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REVIEW PAPER

Nutritional strategies for alleviating the detrimental effects of heat stress in dairy cows: a review

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Abstract
Heat stress responses negatively impact production performance, milk quality, body temperature, and other parameters in dairy cows. As global warming continues unabated, heat stress in dairy cows is likely to become more widespread in the future. To address this challenge, researchers have evaluated a number of potentially available nutritional strategies, including dietary fat, dietary fiber, dietary microbial additives, minerals, vitamins, metal ion buffer, plant extracts, and other anti-stress additives. In this paper, we discuss the evidence for the efficacy of these nutritional strategies aimed at alleviating the detrimental effects of heat stress in dairy cows. It was comprised of the treatment (dosage and usage), animal information (lactation stage and number of dairy cows), THI value (level of heat stress), duration of exposure, the changes of feed intake and milk yield (production performance), the changes of milk protein and milk fat (milk quality), the changes of rectal temperature and respiration rate (body temperature), other indices, and reference resources. The results of these studies are presented with statistical justification in the tables. In total, the 49 kinds of dietary interventions derived from these eight types of nutritional strategies may provide an appropriate means of mitigating heat stress on a particular dairy farm based on the explanation of the results.

Keywords Heat stress · Dairy cows · Nutritional strategies · Improvement

Abbreviations

AA	Amino acids
ADF	Acid detergent fiber
CP	Crude protein
DCAD	Dietary cation-anion difference
DIM	Days in milk
ECM	Energy-corrected milk
FCM	Fat-corrected milk
HSP	Heat shock protein
IL	Interleukin
NDF	Neutral detergent fiber
NEFA	Non-esterified fatty acid
OM	Organic matter
THI	Temperature humidity index
TMR	Total mixed ration
TNFα	Tumor necrosis factor α

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Introduction

As global warming continues unabated, the prevalence of heat stress in animals is projected to increase in terms of frequency, duration, and severity (Min et al. 2017). Heat stress responses are now regarded as an expensive problem in the animal husbandry of many species around the world. In the dairy industry, dairy cows are highly susceptible to heat stress (Bernabucci et al. 2014). Heat stress responses negatively impact the body temperature, health, and a variety of productivity traits of dairy cow, including the increasing of rectal temperature and respiration rate and the decreasing of feed intake, milk production, milk quality, and reproductive performance (Atrian and Shahryar 2012). Moreover, dairy cows can even succumb during the hot summer, the number of deaths rising sharply with the increasing of THI value (level of heat stress) (Vitali et al. 2009). Therefore, heat stress represents a significant financial burden (St-Pierre et al. 2003) that may impede the further development of the dairy industry. Thus, methods of effectively alleviating the negative effects of heat stress that will also improve production performance are urgently required.

At present, advances in genetic, managerial, and nutritional strategies have been applied to mitigate the detrimental effects of heat stress in dairy cows. It has traditionally been considered that cooling systems (shades, ventilation and spray, and fans), assisted with nutritional strategies, are preferentially recommended to be used in heat-stressed dairy cows. The objective of this paper is to assess the efficacy of a range of successful dietary manipulations (nutritional strategies) that have been used in heat-stressed dairy cows in recent years (Tables 1, 2, 3, 4, 5, 6, 7, and 8). By considering a wide range of such nutritional strategies, we aim to identify clues or perspectives that will enable the selection of the most appropriate methodology for particular dairy farms to improve cow health and productivity during heat stress.

Nutritional strategies to ameliorate heat stress in dairy cows

Eight types of nutritional strategies are introduced in the following section, including dietary fat, dietary fiber, dietary microbial additives, minerals, vitamins, metal ion buffer, plant extracts, and other anti-stress additives.

Dietary fat

During heat stress, a significant reduction in feed intake in dairy cows results in negative energy balance, during which energy intake cannot meet the requirement for lactation. The traditional approach to this problem is the supplementation of the diet with additional fat to ameliorate the energy deficit and reduce thermogenesis (because fat generates less heat increment than dietary carbohydrate or protein) (Wang et al. 2010). Specifically, a previous study reported that a supplement of 3% unprotected fat had been advocated for use during hot summers (Drackley et al. 2003). Feeding of a higher energy diet resulted in greater circulating NEFA concentrations, reflecting a diminution in the energy deficit of heat-stressed Holstein dairy cows. As a consequence, milk yield was significantly increased from 28.5 to 30.4 kg/day, but milk fat content was reduced ($P < 0.05$). Presumably, supplementation with unprotected fat interfered with ruminal fermentation, decreasing the ruminal acetate to propionate ratio and therefore milk fat synthesis. Thus, it may be preferable to use a form of protected fat, such as saturated fatty acid, hydrogenated fish fat, fatty acid calcium salts, or oil seeds.

Palmitic acid is a lipid form that is not fermented in the rumen, and when this was fed to early Holstein lactation dairy cows at approximately 450 g/cow/day during the summer (Warntjes et al. 2008), milk yield tended to be higher (36.69 versus 38.04 kg/day, $P = 0.07$) and milk true protein content was significantly higher (1.08 versus 1.13 kg/day, $P < 0.05$). This approach did increase the proportion of C16:0 in the milk fatty acids, but the positive effects of this supplement on milk production outweighed the negative effect on fatty acid composition of the milk. Subsequently, the effects of diet consisting of supplemental saturated fatty acids (contained 1.3% C14:0, 54% C16:0, 34% C18:0, 8% C18:1, 1.2% C18:2, and 0.6% other fatty acids) were evaluated in heat-stressed mid-lactation Holstein dairy cows (Wang et al. 2010). The feeding of a 1.5% saturated fatty acid supplement was associated with a reduction in rectal temperature during the hottest part of the day (14:00 h), an increase in milk yield from 26.4 to 28.6 kg/day, and improvements in milk composition with regard to fat, protein, and lactose content ($P < 0.05$). A remarkable amount of metabolic heat was saved by energetically replacing fermentable carbohydrates with supplemental saturated fatty acids.

Hydrogenated fish fat is another type of dietary fat supplement that is not degraded in the rumen and is used for dairy cows in countries where fishmeal is produced. Dietary supplementation with 200 g/cow/day hydrogenated fish fat in grazing Holando Argentino dairy cows in summer produced a significant increase in milk production from 23.9 to 26.4 l/cow, as well as improvements in milk protein and fat content ($P < 0.05$) (Gallardo et al. 2001). The authors concluded that hydrogenated fish fat would be a good ingredient to sustain high productivity in grazing dairy cows during heat stress.

Another alternative that had been tried was supplementation with 300 g/cow/day (1.5% of diet) calcium salts of fatty acids, and although this had no effect on milk yield in heat-stressed Israeli-Holstein dairy cows, the use of this method to increase the energy density of dairy cow diet dramatically enhanced milk protein and the efficiency of milk yield per kg feed intake, while reducing metabolic heat production from 26.4 to 25.1 Mcal/day ($P < 0.05$) (Moallem et al. 2010). In brief, it was effective at increasing metabolic and production efficiency in heat-stressed dairy cows. Furthermore, Serbester et al. (2005) found that feeding with 2.54% calcium salts of fatty acids in the diet would increase 4% FCM and milk fat yield ($P < 0.05$) of mid-lactation Holstein dairy cows during summer. In addition to its effect on production variables in heat-stressed dairy cows, supplementation with dietary fat can enhance the immune responses of cows exposed to heat stress. Another previous study demonstrated that fat supplementation using 6.5% whole flaxseed during heat stress led to higher titers of Ig G ($P < 0.05$) in Italian Friesian cows, suggesting an improvement in humoral responses. Furthermore,

Table 1 The efficacy of dietary fat for the alleviation of the detrimental effects of heat stress in dairy cows

Treatment	Animal information	THI value	Duration of exposure (days)	Feed intake	Milk yield (control value)	Milk protein	Milk fat	Rectal temperature	Respiration rate	Other indices	References
3% unprotected fat	154 DIM ($n = 9$) and 167 DIM ($n = 9$)	Average 68 to 71	28		+ 6.67% (28.5 kg/day)		− 5.43%			+Circulating NEFA	Drackley et al. (2003)
450 g/cow/day palmitic acid	Early lactation ($n = 324$)	Average 60 to 84[a]	35		+ 3.68% (36.69 kg/day)*	+ 4.63%				+C16:0 in milk fatty acids	Warntjes et al. (2008)
1.5% saturated fatty acids	184 DIM ($n = 48$)	72.2 at 07:00 h, 84.3 at 14:00 h, and 76.6 at 22:00 h	63		+ 7.69% (26.4 kg/day)	+ 18.96%	+ 5.08%	− 2.04% at 14:00 h		+Milk lactose content	Wang et al. (2010)
200 g/cow/day hydrogenated fish fat	Mid-lactation ($n = 32$)	Average 72.9 (63.14 to 77.3)	63		+ 10.5% (23.9 l/cow)	+ 11.2%	+ 10.0%				Gallardo et al. (2001)
300 g/cow/day calcium salts of fatty acids	158 DIM ($n = 42$)	Average 76.8	77			+ 3.0%				+Efficiency of milk yield/feed intake −Metabolic heat production	Moallem et al. (2010)
2.54% calcium salts of fatty acids	150 DIM ($n = 8$)	Average 69 to 80	21				+ 17.1%			+ 4% FCM	Serbester et al. (2005)
6.5% whole flaxseed	100 DIM ($n = 16$)	Average above 72, maximum exceeded 88	84							+Ig G, −IL-10	Caroprese et al. (2009)
Net energy for lactation of 6.95 MJ/kg	169 DIM ($n = 25$)	Average 74.5 to 82.6	45	− 3.32%	+ 4.53% (26.5 kg/day)*		+ 23.3%	− 0.95% at 14:00 h	− 7.30% at 14:00 h	+FCM and milk energy	Yan et al. (2016)

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[a] THI was calculated using [0.8 × ambient temperature (°C)] + [(% relative humidity/100) × (ambient temperature − 14.4)] + 46.4; $*P \leq 0.1$; +, significantly higher; −, significantly lower; blank space, no significant difference

Table 2 The efficacy of dietary fiber for the alleviation of the detrimental effects of heat stress in dairy cows

Treatment	Animal information	THI value	Duration of exposure (days)	Feed intake	Milk yield (control value)	Milk protein	Milk fat	Rectal temperature	Respiration rate	Other indices	References
16.5% corn silage component replaced with soy hulls	125 DIM ($n=42$)	Approximately average 68 to 83[a]	42		+6.06% (36.3 kg/day)		+6.50%			+In vitro OM and NDF digestibilities, feed intake per meal and meal duration, 4% FCM, and economically corrected milk yield	Halachmi et al. (2004)
28.9% dietary NDF	Prepartum (3 weeks) and postpartum (5 weeks) ($n=30$)	Average 77.7 to 86.8	56	+26.5%	+10.3% (26.3 kg/day)					+Calf birth weights and 4% FCM	Kanjanapruthipong et al. (2010)
12% shredded beet pulp instead of corn silage	126 DIM ($n=4$) and 121 DIM ($n=4$)	Exceeded 68 for 19 h/day, 70 for 16 h/day, and 72 for 13 h/day	21		+6.23% (38.5 kg/day)	+8.62%				+Milk lactose content and neutral detergent insoluble CP, −Rumen pH*, rumen concentration of ammonia nitrogen and milk concentration of urea	Naderi et al. (2016)
TMR plus 27% crushed corn	248.4 DIM ($n=24$)	65.4 to 79.0 (76% of the days had average exceeded 72)	29		+6.19% (19.4 kg/day)		−14.0%	−0.51%			Gonzalez-Rivas et al. (2018)

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Table 3 The efficacy of dietary microbial additives for the alleviation of the detrimental effects of heat stress in dairy cows

Treatment	Animal information	THI value	Duration of exposure (days)	Feed intake	Milk yield (control value)	Milk protein	Milk fat	Rectal temperature	Respiration rate	Other indices	References
60 g/cow/day yeast culture	105 DIM ($n = 38$)	NA, temperature exceeded 32 °C (51 days)	84							+ ECM/feed intake	Schingoethe et al. (2004)
30 g/day yeast culture	20 to 140 DIM ($n = 723$)	Average above 72, maximum above 81	Approximately 120		+ 2.84% (42.2 kg/day)	+ 2.52%				+Milk lactose yield	Bruno et al. (2009)
240 g/day yeast culture	204 DIM ($n = 81$)	Average 76.6 (68 to 86)	90		+ 3.37% (20.8 kg/day)			− 0.77% at 14:30 h*		+Net energy balance and feed efficiency −Concentrations of milk urea nitrogen	Zhu et al. (2016)
15 g/day yeast culture	234 DIM ($n = 32$)	Average 72.7 (exceeded 68 was 92.2%)	35	− 4.43%				− 0.74% at 15:00 h	− 7.18% at 07:30 h, − 8.09% at 15:00 h	−Skin temperature	Dias et al. (2018)
0.25 g/kg of live yeast (10^{10} cfu/g) per feed intake	114 DIM ($n = 42$)	Average 69.4 (at morning) to 79.3 (at afternoon)	91	+ 2.49%	+ 4.13% (36.3 kg/day)		+ 7.08%			+ 4% FCM, milk lactose concentration, and feed efficiency	Moallem et al. (2009)
4 g/day live yeast (1.5×10^{10} cfu/g)	145 DIM ($n = 56$)	Average above 79	35				+ 5.30%			+Apparent digestibility of NDF	Dehghan-Banadaky et al. (2013)
10 g/day live yeast (25×10^{10} cfu live cells and 5×10^{10} cfu dead cells)	207 DIM ($n = 28$)	Average 71.8 (60.5 to 85.1, exceeded 68 was 75.6%)	70		+ 5.12% (25.4 kg/day)				− 14.3%	+ ECM, 4% FCM, and milk lactose secretion	Salvati et al. (2015)
1 g/kg zymosan	60 DIM ($n = 40$)	Average 74.8 to 86.2	28	+ 6.77%	+ 16.3% (29.4 kg/day)				− 8.99% at 18:30 h	+Serum Ig A, IL 2, and TNF α and hepatic Bcl 2/Bax-α ratio −Hepatic expression of HSP 70	Sun et al. (2018)
400 g/day live bacterial inoculants (4×10^9 cfu of a combination of *Lactobacillus acidophilus* and *Propionibacterium freudenreichii*)	120 DIM ($n = 60$)	NA, average temperature was 25.6 °C, with a low of 17.4 °C and a high of 35.1 °C	70		+ 7.57% (31.7 kg/day)	+ 6.90%				+ ECM, apparent digestibilities of CP and NDF	Boyd et al. (2011)

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Table 4 The efficacy of minerals for the alleviation of the detrimental effects of heat stress in dairy cows

Treatment	Animal information	THI value	Duration of exposure (days)	Feed intake	Milk yield (control value)	Milk protein	Milk fat	Rectal temperature	Respiration rate	Other indices	References
4 g/day chelated chromium yeast	120 to 130 DIM ($n = 160$)	Averaged 78.6	70	+ 8.59%	+ 11.3% (29.87 kg/day)						Al-Saiady et al. (2004)
6 mg/head/day dietary chromium	3 weeks prepartum through 12 weeks postpartum ($n = 120$)	Averaged 90 to 99	105	+ 10.5%	+ 11.9% (averaged 31.2 kg/day)					+Percentage of pregnant in the first 28 days of breeding, −body weight loss	Soltan (2010)
0.31 and 0.5 mg/kg selenium	Mid-lactation ($n = 40$)	Averaged 72.23 and maximum 79.09	140							+Glutathione peroxidase activity	Calamari et al. (2011)
278 mg/kg selenium yeast	$n = 24$	Averaged 75.9[a]	124				+ 2.46%			−Somatic cell count	Oltramari et al. (2014)
35 mg/kg Zn hydroxychloride plus 40 mg/kg Zn-Met complex	99.7 DIM ($n = 72$)	Average 77	84							+Gene expression of E-cadherin in mammary tissue*	Weng et al. (2018)

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Table 5 The efficacy of vitamins for the alleviation of the detrimental effects of heat stress in dairy cows

Treatment	Animal information	THI value	Duration of exposure (days)	Feed intake	Milk yield (control value)	Milk protein	Milk fat	Rectal temperature	Respiration rate	Other indices	References
100,000 IU/cow/day VA	Late gestation at 45 days before calving ($n = 30$)	59 to 78[a] (minimum temperature was 15.21 °C, maximum was 27.93 °C)	90							+Immune function and reproductive performance	De et al. (2014)
12 g/day rumen-protected niacin	145 DIM ($n = 12$)	Above 72 for 12 of 24 h/d	14					− 0.44%		−Vaginal temperature	Zimbelman et al. (2010)
12 g/day rumen-protected niacin	166 DIM ($n = 427$)	All above 68 and above 80 from 15 to 30 days	60							−Core body temperature and vaginal temperature	Zimbelman et al. (2013)
12 g/day rumen-protected niacin	95 DIM ($n = 24$)	From 70 to 80 for 24 h	21							+Water intake	Rungruang et al. (2014)
19 g/day rumen-protected niacin	53 DIM ($n = 137$) and 188 DIM ($n = 185$)	From 60.5 to 81.0 for 24 h	56						− 9.61% at 09:00 h	−Panting scores at 04:30, 09:00, and 20:30 h	Wrinkle et al. (2012)

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Table 6 The efficacy of metal ion buffer for the alleviation of the detrimental effects of heat stress in dairy cows

Treatment	Animal information	THI value	Duration of exposure (days)	Feed intake	Milk yield (control value)	Milk protein	Milk fat	Rectal temperature	Respiration rate	Other indices	References
2.2% NaCl	27 to 96 DIM ($n = 48$), 32 to 160 DIM ($n = 48$)	Above 78 during 34 to 50% of the period	67 and 42			+ 9.78%	+ 12.6%			+ 4% FCM, −milk production, 4% FCM, fat and protein in mild heat stress	Granzin and Gaughan (2002)
DCAD of 50 mEq/100 g of dry matter with 15 or 17% dietary CP	255 DIM ($n = 32$)	Averaged 81.3 (maximum) and 71.7 (minimum)	42		− 11.5% (31.4 kg/day) in 17% dietary CP		+ 11.1%			+Serum total AA concentrations*, essential AA concentrations and ratio of essential AA: total AA	Wildman et al. (2007a)
DCAD of 58 mEq/100 g of dry matter	188 DIM ($n = 42$)	Averaged 75.6 (70.3 to 80.8)	56							−Blood urea nitrogen	Wildman et al. (2007b)

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Table 7 The efficacy of plant extracts for the alleviation of the detrimental effects of heat stress in dairy cows

Treatment	Animal information	THI value	Duration ofexposure (days)	Feed intake	Milk yield (control value)	Milk protein	Milk fat	Rectal temperature	Respiration rate	Other indices	References
0.25 g/kg *Radix bupleuri* extract	75 DIM ($n = 40$)	Average 78.2 at 06:00 h, 79.7 at 14:00 h, and 78.3 at22:00 h	70	+ 9.09%	+ 8.23% (31.6 kg/day)	+ 8.99%	+ 10.8%	− 0.51%	− 8.12%		Pan et al. (2014)
50/100 g/day Chinese herbal medicine mixture comprised of 18 herbs	230 DIM ($n = 40$)	Average 74.5 (69.4 to 79)	42		+ 3.68/1.84% (16.3 kg/day) in day 14, + 10.7/13.2% (15.9 kg/day) in day 28, + 11.3/14.6% (15.1 kg/day) in day 42	+ 2.60/4.91% in day 14, + 4.96/6.71% in day 28, + 4.65/7.27% in day 42	+ 16.2/20.3% in day 28, + 19.0/17.6% in day 42			+Leukocyte and lymphocyte counts in peripheral blood, immune function, −apoptosis rate of the lymphocytes, serum Bax level, IL 1, Bax and Bak mRNA expression	Shan et al. (2018)
0.25% of *Ascophyllum nodosum* supplementation	138 DIM ($n = 32$)	Average 71.7 (63.5 to 81.7)[a]	56							−Core body temperature and rump skin temperature	Pompeu et al. (2011)
2.27 kg/day yeast combined with essential oil	187 DIM ($n = 36$)	Average 79 (72.1 to 84.0)	70							+Digestibility of ADF, −milk fat percentage	Boyd et al. (2011)
4 g/day citrus extracts	200 DIM ($n = 310$)	Approximately 60 to 70 for 9 h/day, approximately 70 to 80 for 15 h/day	56							+Comfort level and mammary health	Havlin and Robinson (2015)
15 g/day dietary betaine	101 DIM ($n = 32$)	Average 78.68	56	+ 2.63%	+ 5.27% (27.7 kg/day)	+ 4.35%				+Milk lactose, plasma cortisol, glutathione peroxidase, superoxide dismutase, and malondialdehyde levels	Zhang et al. (2014)
57 and 114 mg/kg betaine of body weight	101 DIM ($n = 24$)	Above 68 for 17 h/day	31							+Serum insulin and glucose levels, the expressions of HSP 27 and HSP70 in vitro at high dose of dietary betaine	Hall et al. (2016)

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Table 8 The efficacy of other anti-stress additives for the alleviation of the detrimental effects of heat stress in dairy cows

Treatment	Animal information	THI value	Duration of exposure (days)	Feed intake	Milk yield (control value)	Milk protein	Milk fat	Rectal temperature	Respiration rate	Other indices	References
450 mg/day monensin	89 DIM ($n = 34$)	Peaking at 82 for 2 h/day and gradually declined until 73	18	− 13.1%		− 4.56%	− 4.30%	+ 1.31% at 06:00 h, + 1.02% at 15:00 h, + 0.70% at 18:00 h	+ 14.3% at 06:00 h, + 9.98% at 18:00 h	+Feed efficiency and whole body glucose rate of appearance per unit of feed intake	Baumgard et al. (2011)
40 mg/kg γ-aminobutyric acid of dry matter	141 DIM ($n = 60$)	Average 78.4 at 07:00 h, 80.2 at 14:00 h, and 78.7 at 22:00 h	70	+ 7.08%	+ 6.39% (31.3 kg/day)	+ 4.58%	+ 10.1%	− 0.48% at 07:00 h, − 0.45% at 14:00 h, − 0.43% at 22:00 h		+Milk lactose	Cheng et al. (2014)
56 g/cow/day immunomodulatory in lactation	167 DIM ($n = 32$)	Average 74.2 (above 68 for 633 h within a total of 672 h)	56	+ 7.14%*						+Final body condition score and mean serum insulin concentrations*, −vaginal temperature mostly and mean somatic cell count	Leiva et al. (2017)
56 g/cow/day immunomodulatory in lactation	91 DIM ($n = 30$)	Above 68 for 17 h/day	21	+ 8.77%*			− 14.0%	− 0.57% at 14:00 h	− 7.28% at 14:00 h, − 15.1% at 18:00 h	+Plasma adrenocorticotropic hormone −Plasma cortisol during acute heat stress	Hall et al. (2018)
56 g/cow/day immunomodulatory during the dry period	The dry period and early in lactation ($n = 36$)	Above 68	Approximately 120		+ 12.8% (35.9 kg/day)				− 9.72%	+Body weight	Fabris et al. (2017)
56 g/cow/day immunomodulatory during the dry period	Calves ($n = 16$)	Average 77 (above 68 for the entire period)	Approximately 46					− 3.29%*		+Birth weight*, lymphocytes, neutrophil function, acute phase protein production, red blood cell counts, hematocrit, and hemoglobin	Skibiel et al. (2017)
Rumen-protected capsule consisted of minerals and vitamins	21 days before calving to 63 DIM ($n = 50$)	Average 71.43 and maximum 77.7	84		+ 4.81% (47.8 kg/day)*	+ 6.2%	+ 7.55%			+Solid non-fat percentage and cumulative pregnancy at fifth artificial insemination, −the milk linear somatic cell count score and days open (calving to conception)	Khorsandi et al. (2016)
0.13373 kg K_2SO_4, 0.02488 kg vitamin C, 0.021148 kg niacin, and 0.044784 kg γ-aminobutyric acid	70 DIM ($n = 30$)	Average 80 (above 75 for the entire period)	42	+ 7.08%	+ 18.0% (29.27 kg/day)	+ 18.9%				+ ECM, -HSP 70, adrenocorticotropic hormone, and lactate dehydrogenase in serum	Guo et al. (2017)

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IL-10 secretion was much lower in this study, suggesting that flaxseed supplementation can assist cows in their immune function by suppressing the secretion of Th2 cytokines in hot environments (Caroprese et al. 2009). To sum up, fat supplementations based on whole flaxseed would enhance immune responses of dairy cows exposed to heat stress.

Twenty-five mid-lactation Holstein dairy cows were randomly assigned to five groups (6.15, 6.36, 6.64, 6.95, and 7.36 MJ/kg) to determine the optimal dietary net energy for lactation under heat stress condition (Yan et al. 2016). The dietary net energy for lactation contents were adjusted by changing the proportions of calcium fatty acid and other feed ingredients. Results showed that feed intake decreased significantly with the elevated dietary net energy concentration from 6.15 to 7.36 MJ/kg ($P < 0.01$). Milk fat content, FCM, and milk energy were the highest ($P < 0.05$), and rectal temperature and respiration rate at 14:00 h were the lowest ($P < 0.01$) when the net energy concentration was 6.95 MJ/kg, while milk yield tended to increase quadratically to 6.95 MJ/kg group ($P = 0.08$). On the basis of regression equation, the optimal dietary net energy for lactation in mid-lactation dairy cows under heat stress might range from 6.83 to 6.92 MJ/kg (1.63 to 1.65 Mcal/kg) in this study.

Dietary fiber

Under conditions of heat stress, lactating dairy cows show markedly lower feed intake and higher energy maintenance requirements. A survival strategy to minimize the energy deficiency is to increase energy input by replacing the TMR roughage component with more readily digestible NDF of non-roughage origin. High-quality dietary fiber tends to improve feed digestibility and palatability and further increase feed intake.

Halachmi et al. (2004) evaluated the effects of feeding behavior and productivity in heat-stressed Holstein dairy cows when roughage NDF was replaced by soy hulls, which contain readily digestible dietary fiber. In the experimental group, the 16.5% corn silage component was replaced with soy hulls, reducing the roughage NDF from 18 to 12%, which was associated with a much higher in vitro OM and NDF digestibility ($P < 0.05$). Furthermore, feed intake per meal and meal duration were significantly higher ($P \leq 0.05$). These feeding behavior changes in heat-stressed dairy cows can effectively increase the feeding times and ensure that TMR stay longer in the feeding lane. The aforementioned changes also affected production performance, with milk yield being raised from 36.3 to 38.5 kg/day, and milk fat content, 4% FCM, and economically corrected milk yield being significantly higher in heat-stressed dairy cows that were fed high-quality dietary fiber ($P = 0.05$). In a subsequent study, cassava chips were used to partly replace grass silage in heat-stressed dairy cows (87.5% Holstein × 12.5% Sahiwal) for the 3 weeks before and the 5 weeks after calving, so that dietary NDF values were 34.2%, 32.1%, and 28.9%, respectively (Kanjanapruthipong et al. 2010). During the 3-week period before calving, feed intake gradually increased ($P < 0.01$), which was accompanied by a reduction in dietary NDF (10.2, 11.5, and 12.9 kg/day, respectively). After parturition, calf birth weights, milk yield, and 4% FCM were increased when the amount of roughage NDF was decreased ($P < 0.05$).

Beet pulp contains a high proportion of digestible NDF and pectic substances, implying that it may increase nutrient intake and thereby lead to an improvement of production performance in dairy cows. To evaluate these possibilities, shredded beet pulp was included in the diet of heat-stressed Holstein dairy cows in place of corn silage (Naderi et al. 2016). The dietary groups used in this study were as follows: 16% corn silage, 8% corn silage and 8% beet pulp, 4% corn silage and 12% beet pulp, and 16% beet pulp. Substituting beet pulp for corn silage increased the neutral detergent insoluble CP content of the diet, which tended to reduce mean rumen pH and ruminal acetate and butyrate concentrations, while it increased the ruminal propionate concentration. As a result, milk production increased linearly ($P = 0.03$) (38.5, 39.3, 40.9, and 39.6 kg/day, respectively). Overall, substituting beet pulp for corn silage at up to 12% in the diet of heat-stressed dairy cows resulted in an optimal combination of higher milk yield, milk protein, and milk lactose content (Naderi et al. 2016).

It is hypothesized that feeding slowly fermentable grains would reduce the amount of heat released from fermentation and digestion, which would ameliorate the physiological responses to heat stress and improve productivity in dairy cows during the summer. Gonzalez-Rivas et al. (2018) established that feeding TMR plus 27% crushed corn (a type of slowly fermentable grain) to Holstein-Friesian dairy cows ameliorated the heat stress responses, as indicated by the improved milk yield (19.4 versus 20.3 kg/day, $P < 0.01$) and lower rectal temperature (39.1 versus 38.9 °C, $P < 0.01$), although there was a decline in milk fat percentage ($P < 0.05$).

Dietary microbial additives

Dietary microbial additives, such as yeast and yeast cultures, have been widely used in dairy cows to increase feed intake and feed efficiency, improve rumen fermentation and digestibility, and ultimately increase milk production. Live yeast might scavenge oxygen in the rumen to increase feed efficiency. Yeast cultures might have growth factors produced by *Saccharomyces cerevisiae* that improve lactation performance. During summer, Holstein dairy cows were fed a diet containing 60 g/cow/day Diamond V XP yeast culture (Cedar Rapids, IA) (Schingoethe et al. 2004). As a result, feed efficiency defined as ECM/feed intake was improved by 7% with supplementing yeast culture in the diet of heat-stressed dairy cows ($P < 0.05$). However, the resulting change in milk production did not reach statistical significance in this study. Therefore, to further investigate the effect of feeding a yeast culture on heat stress, 723 Holstein dairy cows (20 to 140 DIM) were randomly assigned to a control diet or one containing 30 g/day of a *Saccharomyces cerevisiae* yeast culture during a period of heat stress (Bruno et al. 2009). The results indicated that supplementation with a yeast culture improved lactation performance in heat-stressed dairy cows, because milk yield was increased from 42.2 to 43.4 kg/day and milk protein and lactose yield were also higher ($P < 0.05$). Zhu et al. (2016) found that the addition of *Saccharomyces cerevisiae* fermentation products had dose-dependent positive effects. Rectal temperature at 14:30 h tended to decrease linearly ($P = 0.07$) in Holstein dairy cows supplemented with 120 or 240 g/day yeast culture compared with control cows, while milk yield increased linearly ($P = 0.02$) with higher levels of supplementation (20.8, 21.3, and 21.5 kg/day, respectively). Net energy balance increased linearly alongside, while milk urea nitrogen decreased linearly with higher levels of supplementation ($P < 0.01$). Therefore, feed efficiency (milk yield/feed intake) was the highest in dairy cows fed a diet supplemented with 240 g/day *Saccharomyces cerevisiae* fermentation products. Furthermore, the supplement also improved the feed efficiency and thermal comfort of dairy cows in late lactation during the summer. The results revealed that 15 g/day yeast culture supplementation (*Saccharomyces cerevisiae*) in heat-stressed Holstein dairy cows improved feed efficiency by reducing feed intake (19.4 versus 20.3 kg/day, $P < 0.05$) at similar milk yield and increased body heat loss ($P < 0.05$) by reducing rectal temperature (15:00 h), skin temperature, and respiration rate (07:30 h and 15:00 h) (Dias et al. 2018).

In addition to yeast culture, live yeast is also reported to be beneficial for dairy cows during the hot season. Moallem et al. (2009) reported that the feeding of 0.25 g/kg of live yeast (10^{10} cfu/g) per feed intake increased daily dry matter intake by 2.49% and increased milk yield from 36.3 to 37.8 kg/day ($P < 0.01$). The 4% FCM, milk lactose concentration, milk fat yield, and the feed efficiency of using dry matter to produce 4% FCM were also greater when live yeast was used to supplement the diet of Israeli-Holstein dairy cows ($P < 0.05$). Thus, it can be concluded that live yeast supplementation in heat-stressed dairy cows increases feed intake and consequently enhances their productivity and efficiency. Nevertheless, no prominent improvement in milk production and feed intake was observed in Holstein dairy cows fed with 4 g/day live yeast (1.5×10^{10} cfu/g) during hot summer conditions (Dehghan-Banadaky et al. 2013). Regardless, the higher milk fat percentage and apparent digestibility of NDF measured in this study ($P < 0.05$) suggests that feeding live yeast may increase dietary cell wall digestibility and improve milk composition (milk fat percentage) in heat-stressed dairy cows. According to a recent study, a diet containing 10 g/day live yeast (25×10^{10} cfu live cells and 5×10^{10} cfu dead cells) increased milk production from 25.4 to 26.7 kg/day and also increased ECM, 4% FCM, and milk lactose secretion of Holstein dairy cows under heat stress ($P \leq 0.05$) (Salvati et al. 2015). In addition, heat-stressed dairy cows consuming yeast supplements had consistently lower respiratory rate throughout the experiment ($P = 0.02$).

Zymosan, which is extracted from yeast, has protective effects against heat stress-induced immunosuppression and apoptosis in Holstein dairy cows (Sun et al. 2018). For usage, 1 g/kg zymosan mixed into the TMR for heat-stressed dairy cows increased feed intake (19.2 versus 20.5 kg/day, $P < 0.01$) and milk yield (from 29.4 to 34.2 kg/day, $P < 0.01$), decreased respiration rate at 18:30 h ($P < 0.01$), and also increased serum Ig A, IL-2, and TNF-α concentrations, as well as hepatic Bcl-2/Bax-α ratio, and decreased hepatic HSP70 expression ($P < 0.05$), suggesting the amelioration of immune and stress responses.

With the exception of yeast and yeast cultures, the addition of 400 g/day live bacterial inoculants (4×10^9 cfu of a combination of *Lactobacillus acidophilus* and *Propionibacterium freudenreichii*) improved milk yield (31.7 versus 34.1 kg/day, $P < 0.01$), milk protein yield, and ECM ($P < 0.05$) for Holstein dairy cows subjected to heat stress (Boyd et al. 2011). Furthermore, improvement in the apparent digestibility of CP and NDF ($P < 0.05$) was observed after heat-stressed dairy cows were fed this supplement.

Minerals

Minerals play an important role in maintaining normal physiological functions in animals. However, heat stress responses are thought to increase mineral loss as well as body fluid loss by excretion in dairy cows. Hence, limiting changes in body mineral balance by adding a trace mineral supplement to the diet might alleviate the adverse effects of such a loss in heat-stressed dairy cows.

Chromium (Cr) is widely used physiologically in a number of oxidation states. The addition of 4 g/day chelated Cr yeast to the diet increased feed intake and milk yield in heat-stressed Holstein dairy cows from 19.56 to 21.24 kg/day and 29.87 to 33.24 kg/day ($P < 0.01$), respectively (Al-Saiady et al. 2004). As further support for this phenomenon, 120 Holstein dairy cows were used to assess the effects of dietary Cr supplementation (6 mg/head/day) on their production and reproductive performance during heat stress (Soltan 2010). They were fed a Cr-supplemented diet for 15 weeks, commencing 3 weeks before calving, which resulted in better retention of body weight and improved feed intake, such that their energy balance deficit after calving was ameliorated. In addition, Cr supplementation markedly increased milk yield ($P \leq 0.05$), by 6.7%, 12.3%, and 16.5%, at 4, 8, and 12 weeks postpartum, respectively. A trend towards an improvement in reproductive performance was also observed, in the form of a higher rate of conception during the first 28 days of breeding.

Selenium (Se) reduces the adverse impact of heat stress on redox balance and metabolism, resulting in improved immune function, milk quality, and dairy cow health (Sejian et al. 2012). It is worth noting that significant decreases in plasma selenoprotein P, which contains most of the Se, occur in heat-stressed dairy cows (Min et al. 2016). Diet supplementation with Se can significantly raise plasma selenoprotein P and Se concentrations (Hill et al. 2012), which might be a potential mechanism to protect dairy cows against heat stress. Indeed, the metabolic responses to heat stress can be partially ameliorated by feeding dietary Se to Italian Friesian dairy cows, as evidenced by an increase in glutathione peroxidase activity in whole blood ($P < 0.01$), implying an improvement in the antioxidant system (Calamari et al. 2011). In a subsequent study, the effects of organic (278 mg/kg Se yeast) and inorganic (0.617 mg/kg sodium selenite) sources of Se in the diet of heat-stressed dairy cows (Holstein-Friesian and Brown Swiss) were evaluated with regard to milk production and quality, mammary gland health, and physiological indicators (Oltramari et al. 2014). Dairy cows that consumed organic Se produced a higher percentage of milk fat and had a lower somatic cell count ($P = 0.01$), suggesting that organic Se improves milk quality and mammary gland health during heat stress. Interestingly, although respiratory rate was lower in cows fed with the inorganic Se, hair coat temperature was lower in those fed with the organic Se ($P < 0.05$).

Zinc (Zn) is an essential micronutrient that has been suggested to improve the epithelial integrity of pigs under heat stress condition (Sanz Fernandez et al. 2014). According to a recent study, heat-stressed Holstein dairy cows fed with 35 mg/kg Zn hydroxychloride plus 40 mg/kg Zn-Met complex tended to show higher levels of E-cadherin expression in mammary tissue ($P = 0.09$), suggesting an improvement in the integrity of the mammary epithelium (Weng et al. 2018).

Vitamins

Vitamins function as enzyme cofactors (coenzymes), participate in a variety of metabolic pathways as catalysts, and are essential for the normal growth and development of a multicellular organism. It is possible that the addition of vitamin supplements to the diet of dairy cows might also contribute to the relief of the negative effects of heat stress.

In an in vitro experiment, oocytes incubated at 41.0 °C, to represent heat stress, were less likely to develop to the blastocyst stage and generated fewer nuclei (Lawrence et al. 2004). However, 5 μM retinol (vitamin A; VA) ameliorated the heat stress-induced defects in the development of bovine oocytes to the blastocyst stage. Following this up, pregnant dairy cows (Karan-Fries, Tharparkar × Holstein-Friesian) in late gestation that were kept in a semi-arid tropical environment were supplemented with 100,000 IU/cow/day VA, which caused significant increases in indicators of immune function, including the phagocytic activity of blood neutrophils and plasma IL-8 concentration ($P < 0.05$). In addition, milk somatic cell count was reduced and indices of reproductive performance (days open and the number of services required per conception) improved (De et al. 2014). As mentioned above, VA supplementation around the peripartum period could boost the immunity and improve the reproductive performance of heat-stressed dairy cows.

It has generally been assumed that heat stress causes oxidative stress, which is accompanied by a reduction in the plasma concentration of vitamin C (VC, an antioxidative vitamin). Padilla et al. (2006) demonstrated that heat stress was associated with a lower plasma VC concentration ($P = 0.04$) in lactating Holstein cows, implying that endogenous VC production may be insufficient. However, it remained unclear whether hypovitaminosis C adversely affected the productivity and health of lactating cows and thus whether dietary supplementation with VC may be beneficial for lactating cows in hot weather. More studies are necessary to investigate these possibilities.

Niacin (vitamin B_3) supplementation increases resistance to heat stress by inducing greater cutaneous vasodilatation and blood flow (Di et al. 1997). The greater cutaneous vasodilatation after niacin supplementation is caused by prostaglandin D produced by epidermal Langerhans cells, which acted on vascular endothelial prostaglandin D2 receptors (Maciejewski-Lenoir et al. 2006; Cheng et al. 2006). The increase in blood flow after niacin supplementation is associated with an increase in the sweating rate and evaporative heat loss from the skin surface (Di et al. 1997). When rumen-protected niacin was fed to Holstein cows (12 g/day), there was a small but detectable reduction in the rectal and vaginal temperature during heat stress compared with the control cows (Zimbelman et al. 2010). A subsequent study of a large number of Holstein dairy cows ($n = 427$) found that their core body and vaginal temperature were moderately lower when they ingested 12 g/day rumen-protected niacin ($P < 0.05$), whereas milk production and milk components were inconsistently affected over the whole trial period (Zimbelman et al. 2013). However, another study of Holstein dairy cows exposed to moderate heat stress in Arizona showed that 12 g/day rumen-protected niacin did not improve thermotolerance but increased water intake ($P < 0.03$) (Rungruang et al. 2014). To further evaluate the effects of niacin on the body temperature of dairy cows during heat stress, Wrinkle et al. (2012) conducted experiments in early (53 DIM, $n = 137$) and mid-lactation Holstein dairy cows (188 DIM, $n = 185$) and found that their respiration rate was lower at 09:00 h ($P = 0.02$) and their panting scores were lower at 04:30, 09:00, and 20:30 h ($P \leq 0.01$), after consumption of niacin. Interestingly, supplementation with rumen-protected niacin reduced the milk fat proportion in early lactation, but increased it in mid-lactation, dairy cows. These inconsistent effects on milk fat were analogous to those identified by Zimbelman et al. (2013). Differences in milk fat responses in early and mid-lactation cows are most likely triggered by reduced plasma triglyceride production. Although a reduction in plasma triglyceride production was also observed in the mid-lactation cows, they produced less milk but consumed a similar amount of dry matter. Dietary fat intake most likely compensated for the reduced de novo synthesis (Wrinkle et al. 2012).

Metal ion buffer

During heat stress, additional dietary Na^+ and K^+ (in the form of a metal ion buffer) are required to compensate for a reduction in feed intake (when animals fail to meet the minimum daily intake of Na^+ and K^+) and losses due to greater sweating in heat-stressed dairy cows (Sanchez et al. 1994). Another rationale for increasing dietary metal ion buffer is to increase urine Na^+ and K^+ excretion. Increases in these excretions are coordinated to increases in bicarbonate ion excretion caused by respiratory alkalosis when lactating cows are under heat stress (West et al. 1991).

Forty-eight Holstein-Friesian dairy cows (27–96 DIM) kept in a humid sub-tropical environment were allocated to one of four groups that were fed diet supplemented with NaCl at concentrations of 0, 1.1%, 2.2%, or 3.3% during summer in experiment one (Maximum THI was ≥ 78 during 50% of the experimental period) (Granzin and Gaughan 2002). These resulted in significantly higher 4% FCM, fat, and protein in cows fed with 2.2% NaCl than in the other groups ($P < 0.05$). However, counter-intuitively, milk yield, 4% FCM, fat, and protein were lower ($P < 0.05$) in cows (32–160 DIM, $n = 48$) fed with 2.2% NaCl in experiment two (Maximum THI was ≥ 78 during 34% of the experimental period). Thus, the success of NaCl supplementation may depend on the degree of heat stress being experienced. The beneficial effect might be more noticeable in warm, humid conditions (maximum THI was ≥ 78 during 50% of the experimental period) than in milder conditions (maximum THI was ≥ 78 during 34% of the experimental period).

Dietary cation-anion difference (DCAD), calculated using Na^+, K^+, and Cl^- concentrations, has a significant effect on productivity and health status by influencing acid base balance (Hu and Murphy 2004). Wildman et al. (2007a) reported that a DCAD of 50 mEq/100 g of dry matter in the diet of Holstein dairy cows during heat stress would improve AA availability for protein synthesis (serum total AA concentrations ($P < 0.1$), essential AA concentrations, and the ratio of essential AA: total AA ($P < 0.05$) were all higher) because additional AA becomes available that would otherwise be used for the maintenance of acid base balance. A higher DCAD also reduced blood urea nitrogen in heat-stressed Holstein dairy cows ($P < 0.01$), suggesting the possibility that it enhanced microbial ammonia utilization for protein synthesis and ruminal N metabolism or utilization (Wildman et al. 2007b).

Plant extracts

In recent years, significant research has focused on the use of dietary plant extracts that have nutritional and medicinal value to improve dairy cow production. Particular plant extracts may have the potential to ameliorate the negative effects of heat stress in dairy cows.

Radix bupleuri is widely known as an oriental folk medicine, to which a number of pharmacological effects have been ascribed, including diaphoretic, antipyretic, and immunomodulatory effects (Ashour and Wink 2011). Pan et al. (2014) assessed the effects of *Radix bupleuri* extract supplementation (0, 0.25, 0.5, or 1.0 g/kg of the basal diet) on body temperature and production variables in heat-stressed Holstein dairy cows. During the experiment, average respiratory rate (65.6, 60.3, and 67.4 versus 71.4 breaths/min) and rectal temperature (39.1, 39.0, and 39.1 versus 39.3 °C) were significantly lower ($P < 0.01$), and feed intake (22.8, 21.6, and 22.1 versus 20.9 kg/day, $P < 0.05$) and milk production (34.2, 33.4, and 32.4 versus 31.6 kg/day, $P < 0.01$) were significantly higher, milk protein and fat yield were also improved ($P < 0.05$) at doses of 0.25, 0.50, and 1.0 g/kg. Taken together, the addition of just 0.25 g/kg *Radix bupleuri* extract to the diet could maximum mitigate the negative effects of heat stress on body temperature and production in dairy cows. The significant decrease in body temperature following *Radix bupleuri* extract supplementation may be due to the increasing of vasodilation, which facilitates heat transfer to the skin via evaporation. The improvement in milk production was probably not only due to the increased feed intake, but also to the direct mitigating effect of heat stress responses (decreased body temperature), which provides more energy for production rather than for homeothermy (Pan et al. 2014).

A fermented mixture of Chinese herbal medicines comprising 18 herbs (including *Radix rehmanniae preparata*, *Fructus crataegi*, *Semen raphani*, *Radix et rhizoma rhei*, *Unguis sus domestica*, *Radix astragali*, *Radix Codonopsis*, *Radix angelicae sinensis*, *Rhizoma atractylodis*, *Pericarpium citri reticulatae*, *Radix glycyrrhizae*, *Rhizoma chuanxiong*, *Herba cistanches*, *Radix ophiopogonis*, *Radix paeoniae alba*, *Cacumen platycladi*, *Artemisia capillaris thumb*, and *Fructus gardeniae*) had also been tested for its effects on productivity and immune function in heat-stressed Holstein dairy cows (Shan et al. 2018). The data clearly confirmed that milk yield (16.3, 16.9, and 16.6 kg/day, respectively, in day 14 of the trial, 15.9, 17.6, and 18.0 kg/day, respectively, in day 28 of the trial, 15.1, 16.8, and 17.3 kg/day, respectively, in day 42 of the trial), milk fat, and protein content were greater ($P < 0.05$) in 50 or 100 g/day of the mixture, when compared with the group that did not receive the supplement. In addition, leukocyte and lymphocyte counts in peripheral blood were higher and the lymphocyte apoptosis rate was lower ($P < 0.05$). Serological and gene expression effects were also observed, suggesting that the supplement could improve immune function in heat-stressed dairy cows: serum concentrations of Ig G, IL-2, IL-6, and Bcl-2 and mRNA expression levels of IL-2, Bcl-2, and Bcl-xl were higher ($P < 0.05$), while serum Bax and mRNA expression levels of IL-1, Bax and Bak were lower in the 100 g/day group ($P < 0.05$). Moreover, some of these measurements were also significantly affected by adding 50 g/day to the diet. The fermented mixture of Chinese herbal medicines promoted milk production and immune function in heat-stressed dairy cows.

A new product derived from *Ascophyllum nodosum* had also been evaluated for its effectiveness in alleviating heat stress in Holstein dairy cows (Pompeu et al. 2011). The inclusion of 0.25% *Ascophyllum nodosum* in the diet had no effect on milk production and reduced feed intake only in some instances. However, the increases in core body and rump skin temperature were less ($P < 0.05$) than in control animals as the ambient temperature increased. Boyd et al. (2011) investigated the effect of a combination of yeast and another plant extract, consisting of essential oils derived from *capsicum*, *cinnamaldehyde*, and *eugenol*, on milk production and the apparent production efficiency of Holstein dairy cows during a hot summer. Although they did not identify any differences in body temperature and production parameters between the treatment groups, the digestibility of ADF was improved ($P < 0.01$), despite a reduction in milk fat percentage ($P < 0.01$). Thus, additional researches are needed to examine the potential role of *Ascophyllum nodosum* and essential oil supplementation in heat-stressed dairy cows.

Citrus extracts contain a large amount of VC and have beneficial effects on rumen fermentation (Benchaar and Calsamiglia 2008). As described above, dairy cows demonstrated VC deficiency in their plasma during heat stress (Padilla et al. 2006). Therefore, the feeding of supplemental citrus extracts might be beneficial in replacing the depleted VC and improving production in heat-stressed dairy cows. Havlin and Robinson (2015) reported that inclusion of citrus extracts at 4 g/cow/day in the diet led to a higher proportion of Holstein cows lying down rather than standing ($P < 0.01$), suggesting an improvement in comfort level. In addition, this level of supplementation improved mammary health, as indicated by lower somatic cell count ($P < 0.05$).

Methionine is frequently one of the most limiting AAs in dairy cows, which is of benefit for milk protein synthesis (Rulquin et al. 2006). In addition, the dietary supply of betaine affects the methionine requirements of dairy cows (Davidson et al. 2008). Heat stress potentially results in a decline in milk protein, and with these facts in mind, Zhang et al. (2014) determined whether supplying betaine to Holstein dairy cows could overcome the effects of heat stress. Feeding 15 g/day dietary betaine to heat-stressed dairy cows for 8 weeks increased feed intake from 22.76 to 23.36 kg/day, milk production from 27.70 to 29.16 kg/day, and also increased milk lactose and milk protein ($P < 0.05$). Moreover, antioxidant capacity was improved based on the increasing of plasma cortisol, glutathione peroxidase, superoxide dismutase, and malondialdehyde levels ($P < 0.05$). However, another study reported slightly lower efficacy of dietary betaine supplementation (Hall et al. 2016). No differences were found between cows that had consumed betaine supplements (57 or 114 mg/kg betaine) and the control group with regard to milk production and composition during heat stress. Nevertheless, serum insulin and glucose levels were higher ($P < 0.05$) in heat-stressed dairy cows, the HSP 27 and HSP 70 expression were higher ($P < 0.05$) in bovine mammary epithelial cells treated with a high dose of dietary betaine in vitro. The overexpression of HSP 27 and HSP 70 in bovine mammary epithelial cells would be beneficial to protect against hyperthermia in heat-stressed dairy cows (Min et al. 2015).

Other anti-stress additives

Monensin is a well-described rumen modifier, which can augment the rumen production of propionate, the predominant gluconeogenic precursor in dairy cows (Ipharraguerre and Clark 2003; Duffield et al. 2008). Monensin increases feed efficiency in lactating ruminants based on the increasing of carbon conservation during fermentation (Schelling 1984). Based on these results, Baumgard et al. (2011) hypothesized that monensin supplementation in Holstein dairy cows would increase gluconeogenesis and glucose homeostatic parameters, which would ameliorate heat stress responses. Actually, dairy cows fed with 450 mg/cow/day monensin consumed less feed intake (1.59 kg/day), which led to a higher feed efficiency (7%), and had a higher whole body glucose rate of appearance per unit of feed intake (10%) ($P < 0.01$), but produced the same amount of milk. It is worth noting that the negative effects of monensin supplementation were increased in rectal temperature (at 06:00 h, 15:00 h, and 18:00 h) and respiration rate (at 06:00 h and 18:00 h) and decreased in milk protein and fat levels in heat-stressed dairy cows ($P < 0.05$). Overall, feeding monensin appears to be of limited value and is associated with some adverse effects in heat-stressed dairy cows.

γ-Aminobutyric acid is an inhibitory neurotransmitter that regulates body temperature (Quéva et al. 2003) and inhibits heat production (Dimicco and Zaretsky 2007). γ-Aminobutyric acid directly inhibits cold-sensitive neurons, central or systemic administration of γ-aminobutyric acid and its agonists result in hypothermia, whereas its antagonists produce hyperthermia (Sanna et al. 1995; Ishiwata et al. 2005). A clinical research has indicated that a single oral administration of γ-aminobutyric acid induced a decrease in body core temperature and total heat production in a hot environment in humans (Miyazawa 2012). In addition, γ-aminobutyric acid would stimulate feed intake (Wang et al. 2013), the injecting of γ-aminobutyric acid agonist into the lateral ventricles increased the feed intake of satiated ruminant (Seoane et al. 1984). It is co-expressed with the neuropeptide Y to promote feed intake (Pu et al. 1999) and plays a positive effect on gastric acid secretion (Piqueras and Martinez 2004). As aforementioned, γ-aminobutyric acid supplementation might improve feed intake and reduce heat production, which would result in better performance in heat-stressed dairy cows. An experiment was performed to assess the effects of rumen-protected γ-aminobutyric acid (0, 40, 80, or 120 mg/kg of dry matter) on productivity in heat-stressed Holstein dairy cows (Cheng et al. 2014). The results showed that γ-aminobutyric acid supplementation dramatically lowered rectal temperature at 07:00, 14:00, and 22:00 h and resulted in higher feed intake and milk production. It also improved milk composition as indicators by milk fat yield, milk protein, and lactose concentrations ($P < 0.05$). The peak values were reached at a dose of 40 mg/kg (Cheng et al. 2014). Thus, feeding γ-aminobutyric acid to dairy cows during heat stress could alleviate heat stress by reducing rectal temperature and improve feed intake, milk production, and milk composition.

Several studies have been conducted regarding the thermoregulatory abilities of the immunomodulatory feed ingredient Omnigen-AF (consisting of a mixture of silicon dioxide, calcium aluminosilicate, sodium aluminosilicate, brewers dehydrated yeast, mineral oil, calcium carbonate, rice hulls, niacin supplement, biotin, D-calcium pantothenate, vitamin B_{12} supplement, choline chloride, thiamine mononitrate, pyridoxine hydrochloride, riboflavin-5-phosphate, and folic acid) in heat-stressed dairy cows (Hall et al. 2018; Skibiel et al. 2017; Leiva et al. 2017; Fabris et al. 2017). Before the experiment proper started, the on-dairy phase of Omnigen-AF supplementation or control diet was conducted to demonstrate differences in markers of homeostatic signals between these two groups (Wu et al. 2017). Thirty-two lactating Holstein × Gir cows were assigned to either receive ($n = 16$) this supplement at 56 g/cow daily or not ($n = 16$) under heat stress conditions (Leiva et al. 2017). Dairy cows supplemented with Omnigen-AF showed reduced vaginal temperature throughout most of the experiment ($P < 0.05$) and showed a lower mean somatic cell count ($P = 0.01$). Mean feed intake (by 7%, $P = 0.1$), final body condition score (by 11%, $P = 0.01$), and mean serum insulin concentrations ($P < 0.1$) were also increased after Omnigen-AF supplementation. In the other studies, a treatment × environment interaction was identified in lactating Holstein cows fed Omnigen-AF, which showed a lower rectal temperature (at 14:00 h, $P < 0.01$) and respiratory rate (at 14:00 h and 18:00 h, $P \leq 0.05$) and higher feed intake (by 8.77%, $P < 0.1$) than in the control group during heat stress (Hall et al. 2018). Furthermore, this study revealed that feeding Omnigen-AF reduced plasma cortisol during acute heat stress and increased basal plasma adrenocorticotropic hormone levels, perhaps indicating that Omnigen-AF altered pituitary or adrenal responses to factors controlling cortisol secretion and regulated the hypothalamic-pituitary-adrenal axis (Hall et al. 2018). Supplementation with this immunomodulatory substance during the dry period might also be able to overcome the negative effects of heat stress and improve subsequent performance in cows (Fabris et al. 2017). Cows given 56 g/day Omnigen-AF had higher body weight during the dry period than the control group ($P < 0.01$) and subsequently produced more milk (35.9 versus 40.5 kg/day, $P < 0.05$). The decrease of respiration rate ($P < 0.01$) also happened in this process. Simultaneously, the addition of Omnigen-AF to a maternal diet during late gestation would improve postnatal calf growth and immune competence under heat stress conditions (Skibiel et al. 2017). Calves born from Omnigen-AF-supplemented Holstein cows tended to have lower rectal temperature and be heavier at birth than those born from non-supplemented dams ($P \leq 0.1$). In addition, they possessed a more responsive immune system through stimulated lymphocytes at birth and increased neutrophil function, acute phase protein production, red blood cell counts, hematocrit, and hemoglobin. Together, these results suggest that adding Omnigen-AF to the diet of heat-stressed cows during late gestation would improve postnatal calf growth and immune competence (Skibiel et al. 2017).

A sustained-release multi-trace element and vitamin was estimated for its efficacy in alleviating the negative effects of heat stress on lactation and reproductive performance of Holstein dairy cows (Khorsandi et al. 2016). The sustained-release multi-trace element and vitamin supplement consisted of minerals (16.2 g Cu, 0.251 g Se, 0.236 g Co, 0.497 g I, 8.28 g Mn, and 13.32 g Zn) and vitamins (545.6×10^3 IU of vitamin A, 109.1×10^6 IU of vitamin D_3, and 1092 IU of vitamin E). The results revealed that dairy cows supplemented with this supplement had higher milk fat, protein, and solid non-fat percentage ($P < 0.05$), and that it tended to result in higher milk yield (47.8 versus 50.1 kg/day, $P = 0.07$) than controls. The supplementation significantly reduced the milk linear somatic cell count ($P = 0.01$), suggesting a positive impact on udder health. The number of days open (calving to conception) was shortened and the cumulative incidence of pregnancy at the fifth artificial insemination was higher in supplemented cows. Thus, supererogatory supplementation with minerals and vitamins had positive effects on production and reproductive performance in heat-stressed dairy cows. Another sustained-release supplement containing niacin, K_2SO_4, vitamin C, and γ-aminobutyric acid was fed to heat-stressed dairy cows (Guo et al. 2017). During summer, 30 dairy cows were fed a diet with or without 0.13373 kg K_2SO_4, 0.02488 kg vitamin C, 0.021148 kg niacin, and 0.044784 kg γ-aminobutyric acid per cow. As a result, feed intake (20.34 versus 21.78 kg/day), milk yield (29.27 versus 34.53 kg/day), milk protein yield, and ECM were higher in the supplemented group than in the control group ($P < 0.05$). For the serological indicators, the supplemented group had lower levels of HSP 70, adrenocorticotropic hormone, and lactate dehydrogenase than the control group. Thus, this mixture may have the potential to ameliorate heat stress-induced impairments in lactation performance and other physiological variables in dairy cows.

Conclusions

We have summarized the effects of eight types of nutritional strategies for heat-stressed dairy cows, which are listed in Tables 1, 2, 3, 4, 5, 6, 7, and 8. The tables show the treatment (dosage and usage), animal information (lactation stage and number of dairy cows), THI value (level of heat stress), duration of exposure, the changes of feed intake and milk yield (production performance), the changes of milk protein and milk fat (milk quality), the changes of rectal temperature and respiration rate (body temperature), other indices, and reference resources.

In general, the most striking predicament of heat-stressed dairy cows is the pronounced reduction in milk production. Concerning this issue, a number of nutritional strategies summarized in this paper are capable of significantly increasing milk production (by > 5%) in heat-stressed dairy cows: 3% unprotected fat, 1.5% saturated fatty acid, 200 g/cow/day hydrogenated fish fat, replacement of 16.5% corn silage with soy hulls, inclusion of 28.9% dietary NDF by the addition of cassava chips, the use of 12% shredded beet pulp instead of corn silage, the feeding of TMR plus 27% crushed corn, 10 g/day live yeast (25×10^{10} cfu live cells and 5×10^{10} cfu dead cells), 1 g/kg zymosan, 400 g/day live bacterial inoculants (4×10^9 cfu of a combination of *Lactobacillus acidophilus* and *Propionibacterium freudenreichii*), 4 g/day chelated Cr yeast, 6 mg/head/day dietary Cr, 0.25 g/kg *Radix bupleuri* extract, 100 g/day of a Chinese herbal medicine mixture containing 18 herbs, 15 g/day dietary betaine, 40 mg/kg γ-aminobutyric acid, 56 g/cow daily immunomodulatory substance during the dry period, or a mixture of 0.13373 kg K_2SO_4, 0.02488 kg VC, 0.021148 kg niacin, and 0.044784 kg γ-aminobutyric acid.

It is hypothesized that supplementation with vitamins or metal ion buffer may play an auxiliary function in heat-stressed dairy cows, such as the amelioration of defects in immune function, reproductive performance, heat dissipation, water intake, energy balance, mammary health, and N utilization. In summary, eight types of nutritional strategies consisting of a total of 49 kinds of dietary interventions should provide clues or perspectives for the selection of an appropriate methodology for particular dairy farms to mitigate heat stress in their stock.

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Compliance with ethical standards

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

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