15	Grossi et al., 2021	Sodium selenite, SeY and hydroxy-selenomethionine	Inorganic and organic	TMR (maize silage, corn meal, wheat bran, soybean meal, distillers, brewers, wheat straw, and cocoa panel)	Bull	0.2
16	Shin et al., 2021	Not described	Organic	TMR (corn grain, corn gluten feed, wheat, palm kernel expeller, coconut meal, lupin)	Cattle	0; and 0.08
17	Mariezcurrena-Berasain et al., 2022	SeY	Organic	TMR (whole sorghum	Sheep	0; 0.35; and 0.6
18	Jia et al., 2022	SeY	Organic	TMR (alfalfa, maize, soybean meal, cottonseed meal)	Sheep	0.25; 0.5; 1; and 2
19	Tian et al., 2022	SeY	Organic	TMR (peanut vines, white distiller's grains, soybean residues, green hay, and corn)	Goat	0; 2.4; and 4.8

SeY – selenium-enriched yeast, Sel-Plex® – organic selenium from Alltech, Inc., TMR – total mixed ration

in relation to feed recovery, we did not use Se recovery, but rather the dose applied directly by the authors.

The parameters integrated in the database were: slaughter weight (SW), hot carcass weight (HCW), dressing percentage (DP), carcass length (CL), fat thickness (FT), rib eye area (REA), loin eye area (LEA), carcass cuts (saddle, breast, ribs, loin, legs, rack, and fore shank), edible organ weight (heart, kidneys, liver, lungs, spleen, and testicles), total Se in meat, meat pH value, lightness (L^*), redness (a^*), yellowness (b^*), drip loss, cooking loss, shear force, tenderness, thiobarbituric acid reactive substances (TBARS), meat cholesterol, meat proximate (moisture, crude protein, crude fat, and crude ash), marbling score, sensory traits (flavour, odour intensity, juiciness, and hardness), average daily gain (ADG), dry matter intake (DMI), and gain to feed ratio. Since the present study considered all experiments with small and large ruminants jointly, body size parameters were standardized based on DMI or body weight (BW). Parameters and values reported in different measurement units were converted to standard units.

Data analysis

The data from the meta-analysis were statistically analysed using linear mixed model methodology (LMM) (St-Pierre, 2001; Sauviant et al., 2008). Individual studies were treated as random effects, whereas Se addition levels were considered fixed effects. The mathematical models employed were as follows:

$$Y_{ij} = \mu + s_i + \tau_j + s\tau_{ij} + \beta_0 + \beta_1 X_{ij} + b_i X_{ij} + e_{ij} \quad (1)$$

$$Y_{ij} = \mu + s_i + \tau_j + s\tau_{ij} + \beta_0 + \beta_1 X_{ij} + \beta_2 X_{ij}^2 + b_i X_{ij} + e_{ij} \quad (2)$$

where: Y_{ij} – the dependent variable, μ – the overall average value, s_i – the random effect of study, i , τ_j – the fixed effect of j from different Se level, $s\tau_j$ – the random interaction factor between different studies and the fixed effect of Se, β_0 – the overall average intercept of Y, β_1 – the linear regression coefficient of Y on X (fixed effect), β_2 – the quadratic regression coefficient of Y on X (fixed effect), X_{ij} – the level of Se in numerical form, b_i – the random effect of the regression coefficient Y on Se level, and e_{ij} – the unexplained residual error.

Statistical analysis was calculated using R software version 4.1.2 by R Core Team (2022) equipped with the ‘lme4’ library version 1.1-28. The residual mean square error (RMSE) and the determination coefficient of Nakagawa $R_{GLMM}(c)^2$ were used to validate the model (Nakagawa and Schielzeth, 2013;

Nakagawa et al., 2017; R Core Team, 2022). The equations used were as follows:

$$RMSE = \sqrt{\frac{\sum(A - P)}{NDP}} \quad (3)$$

$$R_{GLMM}(c)^2 = \frac{(\sigma_f^2 + \sum(\sigma_l^2))}{(\sigma_f^2 + \sum(\sigma_l^2) + \sigma_e^2 + \sigma_d^2)} \quad (4)$$

where: A – the actual value, P – the prediction value, NDP – the number of data points, σ_f^2 – the fixed factor variance, $\sum(\sigma_l^2)$ – the sum of all component variances, σ_e^2 – the variance due to Se level dispersion, and σ_d^2 – the specific distribution from the variance. Significance was declared at $P < 0.05$. If the P -value was between 0.05 and 0.10, it was considered a significant tendency.

Results

Effects of Se supplementation on carcass characteristics

Se supplementation increased HCW and REA of ruminants ($P < 0.01$; Table 2). In contrast, Se addition did not influence SW, CL, and LEA, while FT was elevated ($P < 0.05$). Dietary Se supplementation also tended to increase DP ($P < 0.1$). Se supplementation had no effect on most of carcass cuts (saddle, breast, loin, legs, and rack); however, it decreased rib weight ($P < 0.05$) and increased fore shank weight ($P < 0.05$). With regard to edible organ weight, dietary Se addition decreased lung weight ($P < 0.05$) and increased testicular weight ($P < 0.05$). Se supplementation had no effect on the weight of majority of edible organs (heart, kidneys, liver, and spleen).

Effects of Se supplementation on meat quality and performance

Se supplementation had no effect on lightness (L^*), redness (a^*), yellowness (b^*), shear force, and tenderness of meat (Table 3). Se tended to decrease the pH value (45 min and 24 h), and drip loss of meat ($P < 0.1$). Further, dietary Se increased total Se in meat ($P < 0.01$), decreased cooking loss percentage ($P < 0.05$), and TBARS levels ($P < 0.05$). Generally, Se supplementation did not affect any of the proximate parameters and cholesterol levels. Apart from the hardness value ($P < 0.05$), Se did not affect most of sensory trait parameters. In turn, the addition of Se increased the daily DMI and ADG of the animals ($P < 0.01$), but there was no significant effect on the gain to feed ratio (Table 4).

Table 2. Influence of selenium supplementation (mg/kg) on carcass characteristics of ruminants

Response parameter	Unit	N	Intercept	SE intercept	Slope	SE slope	P-value	RMSE
SW	kg	30	163	59.7	1.40	0.93	0.139	3.98
HCW	kg	56	47.3	31.5	3.15	0.80	0.001	1.94
DP	%	44	47.3	2.35	0.33	0.19	0.098	0.83
CL	cm	15	66.0	2.38	0.71	1.91	0.719	2.08
FT	mm	11	4.12	0.81	-23.7	9.69	0.040	1.55
REA	cm ²	10	44.8	32.4	4.08	0.95	0.005	0.42
LEA	cm ²	10	44.6	19.4	0.54	1.17	0.663	1.19
Carcass cuts								
saddle	kg	4	4.60	0.09	-0.53	0.44	0.348	0.09
breast	kg	7	1.16	0.26	-0.01	0.07	0.944	0.02
ribs	kg	4	3.26	0.03	-0.80	0.16	0.037	0.03
loin	kg	11	2.78	0.87	-1.10	0.61	0.122	0.21
legs	kg	11	4.41	0.65	-0.45	0.51	0.407	0.17
rack	kg	7	0.92	0.03	0.28	0.15	0.117	0.04
fore shank	kg	7	1.09	0.71	1.32	0.43	0.049	0.03
Edible organ								
heart	g	11	169	28.8	-0.62	3.43	0.863	6.42
kidneys	g	15	84.1	11.1	2.40	2.87	0.428	5.55
liver	g	15	465	74.2	-7.94	6.95	0.286	13.2
lungs	g	11	400	58.3	-17.3	5.08	0.014	9.49
spleen	g	7	197	242	350	1180	0.779	349
testicular	g	7	198	39.1	317	68.3	0.026	5.23

SW – slaughter weight, HCW – hot carcass weight, DP – dressing percentage, CL – carcass length, FT – fat thickness, REA – rib eye area, LEA – loin eye area, SE – standard error, RMSE – root mean square error; $P < 0.05$

Table 3. Influence of selenium supplementation (mg/kg) on meat quality of ruminants

Response parameter	Unit	N	Intercept	SE intercept	Slope	SE slope	P-value	RMSE
Total Se	µg/kg	30	98.2	32.8	62.9	13.8	0.001	44.3
45 min								
pH		10	6.61	0.28	-0.06	0.03	0.085	0.09
L^*		16	38.9	1.99	-0.41	0.65	0.543	1.44
a^*		16	15.7	1.62	-0.25	0.33	0.473	0.73
b^*		16	14.7	2.90	-0.17	0.17	0.329	0.36
24 h								
pH		34	5.72	0.07	-0.03	0.02	0.061	0.07
L^*		29	35.9	1.05	0.50	0.45	0.281	1.51
a^*		29	14.1	1.09	0.30	0.31	0.349	1.02
b^*		29	11.1	1.76	0.28	0.25	0.278	0.80
Drip loss	%	25	1.77	0.39	-0.11	0.05	0.054	0.20
48 h								
L^*		10	40.0	2.35	0.13	0.62	0.845	1.14
a^*		10	17.4	0.90	-0.25	0.42	0.579	0.82
b^*		10	14.9	3.39	-0.12	0.43	0.794	0.76
Cooking loss	%	21	30.6	8.69	-0.71	0.26	0.018	0.95
Shear force	kg	17	44.3	4.21	-0.98	0.89	0.289	3.24
Tenderness	kgf	6	4.77	1.18	0.58	1.79	0.765	0.66
TBARS	µg malondialdehyde/kg	21	0.31	0.10	-0.14	0.06	0.045	0.04
Proximate								
moisture	%	25	71.9	1.80	-0.07	0.37	0.846	1.05
crude protein	%	25	22.1	0.31	0.12	0.15	0.441	0.47
crude fat	%	24	3.34	0.87	-0.69	0.64	0.301	0.40
crude ash	%	22	1.21	0.16	0.21	0.12	0.108	0.07
cholesterol	mg/100g	8	43.1	4.11	0.05	1.61	0.977	2.12
Sensory traits								
color		12	7.22	0.65	0.10	0.20	0.624	0.54
flavour		7	8.32	0.23	-1.35	0.94	0.210	0.34
odor intensity		7	8.18	0.62	-0.07	1.95	0.975	0.60
juiciness		7	7.66	1.02	-3.99	2.81	0.245	0.83
hardness		4	9.69	0.18	-4.02	0.83	0.040	0.18
marbling score		9	510	45.8	-10.9	16.6	0.533	39.1

L^* – lightness, a^* – redness, b^* – yellowness, TBARS – thiobarbituric acid reactive substances, SE – standard error, RMSE – root mean square error; $P < 0.05$

Table 4. Influence of selenium supplementation (mg/kg) on animal performance

Response parameter	Unit	N	Intercept	SE intercept	Slope	SE slope	P-value	RMSE
ADG	kg/day	43	0.59	0.16	0.07	0.03	0.009	0.04
DMI	kg/day	30	5.59	1.68	0.12	0.04	0.003	0.14
Gain to feed ratio		30	0.10	0.01	0.01	0.01	0.540	0.01

ADG – average daily gain, DMI – dry matter intake, SE – standard error, RMSE – root mean square error; $P < 0.05$

Effect of different type of Se supplementation on carcass characteristics, meat quality and total Se content in the muscle

Comparing different Se forms, none of them affected colour, flavour, odour intensity or juiciness of meat (Table 5). Dietary inorganic Se treatment had significantly higher DP than control ($P < 0.05$), but did not differ from organic Se. The total Se content in the muscle after addition of organic Se was higher than in control ($P < 0.05$).

cally increased in animals given Se supplementation. Compared to control groups, high Se intake considerably increased the weight of loin, rack, flank, and fat tail due to the accumulation of Se intake, duration periods, and balance Se in rations (Mahmood et al., 2018).

Se plays a role in enhancing immunity, thus it also indirectly increases energy production required for growth. Specialized enzymes convert the Se source to selenocystathionin, which is degraded in the liver to generate selenide. Subsequently, selenide

Table 5. Influence of different type of selenium supplementation (mg/kg) on carcass characteristics, meat quality and total Se on meat

Response parameter	Unit	N	Control	Inorganic	Organic	P-value
Carcass characteristics						
DP	%	44	46.78 ^a	48.10 ^b	47.36 ^{ab}	0.01
CL	cm	15	64.9	64.5	73.1	0.39
REA	cm ²	10	44.8	45.7	45.3	0.78
Meat quality						
color		12	7.09	7.24	7.59	0.68
flavour		7	8.35	7.80	8.06	0.37
odor intensity		7	8.17	8.25	7.84	0.94
juiciness		7	7.62	6.11	7.85	0.31
total Se	µg/kg	30	85.6 ^a	139 ^{ab}	186 ^b	0.03

DP – dressing percentage, CL – carcass length, REA – rib eye area; ^{ab} – means within a row with different superscripts are significantly different at $P < 0.05$

Discussion

Effect of Se supplementation on carcass characteristics

In the livestock industry, carcass yield is a crucial parameter. Therefore, some supplements and antioxidants would be more beneficial if they increased carcass production. Meta-analysis carried out in the present study revealed that HCW was influenced by Se levels. Se supplementation improved HCW due to a higher proportion of muscle tissue in individual ribs and fore shank (Table 2). Dressing and HCW were shown to be affected by different variables, including visceral organ mass (Silva et al., 2020). On the other hand, Mahmood et al. (2018) reported that the increases were due to a higher proportion of muscle tissue in HCW in the rack, loin, and leg regions. In this study, rack and leg parameters were numeri-

is utilized during the formation of selenocysteine (in the active site of selenoproteins) by e.g. glutathione peroxidase. When included in muscles, this enzyme strengthens muscles and protects against peroxidation (Hernandez-Calva et al., 2013). Se supplementation boosted immunological response in ruminants by raising neutrophil expression of L-selectin, IL-8 receptor, and toll-like receptor 4 in sheep with necrotic pododermatitis, contributing to faster recovery (Pecoraro et al., 2022). Previous findings were consistent with our results. Animals consuming a diet with increasing Se levels exhibited an increase in HCW (Silva et al., 2020). The addition of Se improved the commercial and biological carcass yield (Hernandez-Calva et al., 2013). Hot carcass weight in the Se-supplemented groups was 6.89.4% higher compared to the control groups (Aghwan et al., 2016). In contrast, Vignola et al.

(2009) reported that Se supplementation was unlikely to affect carcass quality unless there was an obvious mineral deficiency that affected the growth rate. Se supplementation at 0.3 mg as sodium selenite did not exert a significant effect on HCW. The lack of effect of Se treatments on carcass characteristics could be attributed to the high proportion of the concentrate in the diet, which could have standardized the growth rate (Bezerra et al., 2020).

The present meta-analysis demonstrated that Se supplementation tended to increase DP. In general, a high DP is desirable as it indicates that a greater proportion of live weight (i.e., cost to producers) is converted into marketable yield (i.e., revenue) (Coyne et al., 2019). The increase in HCW directly affected DP of the supplemented groups (Aghwan et al., 2016). Moreover, the enhanced development of leg tissues in the Se-supplemented groups resulted in a significant increase in carcass dressing percentage (Hernandez-Calva et al., 2013). Organic Se may have increased the efficiency of protein deposition or water retention in tissues, which could explain the higher dressing percentage observed in treatments (Marković et al., 2018). On the contrary, Zhu et al. (2022) reported no significant differences in carcass weight and dressing percentage after Se supplementation ($P > 0.05$). Dietary Se addition at 0.3 mg as sodium selenite did not exert a significant effect on DP (Vignola et al., 2009). The effects of selenium supplementation in cattle vary depending on the physiological stage, selenium status of the animals, selenium form and its dose, and delivery methods (Mehdi and Dufrasne, 2016) nitrates, sulfates, calcium or hydrogen cyanide negatively influence the organism's use of the selenium contained in the diet. The Se supplementation may reduce the incidence of metritis and ovarian cysts during the postpartum period. The increase in fertility when adding Se is attributed to the reduction of the embryonic death during the first month of gestation. A use of organic Se in feed would provide a better transfer of Se in calves relative to mineral Se supplementation. The addition of Se yeasts in the foodstuffs of cows significantly increases the Se content and the percentage of polyunsaturated fatty acids (PUFA).

It should be noted that Se supplementation had no effect on the weight of most edible organs (heart, kidneys, liver, and spleen); however a positive effects of increased dietary Se levels on some edible organs have been described (Antunović et al., 2009; Vignola et al., 2009, Joksimovic-Todorovic et al., 2012; Sushma et al., 2015). Apparently, dietary addition of Se did not influence the growth of internal organs.

The liver and kidneys were shown to have the highest selenium contents when selenium supplements were applied (Mehdi and Dufrasne, 2016) nitrates, sulfates, calcium or hydrogen cyanide negatively influence the organism's use of the selenium contained in the diet. The Se supplementation may reduce the incidence of metritis and ovarian cysts during the postpartum period. The increase in fertility when adding Se is attributed to the reduction of the embryonic death during the first month of gestation. A use of organic Se in feed would provide a better transfer of Se in calves relative to mineral Se supplementation. The addition of Se yeasts in the foodstuffs of cows significantly increases the Se content and the percentage of PUFA. On the other hand, dietary Se addition seemed to increase testicular weight. Higher weight of this organ could be attributed to gonadal growth, which could be associated with a lower sperm mortality and, consequently, improved spermatogenesis (Mahmood et al., 2018). Selenium has been shown to promote apoptosis, which eliminates mutant or damaged cells, and affects testosterone production (Liu et al., 2011).

Effects of Se supplementation on meat quality

Meat quality is a key part of the livestock industry and has a substantial impact on economic benefits. It may be necessary to increase human consumption of selenium, an essential element for human health, which is deficient in several regions of the world (Silva et al., 2020). Meat is a significant source of energy and nutrients, including high-quality proteins and minerals (selenium, iron, zinc, manganese) in the human diet (Ursachi et al., 2020). Selenium is a component of the body's antioxidant defence, and dietary Se supplementation can effectively increase its concentration in the meat, thereby enhancing its functional value (Matics et al., 2017). Se-enriched meat also qualifies for a health claim, as a panel of the European Food Safety and Authority has determined a cause and effect relationship between Se consumption and the protection of DNA, proteins, and lipids from oxidative damage, as well as the maintenance of normal immune and thyroid function, and normal spermatogenesis (Haug et al., 2018) vitamin D₃ (+300%).

The meta-analysis demonstrated that dietary Se supplementation increased total Se in the muscle ($P < 0.01$). Vignola et al. (2009) reported a significant increase in muscle selenium content with increasing dietary Se levels. Compared to control meat Se content was higher in all Se supplementation treatments, regardless of its source (Bezerra et al., 2020). Se de-

position generally increases in response to dietary Se supplementation; however, this reaction is tissue-dependent and may vary depending on the species, supplementation doses, and Se source (Vignola et al., 2009). The addition of feed additives containing organic selenium to the ration of small ruminants enables the production of lamb meat enriched with bioavailable micronutrients (Giro et al., 2022). In order to consume Se-enriched meat (up to 0.3 mg/kg DM), it would be necessary to add selenium-rich foods to achieve a daily intake of at least 40 µg Se/day (Silva et al., 2020). Meat may be an effective source of Se since animals fed organic Se showed higher Se levels in their meat (Bezerra et al., 2020). A significant Se enrichment was also reported in the meat of other species as a result of Se supplementation (Matics et al., 2017; Zhang et al., 2020a). Nanotechnology-based dietary Se supplements elevated Se levels in the muscles of broiler chickens (Dukare et al., 2020; Bami et al., 2022).

Dietary Se was also shown to affect cooking loss percentage. Water-holding capacity, a key characteristic of meat quality, is represented by drip loss and cooking loss parameters (Xue et al., 2022). Endogenous enzymes, such as collagenase produced by microorganisms in ruminants, or ionic dissolution, seem to accelerate enzymatic reactions. Collagenase enzymes degrade myofibrillar proteins and connective tissue, thereby increasing the water-holding capacity of proteins (Jama et al., 2008). However, further studies are needed to determine the involvement of Se in this mechanism. The decrease in the cooking loss value observed in the present study was similar to the previous work by Bakhshalinejad et al. (2019). The interaction between Se sources and concentrations had a significant impact on cooking loss ($P < 0.05$). Nanoselenium and Se-yeast supplementation (0.3 mg/kg) reduced cooking losses in breast and thigh muscles. In addition, Bakhshalinejad et al. (2019) reported that Se nanoparticles and organic sources with high bioavailability were more effective at combating oxidation and preserving cell membranes. On the other hand, several studies reported no effect of Se level and/or source on cooking loss ($P > 0.05$) (Vignola et al., 2009; Haug et al., 2018; Silva et al., 2020; Grossi et al., 2021; Tian et al., 2022). These discrepancies in the results of individual studies regarding the effect of Se on meat quality may be due to supplementation with varying Se doses or lack of knowledge about the halothane genetic status of animals (Joksimovic-Todorovic et al., 2012).

The degree of lipid oxidation in meat was assessed using TBARS (thiobarbituric acid reactive

substances), and expressed as malonaldehyde content per kg of meat. Malonaldehyde is one of the most important secondary oxidation products of polyunsaturated fatty acids. As a bifunctional aldehyde, malonaldehyde is highly reactive and can interact through cross-links with DNA and proteins, thereby causing chromosomal abnormalities and decreasing protein synthesis capacity (Silva et al., 2020). The keeping quality of meat was assessed by measuring TBARS values in post-slaughter meat (Calvo et al., 2017). In this study, TBARS values in meat were reduced, which indicated lipid peroxidation control and lower oxidative stress (Juniper et al., 2009; Jia et al., 2022). This finding was also similar to the results reported in previous studies (Bezerra et al., 2020; Silva et al., 2020; Jia et al., 2022). Additional Se supplementation showed a beneficial effect on the regulation of lipid peroxidation and improvement of meat keeping quality (Sushma et al., 2015). Supplementation with antioxidant (like Se and/or tocopherols) is particularly recommended when enriching the diets with oils (fish, rapeseed, castor, or cashew nut shell oils) containing pro-oxidative long-chain polyunsaturated fatty acids (Jaworska et al., 2016; Przybylski et al., 2017; Bezerra et al., 2020).

Meat quality, as indicated by meat colour, is essential to enhance the basic competitiveness of meat products and ensure consumer satisfaction (Jia et al., 2022; Xue et al., 2022). It was apparent that Se supplementation did not compromise colour characteristics and sensory traits (except tenderness) of ruminant meat, and this result was consistent with previous studies. Supplementation with various selenium levels and sources had no effect on meat colour characteristics (Vignola et al., 2009; Hernandez-Calva et al., 2013; Silva et al., 2020). Supplementation with selenium and vitamin E may have inhibited the development of metmyoglobin, thereby preserving the colour and meat quality (Maraba et al., 2018). Preventing ferrous myoglobin oxidation and promoting metmyoglobin reduction are critical to maintain colour stability. This could minimize the formation of H_2O_2 , which in turn maintains meat colour stability by preventing ferrous iron oxidation (Liu et al., 2011).

Effects of Se supplementation on animal performance

In addition to carcass and meat quality, it is necessary to observe livestock performance to determine the effect of Se supplementation on animal growth. Generally, Se addition increased the animals' daily DMI and ADG ($P < 0.01$).

Since Se plays a role in increasing immunity, its addition apparently improves the efficiency of energy utilization for growth, as confirmed in the present meta-analysis. On the other hand, Se has been associated with thyroid function, and specifically with the activity of thyroid deiodinases, selenoenzymes that catalyse the activation of T3 from T4, which explains the beneficial effect of Se on growth (Matics et al., 2017). Previous studies reported that calves inoculated with *Escherichia coli* strain J-5 and fed Se-enriched hay at weaning had better antibody titres and higher total neutrophil antioxidant capacity; this led to reduced mortality and increased weight gain (Hall et al., 2013; Pecoraro et al., 2022). These results are consistent with previous studies reporting that Se supplementation in ruminant diets increased DMI and ADG (Netto et al., 2014; Mariezcurrena-Berasain et al., 2022). In contrast, Vignola et al. (2009), Sushma et al. (2015), and Silva et al. (2020) reported that ADG and DMI values did not differ significantly between Se dietary treatments. However, weight gain in some of these aforementioned studies increased numerically. We hypothesise that these inconsistent results were due to: 1) the variable length of the Se addition period; and 2) different Se requirements of individual animal species. The positive effect of the inclusion of a nutraceutical mixture on growth performance depends on the adaptation process and duration of the fattening period (Grossi et al., 2021).

Conclusions

Irrespective of its chemical form, HCW and Se content in the muscle generally increased with the addition of selenium to the diet. Se supplementation reduced cooking loss and TBARS levels. The decrease in TBARS levels represented a positive effect of the control of lipid peroxidation to maintain meat quality. With regard to animal performance, Se supplementation improved daily DMI and weight gain by enhancing immunity. Moreover, the addition of Se exerted no effect on the sensory characteristics and proximate values of ruminant meat. According to our results, Se supplementation leads to Se enrichment of meat, thereby contributing to its high quality. This strategy is therefore able to improve the quality of ruminant meat. Further meta-analysis studies are needed to evaluate the carcass characteristics and meat quality of ruminants fed diets supplemented with (1) inorganic or (2) organic chemical forms of Se.

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Conflict of interest

The Authors declare that there is no conflict of interest.

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