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RESEARCH ARTICLE

Effect of astaxanthin supplementation on serum biochemical profile of Vrindavani cattle during heat stress

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Abstract: Heat stress poses significant challenges to livestock production, adversely affecting animal health and productivity. This study investigated the effects of astaxanthin supplementation on serum biochemical parameters in heat-stressed Vrindavani cattle. Twelve male Vrindavani cattle (1-2 years) were randomly assigned to two groups (n=6 each): heat-stressed control (HSC) and treatment group (heat-stressed + astaxanthin @ 0.5 mg/kg body weight/day). Following a 15-day acclimatization period, animals were exposed to 38°C for 6 hours daily for 28 days, followed by a 7-day recovery period. Blood samples were collected weekly throughout the experiment. Results revealed a significant ($P<0.05$) decrease in alanine aminotransferase (ALT) levels and a non-significant decrease in aspartate aminotransferase (AST) levels in the treatment group compared to HSC. Total protein and albumin showed significant ($P<0.05$) group differences on day 14, with lower values in treatment animals. Serum urea and creatinine were significantly ($P<0.05$) reduced in astaxanthin-supplemented cattle compared to HSC. These findings demonstrate that astaxanthin supplementation effectively alleviates heat stress-induced metabolic alterations in Vrindavani cattle, supporting its potential as a nutritional strategy to enhance heat tolerance in livestock.

Keywords: Astaxanthin, Heat stress, Liver enzymes, Renal function, Vrindavani cattle

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Introduction

Livestock production is a fundamental pillar of global food security and agricultural economies, particularly in developing nations such as India, where a substantial proportion of the population depends on agriculture and animal husbandry for sustenance. The livestock sector contributes significantly to India's agricultural economy, accounting for 30.87% of the agricultural Gross Value Added (GVA) and 6.17% of the total GVA (DAHD Annual Report, 2022-23). India's livestock population has increased by 4.82% to 535.78 million, with cattle populations rising by 0.8% to 192.49 million (20th Livestock Census). India remains the world's largest milk producer, with 221.06 million tonnes in 2022-2023, with crossbred cattle accounting for approximately 30% of total milk production.

Climate change projections indicate a mean temperature increase of 0.2°C per decade, with anticipated rises between 1.8°C and 4.0°C by 2100 (IPCC, 2022). These climatic shifts pose substantial threats to livestock production systems through increased frequency and intensity of heat stress events. Heat stress, characterized by elevated ambient temperature and humidity exceeding the thermoneutral zone of animals, compromises productivity through multiple mechanisms, including reduced feed intake, altered metabolic functions, impaired reproductive performance, suppressed immune function, and decreased growth rates (Bernabucci et al. 2022; Gao et al. 2023). Vrindavani cattle, a crossbred indigenous breed developed in India, exhibit particular vulnerability to heat stress due to their genetic composition combining heat-susceptible exotic germplasm with indigenous breeds.

Effective mitigation of heat stress is essential for sustainable livestock production and animal welfare. Mitigation strategies encompass environmental modifications (shade provision, optimized housing), genetic selection for heat-tolerant traits, and appropriate management practices during high-temperature periods (Beede and Collier, 1986; Nardone et al. 2010). Nutritional interventions have emerged as particularly promising approaches, with antioxidant supplementation demonstrating protective effects against reactive oxygen species (ROS)-induced oxidative damage (Becker et al. 2020; Liu et al. 2022). Trace elements,

including zinc, selenium, and chromium, function as antioxidant cofactors and can ameliorate oxidative stress associated with heat exposure (Kumar et al. 2019; Sammad et al. 2022).

Astaxanthin (3,3'-dihydroxy-β, β-carotene-4,4'-dione), a xanthophyll carotenoid, exhibits potent antioxidant and anti-inflammatory properties through its unique molecular structure featuring conjugated double bonds and terminal keto and hydroxyl groups on each ionone ring (Ekpe et al. 2018; Raza et al. 2021). This structural configuration enables astaxanthin to span cell membranes and neutralize both lipophilic and hydrophilic reactive species. Notably, astaxanthin demonstrates antioxidant activity approximately 10-fold greater than β-carotene and 100-500 times more potent than α-tocopherol against specific reactive oxygen species (Miki, 1991; Yang et al. 2011). Naturally occurring in marine organisms, including salmon, lobster, algae, and crustaceans, astaxanthin exhibits diverse biological activities, including protection against polyunsaturated fatty acid (PUFA) oxidation, immunomodulation, and reproductive enhancement (Guerin et al. 2003).

Recent investigations have elucidated astaxanthin's capacity to normalize stress-elevated hepatic enzymes. Alam et al. (2018) reported that astaxanthin administration in isoproterenol-treated rats reduced elevated AST, ALT, and creatine kinase-MB activities, indicating hepatoprotective and cardioprotective effects. Majumder et al. (2024) reported that dietary astaxanthin supplementation (150 mg/animal/day) significantly reduced serum ALT and AST levels in heat-stressed Vrindavani calves, helping restore these liver enzymes toward physiological norms. These hepatoprotective effects are mediated through ROS scavenging, reduced lipid peroxidation, and enhanced endogenous antioxidant defenses via activation of the Keap1-Nrf2 pathway (Chen et al. 2020; Somagond et al. 2022).

Furthermore, astaxanthin exerts beneficial effects on renal function and nitrogen metabolism under oxidative challenge. Experimental models of renal ischemia-reperfusion injury and nephrotoxicity demonstrate that astaxanthin administration significantly reduces serum urea and creatinine concentrations, reflecting improved glomerular filtration and attenuated renal damage (Kisaoglu et al. 2024; Naderi et al. 2025). Kittur et al. (2024) demonstrated that astaxanthin supplementation exerts renoprotective effects in heat-stressed goats, as evidenced by reduced serum urea and creatinine and improved antioxidant status. These effects are mediated through modulation of redox-sensitive signaling pathways, particularly Keap1-Nrf2 and NF-κB, which help maintain redox homeostasis and preserve tissue integrity (Zhang et al. 2021; Wang et al. 2023).

Despite accumulating evidence for astaxanthin's antioxidant properties, limited research has examined its effects on comprehensive biochemical profiles in crossbred cattle under controlled heat stress conditions. Therefore, this study aimed to evaluate the efficacy of astaxanthin supplementation in modulating serum biochemical parameters, including hepatic enzymes, proteins, and renal function markers in Vrindavani cattle subjected to experimental heat stress.

Materials and Methods

Study site

The experiment was conducted at the Nuclear Research Laboratory, Division of Physiology and Climatology, ICAR-Indian Veterinary Research Institute, Bareilly, India (28°21'2" N, 79°24'2" E; elevation 170 m above mean sea level). The region experiences a humid subtropical climate.

Experimental animals and management

Twelve healthy, growing male Vrindavani cattle aged 12-24 months with body weight ranging from 150-200 kg were selected from the Experimental Animal Shed, Division of Physiology and Climatology. Animals were housed in the well-ventilated antechamber of the psychrometric facility, which was equipped with individual mangers, coolers, and fans and had a capacity for 12 animals simultaneously (Figure 1). Animals were kept under hygienic conditions throughout the experiment, with *ad libitum* access to clean water and a standard feed as per routine farm protocols. All animals were dewormed 14 days before the experiment initiation.

Experimental design and heat stress protocol

Following a 15-day acclimatization period, animals were randomly allocated into two groups (n=6 each):

- Group I (HSC): Heat-stressed control (no supplementation)
- Group II (Treatment): Heat-stressed + astaxanthin supplementation @ 0.5 mg/Kg body weight/day

Astaxanthin (*Haematococcus pluvialis* extract) was administered orally daily during the acclimatization and heat exposure periods. Animals were exposed to 38°C in a psychrometric chamber for 6



Fig.1 Psychometric chamber

hours daily (08:00-14:00 h) for 28 consecutive days. Following heat exposure, animals underwent a 7-day recovery period in ambient shed conditions without astaxanthin supplementation. Environmental heat stress was quantified using the Temperature Humidity Index (THI) calculated according to McDowell (1972):

$$THI = 0.72(Tdb + Twb) + 40.6$$

where Tdb = dry bulb temperature (°C), Twb = wet bulb temperature (°C)

Blood sampling and serum biochemical analysis

Blood samples (4 mL) were collected via jugular venipuncture at weekly intervals throughout acclimatization (day -7), heat exposure (days 1, 7, 14, 21, 28), and recovery (day 35) periods. Samples were collected in clot-activator vacutainers (1400 h) and centrifuged at 3000 rpm for 30 minutes at 4°C. Harvested serum was stored at -20°C until analysis. Serum biochemical parameters, including alanine aminotransferase (ALT), aspartate aminotransferase (AST), total protein, albumin, urea, and creatinine, were determined using UV-visible spectrophotometry with commercial reagent kits (Coral Clinical Systems, India) following manufacturer protocols.

Statistical analysis

Data were expressed as mean ± standard error of mean (SEM) and analyzed using one-way analysis of variance (ANOVA) followed by Tukey's post-hoc test for multiple comparisons. Statistical significance was set at $P<0.05$. All analyses were conducted using SPSS software version 26.

Results and Discussion

Hepatic function parameters

Serum ALT and AST concentrations across experimental periods are presented in Table 1. Throughout heat exposure, ALT concentrations progressively increased in both groups, reaching maximum values on day 21. However, the treatment group showed significantly lower ($P < 0.05$) ALT levels than the HSC group from day 7 to day 28. On day 21, HSC animals showed peak ALT (27.02±0.71 U/mL) versus treatment animals (22.37±0.51 U/mL), representing a 17.2% reduction. During recovery (day 35), ALT returned toward baseline in both groups with no significant inter-group difference. Similar temporal patterns were observed for AST, with the treatment group consistently showing numerically lower values throughout heat exposure. Significant inter-group differences ($P<0.05$) were detected from day 7 through day 28. Maximum AST values occurred on day 21 (HSC: 141.59±0.79 U/mL; treatment: 129.22±0.45 U/mL), reflecting an 8.7% reduction in supplemented animals.

The significant elevation of serum ALT and AST in HSC animals reflects heat stress-induced hepatocellular injury and altered hepatic metabolism. These enzymes, ALT primarily in the hepatocyte cytoplasm and AST in both the cytoplasm and mitochondria, are released into the circulation following cellular damage or increased membrane permeability (Kaneko et al. 2008). The progressive increase during heat exposure aligns with previous observations in buffaloes (Wankar et al. 2014), goats (Kittur et al. 2024), and dairy cows (Min et al. 2023) under thermal stress. This elevation likely results from glucocorticoid-mediated stimulation of gluconeogenesis to meet increased energy demands during heat stress (Fernando et al. 2013; Koch et al. 2022). Astaxanthin supplementation significantly attenuated these elevations, with treatment animals showing 17.2% and 8.7% reductions in peak ALT and AST concentrations, respectively. These findings corroborate recent reports in Vrindavani calves (Majumder et al. 2024) and goats (Kittur et al. 2024), where astaxanthin similarly reduced hepatic enzymes during thermal stress. The hepatoprotective mechanism involves multiple pathways: (1) direct ROS scavenging, protecting hepatocyte membranes from oxidative damage (Raza et al. 2021); (2) activation of the Keap1-Nrf2 pathway, enhancing endogenous antioxidant enzyme expression (Chen et al. 2020; Zhang et al. 2021); (3) suppression of NF-êB-mediated inflammatory responses, reducing secondary liver injury (Wang et al. 2023); and (4) preservation of mitochondrial membrane integrity and function (Liu et al. 2022).

Table 1: Effect of astaxanthin supplementation on serum ALT and AST concentrations in heat-stressed Vrindavani cattle

Days of experiment	ALT (U/mL)		AST (U/mL)	
	HSC	Treatment	HSC	Treatment
-7 (pre-exp)	18.31±0.44a	18.31±0.44a	102.44±0.33a	103.32±0.38a
1	18.28±0.18a	18.06±0.29a	113.20±0.33cB	109.88±0.84bA
7	23.41±0.23cB	20.10±0.51cA	137.72±0.57cB	126.37±0.87dA
14	27.02±0.71dB	22.37±0.51eA	141.59±0.79dB	129.22±0.45eA
21	24.33±0.47cB	21.11±0.59deA	138.77±0.86cB	126.39±1.02bA
28	21.45±0.55b	20.09±0.26bcd	131.62±1.21dB	122.87±0.67cA
35 (Recovery)	18.99±0.47a	18.53±0.41abc	109.35±0.51b	109.47±0.59b

*Values are mean ± SEM (n=6). a-g: Different superscripts within a column indicate significant differences ($P<0.05$) across sampling days. A-B: Different superscripts within a row for each parameter indicate significant differences ($P<0.05$) between groups.

Protein Profile

Serum total protein and albumin concentrations are presented in Table 2. Significant inter-group differences (P<0.05) were observed only on day 14, with treatment animals showing lower values (7.29±0.17 g/dL) compared to HSC (7.81±0.18 g/dL). No significant differences were detected at other time points. Parallel patterns were observed, with the treatment group showing significantly lower (P<0.05) albumin concentrations on day 14 (2.96±0.07 g/dL) versus HSC (3.17±0.04 g/dL).

The progressive increase in serum total protein and albumin during heat exposure reflects multiple physiological adaptations, including haemoconcentration from reduced feed and water intake, acute phase protein synthesis, and altered nitrogen metabolism (Kamiya et al. 2006; Korde et al. 2007). The significant inter-group difference observed on day 14, with treatment animals showing lower protein concentrations, suggests that astaxanthin may moderate the acute phase response and reduce protein catabolism during heat stress. Heat stress typically increases glucocorticoid secretion, promoting protein catabolism and hepatic gluconeogenesis from amino acids to meet elevated energy demands (Guo et al. 2018; Bernabucci et al. 2022). The moderated protein response in astaxanthin-supplemented animals may reflect improved energy balance and reduced reliance on protein mobilization. Additionally, astaxanthin's anti-inflammatory properties may attenuate acute phase protein synthesis by hepatocytes, contributing to the observed differences (Raza et al. 2021; Sammad et al. 2022).

Renal Function parameters

Serum urea and creatinine concentrations are presented in **Table 3**. Heat exposure significantly increased serum urea in both groups, with HSC animals showing consistently higher values throughout the experimental period. Significant inter-group differences (P<0.05) were observed from day 7 through day 28. Peak urea concentrations occurred on day 21 (HSC: 36.33±1.10 mg/dL; treatment: 31.10±1.18 mg/dL), representing a 14.4% reduction in astaxanthin-supplemented animals. Similar patterns were observed for serum creatinine, with the treatment group showing significantly lower (P<0.05) concentrations on days 7, 14, and 21. Maximum creatinine values were recorded on day 14 (HSC: 2.28±0.06 mg/dL; treatment: 1.91±0.07 mg/dL), reflecting a 16.2% reduction in supplemented animals.

Table 2: Effect of astaxanthin supplementation on serum total protein and albumin concentrations in heat-stressed Vrindavani cattle

Days of experiment	Total Protein (g/dL)		Albumin (g/dL)	
	HSC	Treatment	HSC	Treatment
-7 (pre-exp)	5.33±0.12a	5.60±0.20a	2.28±0.07a	2.37±0.03a
1	6.45±0.10b	6.54±0.10b	2.50±0.09b	2.61±0.04b
7	7.11±0.19c	6.89±0.18bc	2.92±0.10c	2.82±0.05c
14	7.81±0.18cB	7.29±0.17cA	3.17±0.04cB	2.96±0.07cA
21	7.38±0.15c	7.19±0.12c	3.03±0.04cd	2.92±0.04c
28	7.41±0.19cd	7.30±0.18c	3.02±0.06cd	2.93±0.09c
35 (Recovery)	7.10±0.14c	7.02±0.15bc	2.84±0.03c	2.82±0.07c

*Values are mean ± SEM (n=6). a-g: Different superscripts within a column indicate significant differences (P<0.05) across sampling days. A-B: Different superscripts within a row for each parameter indicate significant differences (P<0.05) between groups.

Table 3: Effect of astaxanthin supplementation on serum urea and creatinine concentrations in heat-stressed Vrindavani cattle

Days of experiment	Urea (mg/dL)		Creatinine (mg/dL)	
	HSC	Treatment	HSC	Treatment
-7 (pre-exp)	24.47±0.57a	23.90±0.74a	1.31±0.07a	1.22±0.04a
1	25.14±0.44a	24.24±0.71ab	1.41±0.07a	1.35±0.04a
7	32.46±0.81bB	26.78±1.29bcA	1.98±0.07cB	1.65±0.05bA
14	35.80±1.18cB	29.98±0.66deA	2.28±0.06dB	1.91±0.07cA
21	36.33±1.10cB	31.10±1.18cA	1.94±0.06cB	1.81±0.05cA
28	32.50±0.55bB	28.35±0.87cdA	1.74±0.05b	1.59±0.05b
35 (Recovery)	24.95±0.58a	24.40±0.57ab	1.37±0.04a	1.36±0.04a

*Values are mean ± SEM (n=6). a-g: Different superscripts within a column indicate significant differences (P<0.05) across sampling days. A-B: Different superscripts within a row for each parameter indicate significant differences (P<0.05) between groups.

The significant elevation of serum urea and creatinine in HSC animals indicates impaired renal function during heat stress, consistent with previous observations in cattle (Guo et al. 2018; Min et al. 2023) and buffaloes (Somagond et al. 2022). The 14.4% and 16.2% reductions in peak urea and creatinine concentrations, respectively, in astaxanthin-supplemented animals demonstrate significant renoprotection. Several mechanisms explain these renoprotective effects. First, heat stress induces peripheral vasodilation for heat dissipation, reducing renal blood flow and glomerular filtration rate (GFR) (Koch et al. 2022). The reduced creatinine clearance elevates serum creatinine concentrations. Second, heat stress increases protein catabolism and amino acid deamination, elevating urea production (Guo et al. 2018). Third, oxidative stress and inflammation directly damage renal tubular epithelium, impairing excretory function. Astaxanthin's renoprotection likely involves: (1) preservation of renal hemodynamic through modulation of vasoactive mediators; (2) direct antioxidant protection of renal tubular cells against oxidative damage (Kisaoglu et al. 2024; Naderi et al. 2025); (3) reduction of protein catabolism through improved energy status; and (4) suppression of renal inflammatory responses (Chen et al. 2020). These findings align with experimental models demonstrating astaxanthin's efficacy in renal ischemia-reperfusion injury (Naderi et al. 2025) and nephrotoxicity (Kisaoglu et al. 2024).

Conclusion

This study demonstrates that astaxanthin supplementation at 0.5 mg/kg body weight/day effectively mitigates heat stress-induced alterations in serum biochemical parameters of Vrindavani cattle. The significant reductions in hepatic enzymes (ALT, AST), moderation of protein responses, and preservation of renal function markers (urea, creatinine) in supplemented animals indicate that astaxanthin exerts multi-organ protective effects during thermal stress through its potent antioxidant and anti-inflammatory properties.

As climate change intensifies heat stress challenges in livestock production, nutritional interventions with natural antioxidants like astaxanthin offer sustainable, cost-effective strategies to enhance animal resilience, welfare, and productivity. These findings support the integration of astaxanthin supplementation into heat stress mitigation programs for crossbred cattle, contributing to climate-resilient livestock production systems. Further research investigating optimal dosage regimens, long-term effects, and underlying molecular mechanisms will facilitate the practical implementation of this promising nutritional strategy.

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References

20th Livestock Census Government of India (GOI) 2019 Ministry of Fisheries, Animal Husbandry, and Dairying

Alam MN, Hossain MM, Rahman MM, Subhan N, Mamun MAA, Ulla A, Reza HM, Alam MA (2018) Astaxanthin prevented oxidative stress in the heart and kidneys of isoproterenol-administered aged rats. J Diet Suppl 15:42-54

Becker CA, Collier RJ, Stone AE (2020) Invited review: Physiological and behavioral effects of heat stress in dairy cows. J Dairy Sci 103:6751-6770

Beede DK, Collier RJ (1986) Potential nutritional strategies for intensively managed cattle during thermal stress. J Anim Sci 62:543-554

Bernabucci U, Lacetera N, Baumgard LH, Rhoads RP, Ronchi B, Nardone A (2022) Metabolic and hormonal acclimation to heat stress in domesticated ruminants. Animal 16:100482

Chen Z, Xiao J, Liu H, Yao K, Hou X, Cao Y, Liu X (2020) Astaxanthin attenuates oxidative stress and immune impairment in D-galactose-induced aging in rats by activating the Nrf2/Keap1 pathway and suppressing the NF-κB pathway. Food Funct 11:8099-8111

DAHD (2022-23) Government of India (GOI) Annual Report. Ministry of Fisheries, Animal Husbandry, and Dairying, New Delhi

Ekpe L, Inaku K, Ekpe V (2018) Antioxidant effects of astaxanthin in various diseases—a review. J Mol Pathophysiol 7:1-6

Fernando HA, Chin HF, Ton SH, Abdul Kadir K (2013) Stress and its effects on glucose metabolism and 11β-HSD activities in rats fed on a combination of high-fat and high-sucrose diet with glycyrrhizic acid. J Diabetes Res 2013: Article ID 190395

Gao ST, Guo J, Quan SY, Nan XM, Fernandez MVS, Baumgard LH, Bu DP (2023) The effects of heat stress on protein metabolism in lactating Holstein cows. J Dairy Sci 106:2189-2201

Guerin M, Huntley ME, Olaizola M (2003) Haematococcus astaxanthin: Applications for human health and nutrition. Trends Biotechnol 21:210-216

Guo J, Gao S, Quan S, Zhang Y, Bu D, Wang J (2018) Blood amino acids profile responding to heat stress in dairy cows. Asian-Australas J Anim Sci 31:47-53

IPCC (2022) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

Kamiya M, Kamiya Y, Tanaka M, Shioya S (2006) Milk protein production and plasma 3-methylhistidine concentration in lactating Holstein cows exposed to high ambient temperatures. Anim Biosci 19:1159-1163

Kaneko JJ, Harvey JW, Bruss ML (Eds.) (2008) Clinical Biochemistry of Domestic Animals (6th ed.). Academic Press

Kisaoglu A, Kose E, Yilmaz N, Tanbek K, Yildiz A, Yilmaz U, Ozbag D (2024) Investigation of the effect of astaxanthin on autophagy in renal ischemia-reperfusion modeled rats. Medeni Med J 39:112-120

Kittur PM, Karthiga K, Sarma L, Gururaj AV, Lata K, Verma V, Chouhan VS, Maurya VP (2024) Astaxanthin supplementation ameliorates simulated heat stress by regulating physio-biochemical responses in Sirohi goats. Vet Res Commun 48:2789-2796

Koch F, Thom U, Albrecht E, Weikard R, Nolte W, Kuhla B, Kuehn C (2022) Heat stress directly impairs gut integrity and affects intestinal and renal function in dairy cows. J Dairy Sci 105:6945-6958

Korde JP, Singh G, Varshney VP, Shukla DC (2007) Effect of long-term heat stress on some biochemical and hormonal parameters in goats. Indian J Anim Sci 77:284-287

Kumar S, Singh SV, Bhan SC (2019) Effect of dietary supplementation of astaxanthin (potent antioxidant) on growth rate, DMI, FCR and metabolic changes in Karan Fries heifers during heat stress. J Agrometeorol 21:80-88

Liu Y, Li Y, Wang X, Chen Z (2022) Astaxanthin protects against heat stress-induced intestinal barrier dysfunction in Caco-2 cells by activating Nrf2 signaling pathway. Nutrients 14:1602

Majumder S, Kant L, Verma P, Chouhan VS, Samad HA, Singh G, Maurya VP (2024) Effect of astaxanthin supplementation on liver profile in growing Vrindavani calves exposed to thermal stress. Int J Vet Sci Anim Husb 8:700-704

McDowell RE (1972) Improvement of Livestock Production in Warm Climates. WH Freeman and Company

Miki W (1991) Biological functions and activities of animal carotenoids. Pure Appl Chem 63:141-146

Min L, Li D, Tong X, Nan X, Ding D, Xu B, Wang J (2023) Heat stress negatively affects the physiology, metabolism, and milk production of dairy cows: A meta-analysis. J Dairy Sci 106:3520-3535

Naderi S, Najafi H, Abbaszadeh F, Naderi N, Fakhri S (2025) The effects of astaxanthin on ischemia-reperfusion induced renal functional and histopathological disturbances in rats: Relevance to its antioxidant effects. J Rep Pharm *Sci* 13:45-56

Nardone A, Ronchi B, Lacetera N, Ranieri MS, Bernabucci U (2010) Effects of climate change on animal production and the sustainability of livestock systems. Livest Sci 130:57-69

Raza SHA, Naqvi SRZ, Abdelnour SA, Schreurs N, Mohammedsaleh ZM, Khan I, Shater AF, Abd El-Hack ME, Khafaga AF, Quan G, Khan R (2021) Beneficial effects and health benefits of astaxanthin molecules on animal production: A review. Res Vet Sci 138:69-78

Sammad A, Umer M, Shi R, Zhu H, Zhao X, Wang Y (2022) Dairy cow heat stress: A review of nutritional and metabolic effects. Animals 12:1515

Somagond YM, Singh SV, Deshpande A (2022) Effect of dietary supplementation of astaxanthin, prill fat and combination on stress indicators, milk yield and composition during heat stress in buffaloes. Biol Rhythm Res 53:665-675

Wang Y, Zhang H, Chen X, Li W (2023) Astaxanthin attenuates oxidative stress and inflammatory response in the liver of heat-stressed rats via the Nrf2/HO-1 and NF-κB pathways. Antioxidants 12:678

Wankar AK, Singh G, Yadav B (2014) Thermoregulatory and adaptive responses of adult buffaloes (Bubalus bubalis) during hyperthermia: Physiological, behavioral, and metabolic approach. Vet World 7:825-830

Yang Y, Seo JM, Nguyen A, Pham TX, Park HJ, Park Y, Kim B, Bruno RS, Lee J (2011) Astaxanthin-rich extract from the green alga Haematococcus pluvialis lowers plasma lipid concentrations and enhances antioxidant defense in apolipoprotein E knockout mice. J Nutr 141:1611-1617

Zhang XS, Lu Y, Li W, Tao T, Peng L, Wang WH, Gao S, Liu C, Zhuang Z, Xia DY, Hang CH (2021) Astaxanthin ameliorates oxidative stress and neuronal apoptosis via SIRT1/NRF2/Prx2/ASK1/p38 after traumatic brain injury in mice. Br J Pharmacol 178:1114-1132