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The effect of boron mineral on energy metabolism and antioxidant activity in purebred arabian foals

El efecto del mineral boro sobre el metabolismo energético y la actividad antioxidante en potros árabes de pura raza

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ABSTRACT

Boron mineral is reported to have important functions in lipid and energy metabolism, immune and endocrine systems, and brain activity, positively affecting performance. This study investigated the effects of different doses of boron mineral (0, 5, 10, 15 mg·d^{-1}·animal^{-1}) at 30, 60, and 90 days on energy metabolism and antioxidant activity parameters in Purebred Arabian foals. The experiment was conducted on 32 foals, grouped randomly, with similar initial body weights, consisting of 8 foals per group (n=8). The experimental groups were defined by the doses of boron mineral administered. The control group (Group K) received no boron, Group B5 received 5 mg of elemental boron, Group B10 received 10 mg, and Group B15 received 15 mg per day per animal. Boric acid was used as the boron source. The study lasted 90 days. Feed consumption and body weight gain were similar across all groups (P>0.05). Throughout the study, no significant differences were detected in serum glucose, cholesterol, triglyceride, AST and ALT levels among the groups (P>0.05). MDA levels decreased dose–dependently after the initial measurements (P<0.001), while GSH–Px and CAT levels increased dose–dependently after the baseline measurements (P<0.001). In conclusion, boron mineral positively affected antioxidant activity in Purebred Arabian foals, with the most effective dose being 15 mg·d^{-1}·animal^{-1}.

Key words: Boron; foals; energy metabolism; antioxidant level

RESUMEN

Se ha comprobado que el mineral boro desempeña funciones significativas en el metabolismo lipídico y energético, los sistemas inmunitario y endocrino, y la actividad cerebral, ejerciendo un impacto positivo en el rendimiento. El objetivo del presente estudio fue investigar los efectos de diferentes dosis de boro mineral (0, 5, 10, 15 mg·d^{-1}·animal^{-1}) sobre el metabolismo energético y los parámetros de actividad antioxidante en potros árabes de pura raza a los 30, 60 y 90 días. El ensayo se llevó a cabo en un total de 32 potros, agrupados aleatoriamente con base en su peso corporal inicial, conformando 8 potros por grupo (n=8). Los grupos experimentales se definieron en función de las dosis de boro mineral administradas. El grupo de control (Grupo K) no recibió boro, el Grupo B5 recibió 5 mg de boro elemental, el Grupo B10 recibió 10 mg y el Grupo B15 recibió 15 mg al día por animal. Se empleó ácido bórico como fuente de boro. El estudio tuvo una duración de 90 días. Se observó que el consumo de pienso y el aumento de peso corporal fueron similares en todos los grupos (P>0,05). Durante el transcurso del estudio, no se observaron diferencias significativas en los niveles séricos de glucosa, colesterol, triglicéridos, AST y ALT entre los grupos (P>0,05). Se observó una disminución dependiente de la dosis en los niveles de MDA tras las mediciones iniciales (P<0,001), mientras que los niveles de GSH–Px y CAT aumentaron de forma dependiente de la dosis tras las mediciones iniciales (P<0,001). En conclusión, el boro mineral afectó positivamente a la actividad antioxidante de los potros árabes de pura raza, siendo la dosis más eficaz la de 15 mg·d^{-1}·animal^{-1}.

Palabras clave: Boro; potros; metabolismo energético; nivel antioxidante

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INTRODUCTION

The boron (B) element was recognized as essential for plants in 1923 [1]. Recent studies have suggested that it may also be essential for animals and humans [2]. Boron is a trace mineral found in biological systems and is believed to play significant roles in various physiological functions. It affects multiple organs and systems in the body, including the skin, brain, digestive system, skeleton, and immune system. Boron is also known to function in mineral metabolism and the immune and endocrine systems [3, 4]. Recent research has identified its role in reproductive and embryonic health [5]. Furthermore, boron has been shown to influence energy metabolism, insulin secretion, and the activity of enzymes involved in the immune system [6].

Boron has been reported to affect energy parameters such as triglycerides and glucose [7]. Another study suggested that boron might help conserve plasma glucose in chicks by reducing *in situ* insulin secretion from the pancreas [8]. In rats, dietary boron supplementation decreased low–density lipoprotein (LDL), cholesterol, and triglyceride (TG) levels after 14 days (d). This finding led to the hypothesis that boron might promote cholesterol excretion from tissues and reduce lipid accumulation, making it potentially beneficial for atherosclerosis patients [9]. These findings collectively highlight the diverse and potentially beneficial roles of boron in energy metabolism, lipid regulation, and overall health in various species.

Antioxidants prevent cellular oxidation damage by inhibiting or neutralizing reactive oxygen species, reducing degenerative disease risk [10]. Studies show boron decreases oxidative stress by increasing reduced glutathione levels [11, 12]. In rats (*Rattus norvegicus*) under abiotic stress, dietary boron enhanced immune and antioxidant responses [13]. Kurtoglu *et al.* [14] found boron supports weakened antioxidant defenses and metabolic profiles in mice. It also helps restore liver function by modulating oxidative stress and influences key metabolic cycles to reduce oxidative damage [15, 16].

Boron plays regulatory roles in the metabolism of carbohydrates, lipids, and proteins within energy metabolism. However, further research is needed to fully elucidate these effects of boron. A review of the literature reveals numerous studies examining the effects of boron on animals, including poultry *(Gallus gallus domesticus*), rodents, and ruminants, but limited research focuses on the effects of boron on equines. In this context, the present study investigated the use of boron in Thoroughbred Arabian foals (*Equus caballus*) and its effects on energy metabolism and antioxidant activity.

MATERIALS AND METHODS

Animals and feed materials

The experiment was conducted at the Horse Unit of the Sultansuyu Agricultural Enterprise in Malatya. The study population consisted of 32 purebred Arabian foals, approximately 6 months old and with an average live weight of around 238 kg, obtained from the Sultansuyu Agricultural Enterprise in Malatya. The feed materials used in the experiment consisted of meadow hay (*Bromus inermis*, *Lolium perenne*, *Poa pratensis, Dactylis, Glomerata, Agropyron cristatum*) (as roughage) and oats (*Avena sativa*), which were obtained from the same enterprise, and compound feed (25% crude protein, 2700 Kcal ME), which was sourced from Gözlü Agricultural Enterprise Directorate.

All foals were fed individually with the same diet at the same time of day across all groups. Water was provided *ad libitum*. As a boron mineral source in the experiment, “Boric Acid” was used [11, 17, 18]. Boric acid was obtained from the National Boron Research Institute (BOREN, Ankara, Türkiye). The experiment lasted for 90 d. During the study, no exercise or conditioning was applied to the foals, and they were allowed to roam freely in the open field. There is no grass available for the animals to graze in the open area. The study was approved by the Local Animal Ethics Committee of Inönü University (Decision No: 2021/26-2-13092).

The composition of the compound feed used in the experiment is provided in TABLE I, the amounts and proportions of roughage and concentrate feed given to the animals are presented in TABLE II, and the nutrient content of the feeds and ration [19] is shown in TABLE III.

TABLE I
Composition of the Concentrate Feed

Feeds	Percentage
Oats	66.00
Barley	11.90
Wheat Bran	3.40
DDGS	2.38
Corn	3.40
Soybean meal	10.20
Vegetable oil	0.34
Salt	0.41
Limestone	0.68
Dicalcium Phosphate	0.34
Mycotoxin Binder	0.13
Molasses	0.68
Trace Minerals*	0.14

*: Per 1 kg of compound feed: 4,200,000 IU of vitamin A, 1,400,000 IU of vitamin D3, 10,500 mg of vitamin E, 180,000 mg of niacin, 75,000 mg of choline, 20,000 mg of manganese, 25,000 mg of iron, 25,000 mg of zinc, 5,000 mg of copper, 50 mg of cobalt, 200 mg of iodine, 180 mg of selenium.

TABLE II
Amounts and proportions of roughage and concentrate feed given to the animals

Days	Roughage		Concentrate Feed	
	Kg	%	Kg	%
0 – 30	6.00	71.43	2.40	28.57
30 – 60	6.50	71.43	2.60	28.57
60 – 90	6.75	71.43	2.70	28.57

TABLE III
The nutrient values of the feeds and ration

	Roughage	Concentrate Feed	Ration
Dry matter , %	94.09	92.33	93.58
Crude protein, %	14.41	16.28	14.94
Ash, %	10.36	4.14	8.58
Crude fat, %	2.63	3.49	2.87
Crude fiber, %	25.28	10.46	21.04
Energy, ME, kcal·kg^{-1}*	2300	2727	2422
Boron, %	0.029	0.030	0.029

*: It was obtained through calculation. ME (Mcal·kg^{-1})=4.184×[4.22-(0.11×NDF)+(0.058×EE)+(0.18×NFC)+(0.19×CP)]

Experimental design

The study was conducted on four groups, each consisting of 8 foals (n=8), with similar initial body weights (with an average weight of 238 kg), and the groups were randomly assigned. The experimental groups were formed based on the different doses of boron mineral added to the diet. The groups were as follows: the control group received no boron, the B5 group received 5 mg of elemental boron, the B10 group received 10 mg of elemental boron, and the B15 group received 15 mg of elemental boron at 30, 60, and 90 d [1, 20, 21]. Boric acid was diluted with 10 mL of distilled water and administered orally via a feeding syringe at the same time day (3:00 PM).

Measurements and analyses

Live body weight (LBW) and feed intake

At the beginning of the experiment, the foals were weighed using a calibrated scale (Taralsa, Türkiye) with a sensitivity of 0.5 kg to determine their initial body weight. The groups were then distributed so that the average live body weights (average of 238 kg) were similar across groups, and the experiment began. The foals were weighed again on d 30, 60, and 90, and the live body weight (LBW) was regularly recorded. Feed intake was measured daily. The feed was weighed and provided to the foals, and any leftover feed was collected and weighed the following day. The difference between the given feed and the leftover feed was used to calculate the daily feed intake for each individual foal.

Determination of the nutrient composition of the roughage and concentrate feed

The determination of the nutrient composition of the roughage and concentrate feeds was carried out at the Animal Nutrition and Nutritional Diseases Department Laboratory, Faculty of Veterinary Medicine, Fırat University. The dry matter (Dedeoğlu, Türkiye), ash (Protherm Furnaces, Türkiye), crude protein (Gerhardt, Germany), and crude fat (Soxhlet, Türkiye) levels of the feeds were determined according to the analytical methods reported by AOAC [22], and the crude fiber level was determined according to Crampton and Maynard [23]. The energy content of the feeds was calculated using the ration program (At_V5.05) developed by Coşkun *et al.* [24]. The boron content of the roughage and concentrate feeds was determined at the Boron Research Institute (BOREN) under the Turkish Atomic Energy Authority, using adapted internal methods (EPA 3051 A and 6010 D methods) [25].

Determination of blood parameters

Blood samples were collected from fasting foals at the start and on d 30, 60, and 90 before feeding. After centrifugation (3220 G, 15 min) (Nüve NF800R, Türkiye) serum was analyzed for glucose (Enzymatic colorimetric, H_2O_2 → colorful product @500–550 nm), triglycerides (Enzymatic colorimetric, H_2O_2 → colorful product @500–550 nm), cholesterol (Enzymatic colorimetric, H_2O_2 → colorful product @500 nm), aspartate transferase (AST) (Kinetic UV (IFCC standard), NADH depletion @340nm), and alanine aminotransferase (ALT) (Kinetic UV (IFCC standard), NADH depletion @340nm) using a biochemical analyzer (ADVIA 1800–SIEMENS, Germany) at the Biochemistry Department of Fırat University Faculty of Medicine [26].

Determination of oxidative stress and antioxidant parameters in serum

At the beginning of the trial and on the 30th, 60th, and 90th d, oxidative stress and antioxidant parameters in the serum samples obtained from the collected blood were analyzed in the laboratories of the Department of Physiology, Faculty of Veterinary Medicine, Fırat University. Lipid peroxide levels (malondialdehyde; MDA) in the serum were determined using the spectrophotometric method (Shimadzu, UV–1700 PharmaSpec, Kyoto Japan) described by Placer *et al.* [27]. Catalase (CAT) activity in serum was determined using a spectrophotometer by the Goth method [28]. Glutathione peroxidase (GSH–Px) activity in serum was determined using a spectrophotometer according to the method described by Lawrence and Burk [29].

Statistical analyses

In this study, the sample size was determined using the G*Power software package (Version 3.1.9.2) with an effect size of 0.67, an alpha error of 0.05, and a power of 85%, resulting in a total of 32 foals (n=8 per group, 4 groups). Data analysis was performed using the SPSS statistical software package (IBM SPSS Version 22.0) [30]. Normality was tested with Shapiro–Wilk, and variance homogeneity with Levene's test. If parametric assumptions were met, ANOVA was used, with Tukey or Tamhane T2 for post–hoc analysis. If not, the Kruskal–Wallis test and Mann–Whitney U test were applied. Parametric data are presented as mean ± SD, and non–parametric as median (interquartile value), maximum and minimum. Significance was set at $P<0.05$.

RESULTS AND DISCUSSION

In the study, the effects of different doses of boron on feed intake, live weight gain, and feed conversion efficiency in purebred Arabian foals; energy metabolism parameters (glucose, cholesterol, and triglyceride levels) in blood serum; antioxidant activity parameters (MDA, GSH–Px, and CAT levels); and serum AST and ALT levels were investigated.

Daily feed consumption and live weight were similar in all groups ($P>0.05$) (TABLE IV).

TABLE IV
The effect of different doses of boron on feed intake and weight gain in animals (n=8)

	Days	Groups				*P**	Linear
		Control	B5	B10	B15		
Feed intake, kg	0 – 30	8.4	8.4	8.4	8.4	>0.05	>0.05
	30 – 60	9.1	9.1	9.1	9.1	>0.05	>0.05
	60 – 90	9.45	9.45	9.45	9.45	>0.05	>0.05
Live weight, kg	0	239.3 ± 3.3	238.4 ± 5.9	239.2 ± 4.3	237.3 ± 6.2	>0.05	>0.05
	30	258.5 ± 4.1	259.0 ± 4.9	261.9 ± 3.9	260.8 ± 5.4	>0.05	>0.05
	60	268.8 ± 3.1	268.9 ± 5.1	273.9 ± 4.6	274.8 ± 5.3	>0.05	>0.05
	90	284.5 ± 3.5	284.5 ± 5.8	288.1 ± 5.1	288.4 ± 6.0	>0.05	>0.05

Control: no boron. B5: 5 mg elemental boron. B10: 10 mg elemental boron. B15: 15 mg elemental boron. The data are presented as mean ± standard error. *One–way ANOVA (Post–hoc Tukey test was performed for group comparisons)

During the study, no statistically significant differences were observed in serum glucose, cholesterol, triglyceride levels among the groups at different measurement times (P>0.05) (TABLE V). Similarly, no statistically significant dose–dependent differences were detected in these parameters (P>0.05). At the end of the experiment, the highest glucose level was observed in the control group (96.0 mg·dL^{-1}), followed by the B5 (91.1 mg·dL^{-1}), B10 (87.4 mg·dL^{-1}), and B15 (85.6 mg·dL^{-1}) groups. This indicates that, compared to the control group, the experimental groups showed a dose–dependent decrease in serum glucose levels with boron supplementation. Similarly, Çakır *et al.* [31] reported significant reductions in glucose levels with boron supplementation. Boron supplementation has been found to reduce plasma glucose in broilers [32], and plasma glucose, insulin, and pyruvate concentrations in rats. It is suggested that these reductions are due to boron forming complexes with the hydroxyl groups in the glucose molecule [33]. Conversely, a study by Bakken and Hunt [8] reported no changes in glucose concentration with boron supplementation, indicating that its effects might vary depending on conditions, dosages, or species.

TABLE V
The effect of different doses of boron on serum glucose, cholesterol, triglyceride, AST, and ALT levels

	Days	Groups				*P**	Linear
		Control	B5	B10	B15		
Glucose, mg·dL^{-1}	0	100.5 ± 7.3	99.9 ± 5.3	100.1 ± 6.8	101.3 ± 6.6	>0.05	>0.05
	30	98.4 ± 8.1	96 ± 7.7	96.1 ± 5.9	91.5 ± 6.0	>0.05	>0.05
	60	97.4 ± 8.8	97.3 ± 8.3	93.5 ± 7.3	91.8 ± 6.0	>0.05	>0.05
	90	96 ± 10.6	91.1 ± 8.3	87.4 ± 10.6	85.6 ± 9.3	>0.05	>0.05
	RM	>0.05	>0.05	>0.05	>0.05		
Cholesterol, mg·dL^{-1}	0	76.9 ± 2.4	76.9 ± 3.3	77.3 ± 2.2	76.9 ± 3.4	>0.05	>0.05
	30	74.9 ± 3.0	73 ± 3.5	72 ± 3.0	70.5 ± 2.6	>0.05	>0.05
	60	70.6 ± 3.7	68.6 ± 3.6	68.9 ± 2.5	69.1 ± 4.3	>0.05	>0.05
	90	73.1 ± 2.9	67 ± 3.4	65.8 ± 3.1	65.8 ± 2.7	>0.05	>0.05
	RM	>0.05	>0.05	>0.05	>0.05		
Triglyceride, mg·dL^{-1}	0	25.4 ± 2.4	26.4 ± 1.4	25.6 ± 1.9	25.3 ± 1.6	>0.05	>0.05
	30	26.3 ± 1.3	24.8 ± 1.5	24.4 ± 1.5	24.3 ± 1.5	>0.05	>0.05
	60	25.1 ± 1.3	24.4 ± 1.6	23.0 ± 1.4	22.9 ± 2.4	>0.05	>0.05
	90	24.6 ± 1.6	22.8 ± 1.7	22.5 ± 1.5	21.1 ± 1.0	>0.05	>0.05
	RM	>0.05	>0.05	>0.05	>0.05		
AST, U·L^{-1}	0	262.3 ± 4.1	257.4 ± 10.1	260.9 ± 5.3	258.4 ± 11.6	>0.05	>0.05
	30	258.6 ± 6.3	260.1 ± 9.4	260.3 ± 5.8	260.4 ± 5.6	>0.05	>0.05
	60	257.3 ± 13.4	256.4 ± 13.8	258.8 ± 9.4	253.9 ± 10.4	>0.05	>0.05
	90	266.8 ± 9.4	255.1 ± 4.7	256 ± 8.0	255.9 ± 2.9	>0.05	>0.05
	RM	>0.05	>0.05	>0.05	>0.05		
ALT, U·L^{-1}	0	17.6 ± 0.7	17.6 ± 0.7	18.0 ± 0.5	18.1 ± 0.6	>0.05	>0.05
	30	17.9 ± 0.7	17.8 ± 0.8	17.8 ± 0.8	17.3 ± 0.8	>0.05	>0.05
	60	17.8 ± 0.8	18.1 ± 1.3	18.5 ± 0.9	16.6 ± 0.7	>0.05	>0.05
	90	18.6 ± 1.9	18.4 ± 1.1	19.4 ± 1.5	16.8 ± 1.4	>0.05	>0.05
	RM	>0.05	>0.05	>0.05	>0.05		

AST: Aspartate transferase, ALT: Alanine aminotransferase. Control: no boron. B5: 5 mg elemental boron. B10: 10 mg elemental boron. B15: 15 mg elemental boron. (n=8). The data are presented as mean ± standard error. *One–way ANOVA was performed with Tukey's test used for post hoc comparisons between groups. Differences between measurement times were analyzed using repeated measures (RM) analysis

At the end of the experiment, the highest cholesterol level was observed in the control group (73.1 mg·dL^{-1}), followed by the B5 (67.3 mg.dL^{-1}), B10 (65.8 mg.dL^{-1}), and B15 (65.8 mg·dL^{-1}) groups. Similar to glucose levels, serum cholesterol levels showed a dose–dependent decrease with boron supplementation compared to the control group. The same trend was observed for serum triglyceride levels. Studies supporting these findings indicate that dietary boron reduces serum cholesterol and triglyceride levels in broilers [34, 35] and rats [29, 36]. Contradictory findings exist, as some studies reported no effect of boron supplementation on serum cholesterol and triglyceride levels [37]. Others even reported an increase in plasma triglyceride [33] and plasma cholesterol [38] levels with boron addition. The variability in findings may be due to differences in animal species, the chemical form and dosage of boron used, and experimental conditions. Boron may regulate cholesterol metabolism by lowering total cholesterol, low–density lipoprotein (LDL, "bad" cholesterol), and triglycerides while increasing high–density lipoprotein (HDL, "good" cholesterol) levels. These effects are linked to its role in enzyme activity and oxidative stress reduction. Further research is needed to confirm its cardiovascular benefits.

Aspartate Aminotransferase (AST) and Alanine Aminotransferase (ALT) are enzymes that play critical roles in the body's energy metabolism. The activities of both AST and ALT are essential for maintaining the efficiency of metabolic pathways involved in energy production. An increase in the levels of these enzymes is typically considered an indicator of liver cell damage [39]. Under normal conditions, the activities of these enzymes in the serum are low. However, it is suggested that after hepatocellular damage, these enzymes gradually leak into the bloodstream [40]. During the study, there were no statistically significant differences in serum AST and ALT levels between groups at different measurement times (P>0.05) (TABLE V).

Similarly, no statistical differences were detected based on the dose for these parameters. However, previous studies have reported that under inappropriate conditions and stress, boron supplementation significantly reduced serum AST and ALT levels [32]. The lack of this effect in the study may be attributed to the fact that the doses administered were insufficient for animals with higher body weights, such as horses, and that the horses were kept in a suitable and comfortable environment.

Boron helps reduce oxidative stress at the cellular level. This effect occurs by increasing the levels of reduced glutathione (GSH) and neutralizing free radicals. Boron supports the protection of cells from oxidative damage by enhancing the activities of enzymes like CAT and GSH–Px. In stressful conditions the production of mitochondrial reactive oxygen species (ROS) increases in tissues. Accumulation of ROS in cells leads to irreversible damage to molecules such as lipids, proteins, and DNA, causing cellular dysfunction [41, 42]. MDA, a major byproduct of lipid peroxidation, is commonly used to assess oxidative damage. In contrast CAT and GSH–Px levels serve as important markers of the body's defense against oxidative damage.

MDA levels decreased dose–dependently at all times except baseline (P<0.001), with the lowest in B15 on d 30 and 60. No difference was seen among B5, B10, and B15 on d 90 (P>0.05). CAT and GSH–Px levels increased dose–dependently except at baseline (P<0.001). B15 had the highest CAT levels at all times (P<0.001). GSH–Px was lowest in the control on d 30 and highest in B10 and B15 on d 90 (P<0.001). Boron supplementation reduced MDA (35% in B5, 40% in B10, and 45% in B15, respectively) and increased CAT (8% in B5, 12% in B10, and 28% in B15) and GSH–Px (14% in B5, 28% in B10 and 34% in B15, respectively), indicating its effectiveness in preventing oxidative damage (TABLE VI).

TABLE VI
The effect of different doses of boron on serum MDA, CAT, and GSH–Px levels (n=8)

	Days	Groups				*P**	Linear
		Control	B5	B10	B15		
MDA, nmol·mL^{-1}	0	10.1 ± 0.7	10.2 ± 0.2^{A}	10.1 ± 0.8^{A}	10.0 ± 0.5^{A}	>0.05	>0.05
	30	10.1 ± 0.4^{a}	9.3 ± 0.3$^{ab, AB}$	8.4 ± 0.2^{bc,A}	7.9 ± 0.2^{c,B}	<0.001	<0.001
	60	9.8 ± 0.4^{a}	8.5 ± 0.5^{ab,B}	7.5 ± 0.3^{bc,B}	6.9 ± 0.3^{c,C}	<0.001	<0.001
	90	10.0 ± 0.5^{a}	6.5 ± 0.2^{b,C}	5.8 ± 0.2^{b,C}	5.5 ± 0.3^{b,D}	<0.001	<0.001
	RM	>0.05**	<0.001	0.002**	<0.001		
CAT, ku·L^{-1}	0	60.1 ± 1.2	60.4 ± 0.7^{C}	60.1 ± 0.8^{C}	60.1 ± 0.4^{D}	>0.05	>0.05
	30	59.8 ± 0.7^{c}	61.7 ± 0.5^{bc,C}	63.7 ± 0.6^{b,B}	66.8 ± 0.6^{a,C}	<0.001	<0.001
	60	60.1 ± 1.0^{d}	64.2 ± 0.3^{c,B}	66.7 ± 0.3^{b,A}	70.8 ± 0.6^{a,B}	<0.001	<0.001
	90	60.2 ± 0.6^{d}	65.1 ± 0.4^{c,A}	67.6 ± 0.4^{b,A}	77.5 ± 0.4^{a,A}	<0.001	<0.001
	RM	>0.05	<0.001	<0.001	<0.001		
GSH–Px, IU·L^{-1}	0	19.9 ± 0.6	20.4 ± 0.7^{B}	20.0 ± 0.8^{D}	20.2 ± 0.7 ^{D}	>0.05	>0.05
	30	19.9 ± 0.5^{b}	21.9 ± 0.4^{a,B}	22.1 ± 0.5^{a,C}	23.4 ± 0.4^{a,C}	<0.001	<0.001
	60	20.1 ± 0.6^{c}	23.3 ± 0.3^{b,A}	24 ± 0.3.0^{b,B}	25.8 ± 0.2^{a,B}	<0.001	<0.001
	90	20.4 ± 0.5^{c}	23.7 ± 0.4^{b,A}	26.3 ± 0.2^{a,A}	27.5 ± 0.2$^{a, A}$	<0.001	<0.001
	RM	>0.05	<0.001	<0.001**	<0.001		

MDA: Malondialdehyde, CAT: Catalase, GSH–Px: Glutathione peroxidase Control: no boron. B5: 5 mg elemental boron. B10: 10 mg elemental boron. B15: 15 mg elemental boron. Data are presented as mean ± standard error. *One–way ANOVA was performed. and Tukey's post hoc test was used for intergroup comparisons. Differences between measurement times were analyzed using repeated measures (RM) analysis. **Greenhouse–Geisser correction was applied. Different lowercase letters $^{(a–d)}$ above the groups indicate significant differences among means in the same row. Different uppercase letters $^{(A–D)}$ above the groups indicate significant differences among means in the same column

Several studies support these findings, reporting that boron supplementation increases the amount of reduced glutathione in cells, reducing oxidative stress and oxidative damage [11, 12]. Another study found that boron supplementation in the diet of rats exposed to abiotic stress enhanced immune and antioxidant responses [13]. In a study with mice (*Mus musculus*), Kurtoglu *et al*. [14] reported that boron weakened certain enzyme systems and could affect antioxidant defense mechanisms and other biochemical metabolic profiles. There is evidence that boron helps balance harmful effects on the liver by modifying oxidative stress parameters and returning the liver to normal functional levels [15]. It has also been noted that boron affects processes such as the Krebs cycle, the glucose–alanine cycle, and methionine metabolism, which in turn reduces oxidative stress [16].

CONCLUSION

In conclusion, it has been determined that the boron mineral positively influences energy metabolism and antioxidant activity in purebred Arabian foals. with the most effective dose being 15 $mg \cdot d^{-1} \cdot animal^{-1}$. However, it was concluded that the doses used in the study might be insufficient for horses, and further studies with higher doses are necessary to determine the effects of boron on the targeted parameters. Only then can the optimal dose for horses be identified.

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Conflict of interest

The authors declare no conflicts of interest.

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