Veterinary World, EISSN: 2231-0916
Available at www.veterinaryworld.org/Vol.6/Dec-2013/10.pdf

REVIEW ARTICLE
Open Access

Impact of heat stress on rumen functions

Brijesh Yadav[1], Gynendra Singh[2], A. K. Verma[3], N. Dutta[3] and V. Sejian[4]

1. Department of Physiology, College of Veterinary Science and Animal Husbandry, Veterinary University, Mathura, Uttar Pradesh-281001, India; 2. Division of Physiology and Climatology, Indian Veterinary Research Institute, Izatnagar, Bareilly-243001, India; 3. Division of Animal Nutrition, Indian Veterinary Research Institute, Izatnagar, Bareilly-243001, India; 4. National Institute of Nutrition and Physiology, Bangalore, Karnataka, India
Corresponding author: Brijesh Yadav, email- drbrijvet@gmail.com
Received: 04-10-2013, Revised: 07-11-2013, Accepted: 08-11-2013, Published online: 20-12-2013

doi: 10.14202/vetworld.2013.992-996
How to cite this article: Yadav B, Singh G, Verma AK, Dutta N and Sejian V (2013) Impact of heat stress on rumen functions, *Veterinary World* 6(12): 992-996.

Abstract

The livestock sector is evolving in response to rapidly increasing demand for livestock products. Ruminant population is the main driver of the growth of the livestock sector besides pig and poultry. The rise in environment temperature due to climate change alters the basic physiology of rumen which negatively affects production. Dry matter intake begins to decline in an adaptive response to heat stress. Increased environmental temperature reduces the gut motility, rumination, ruminal contractions and depresses appetite in ruminants. Heat stress reduces the total production of volatile fatty acid (VFA) with individual variation and also results in changes in ruminal pH. Passage rate and retention time of digesta is also influenced by rise in ambient temperature and thus affects digestibility. The change in microbiota due to heat stress may change the fermentation pattern in the rumen resulting in variation in digestibility, VFA production and also methane emission.

Keywords: heat stress, ruminants, digestibility, methane emission

Introduction

The livestock sector globally is highly progressive. In developing countries, it is evolving because of rapidly increasing demand for livestock products, however in developed countries; demand for livestock products is stagnating [1]. Currently, livestock is one of the fastest growing sector among agriculture in developing countries [1]. Its share to agricultural GDP is 33% and is quickly increasing [1]. This growth is driven by the rapidly increasing demand for livestock products and this demand is being driven by population explosion, urbanization and increasing per capita income in developing countries [2]. India possesses the largest livestock ruminant population in the world (520.6 million), and accounts for the largest number of cattle (world share 16.1%), buffaloes (57.9%), second largest number of goats (16.7%) and third highest number of sheep (5.7%) in the world [3]. Climate change projections for India suggest that temperature is expected to increase between 2.3 and 4.8°C because of doubling of carbon dioxide concentration in the atmosphere [4] and further this increase in temperature is expected for all the months of the year. Rise in the environmental temperature may impair production through reduced growth, meat, milk and egg, impaired reproductive performance, imbalanced biochemical and physiological process of metabolism and immune response [5]. The rise in environment temperature alters the basic physiology of rumen which negatively affects the nutrient energy balance [6]. Heat stress reduces the dry matter intake, decreases ruminal motility and contraction, changes the fermentation pattern and volatile fatty acid production, affects the digestibility and nutrient utilization, and thus impairs productivity. This review is aimed to give an insight into alterations in rumen function in response to increase in environmental temperature.

Copyright: The authors. This article is an open access article licensed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/2.0) which permits unrestricted use, distribution and reproduction in any medium, provided the work is properly cited.

Effect of heat stress on feed intake

Feed intake in lactating cows begins to decline at ambient temperatures of 25–26°C and reduces more rapidly above 30°C [8]. At 40°C, the dietary intake may decline by as much as 40% [7]. Increased heat load decreases nutrient uptake in almost all species and in case of cattle, the nutrient uptake decreases upto about 30% of dry matter intake [8,9]. Heat stress leads to the rostral cooling center of the hypothalamus to stimulate the medial satiety center which inhibits the lateral appetite center, and thus reduced dietary intake and consequently lower milk production [10]. Increasing environmental temperature and rising rectal temperature above critical thresholds are related to decrease in the dry matter intake (DMI) [10]. A decrease in the dry matter intake in dairy cattle was found on exposure to heat stress [11]. High environmental temperature reported to reduce feed intake in Friesian heifers [12]. At 28°C, dry matter intake was similar to that at 20°C; whereas, at 33°C dry matter intake was lower by about 9% as compared to DM intake at 20°C [13] in Holstein heifers. Food intake by the Alentejana and Limousine breeds decreased by 10% and 9.6% respectively, at 36.0±1°C and 45±1% humidity; whereas, in Mertolenga and Frisian animals feed intake did not change [14] at similar environmental conditions which indicates variation in feed intake in response to heat stress also depends upon breed. A decrease in DM intake in crossbred cattle was reported at 35 and 40°C thermal exposure as compared to thermal exposure at 25 and 30°C [15]. A reduction in DMI in Jersey cows was also reported when minimum temperature humidity index (THI) exceeded 56 and continued until THI reached 72 [16]. During heat stress, DMI was reduced in the lactating goats because of metabolic rate and more heat production [17]. Daily DMI of cooled animals was higher while water intakes were lower than those of noncooled animals where the maximum ambient temperature and relative humidity for the non-cooled group were 33°C and 61%, with the corresponding values for the cooled barn being 28°C and 84%, respectively [18]. The concentrate intake during cool comfort, hot-dry and hot-humid exposures did not change in buffalo calves; whereas, wheat straw intake decreased significantly by 29.65% and 30.09% during hot-dry and hot-humid exposures, respectively [19].

Effect of heat stress on rumination and rumen motility

Alteration of the dynamic characteristics of digestion is recognized as a possible mechanism through which heat stress can affect the nutrition of animals [20]. Increased environmental temperature reduces the rumination time [21] and depresses appetite [22] by having a direct negative effect on appetite center of the hypothalamus [23]. Available data suggest that rumination is depressed during dehydration and heat stress [21,24]. Also, blood flow to rumen epithelium is depressed during heat stress and reticular motility and rumination is decreased whereas, the volume of digesta in the rumen of beef cows, Bedouin goats [25], riverine buffalo [19] and Egyptian buffalo [26] increased. Higher concentrations of lactic acid and lower ruminal pH was observed in heat-stressed cattle, which may imply that a higher lactic acid concentration and lower ruminal pH might be involved in inhibiting rumen motility during heat stress [27]. There is no clarity on the involvement of gastrointestinal hormones and peptidergic neurons in mediating the effect of temperature on gastrointestinal motility. Some of the gastrointestinal hormones that influence motility also affect feed intake in ruminants [28]. The large number of biologically active compounds produced in the gut that may influence motility and passage makes this area very complex [29].

Effect of heat stress on volatile fatty acid (VFA) production and ruminal pH

Heat stress reduced the total production of volatile fatty acid [13,30,31]. The ratio of acetate to propionate decreased during heat stress and more specifically, the molar concentration of acetate decreased whereas propionate and butyrate concentration increased nonsignificantly ($p>0.05$) [13]. The effects of ruminal temperature on a dual-flow, continuous-culture system on in vitro fermentation characteristics was investigated and found that high ruminal temperature decreased total VFA concentration as compared with the normal ruminal temperature however; ruminal temperature did not affect molar proportion of VFA [32,33]. Decrease in molar concentration of volatile fatty acid during heat stress was mainly attributed to decrease in roughage intake [30] and variation in fermentation pattern due to changes in microbial population [34]. High ruminal temperature increased culture pH from 5.73 to 5.82 on averages; whereas, an increase in ruminal pH form 5.82 to 6.03 was reported during heat stress in lactating dairy cattle [16].

Effect of heat stress on nutrient digestibility

Some authors reported an increase in diet digestibility in cattle exposed to hot environments [13, 35-37]. In contrast, negative or no relationships between high ambient temperatures and diet digestibility have been reported in dairy cattle [35,38,39] and small ruminants [25]. The positive effects of high environmental temperature on the digestibility of feed is attributed to either the reduction in the passage rate of digesta [21,22,35,40], the changes in feed composition [12,22,35] or the reduction in DMI [12,35]. The DM digestibility in cattle was reported to increase in a hot environment when given forage-based diets [35]. The DM digestibility in Ayrshire cattle was significantly higher at 33°C than at 20°C with moderate quality diet, but was similar at 33°C and at 20°C with a high-quality diet [38].

The digestibility patterns of different feed components during hot dry and hot humid thermal exposures were studied [41] and found that the digestibility of CP, OM, NDF, ADF and NFCD increased during both type of exposures as compared to cool comfort whereas the digestibility of NDF, ADF and NFCD was lower during hot-humid exposure compared to hot-dry. High ruminal temperature did not affect DM and NDF digestibility whereas it tended to decrease OM digestibility as compared with the normal ruminal temperature (66.6 vs. 67.4%) [33]. The digestibility patterns at different thermal exposures were investigated [15] and reported that digestibility at 25 and 30°C did not change whereas digestibility increased at 35°C and then decreased at 40°C thermal exposure. The decrease in nutrient digestibility at 40^0C could be attributed to change in rumen environment (pH, rumen temperature, rumen motility, rumen flora and fauna) due to higher intensity of thermal stress [15]. Higher concentrations of lactic acid and lower ruminal pH were observed in heat-stressed cattle, which may imply that a high lactic acid concentration and lower ruminal pH might be involved in inhibiting rumen motility during heat stress [27].

Variation in the rate at which feed passes through the digestive tract is a major factor in the positive relationship between environmental temperature and digestibility [40]. The increase in diet digestibility in heat-stressed ruminants was explained by increased mean retention time in the whole gastrointestinal tract

[42]. Slower passage rate and longer mean retention time of digesta have been described in dairy cows [43], buffalo [19] and heifers [13] maintained under hot environments. A significant increase in DM digestibility was reported at 33°C as compared to 20°C in Holstein heifers [13]. An improvement of diet digestibility during a short time exposure of Holstein heifers to hot conditions was reported; however, it was found to be reduced when the exposure to hot conditions was prolonged [44]. In the same study, changes in diet digestibility observed under hot environments were not related to DMI and passage rate of digesta. Although a positive relationship between digestibility, especially of fiber components, and ambient temperatures has been reported [45], high temperatures had little effect on diet digestibility in dairy cows [46] and goats [45]. Digestibility coefficients of dry matter, organic matter, neutral detergent fiber and acid detergent fiber in sheep were not affected by short exposure (10 days) to a THI of 82, but were lower after prolonged exposure to heat [39]. Dilution of rumen content due to higher water intake, reduction in rumen bacteria activity, decline in rumen motility and reduction of saliva production may be responsible for digestibility changes when animals are chronically exposed to extreme temperature humidity index [47]. In the later study [47] it was suggested that ewes chronically exposed to heat showed lower diet digestibility and had lower pH and cellulolytic and amylolytic bacteria concentrations, slower digesta passage rate and lower osmolarity of rumen content, indicating a possible impairment of bacterial activity and high dilution of rumen fluid. The negative effect of such a depression of rumen bacteria activity on diet digestibility might have overcome the positive effects caused by the decline in DMI and digesta outflow rate, resulting in a net reduction of diet digestibility in chronically heat-stressed ewes. The microbiota composition was significantly different at elevated environmental temperatures and humidity [31]. In a recent study, four Holstein heifers were exposed at three temperatures (20 °C, 28 °C and 33 °C) in a climatic chamber for two weeks and found that the relative populations of the *Clostridium coccoides– Eubacterium rectal* group and the genus *Streptococcus* increased and that of the genus *Fibrobacter* decreased in response to increasing temperature [34]. The change in microbiota due to thermal exposure may change the fermentation pattern in the rumen resulting in variation in digestibility of different feed components and also composition of fermentation products. Other than alteration of bacterial activity, the different responses in digestibility when ewes were exposed to thermal exposure for different times might be related to the changes of ruminal and intestinal absorption of nutrients that can occur in animals chronically exposed to high ambient temperature [35].

Effect of heat stress on methane production in rumen

Methanogens belong to a separate domain archaea in the kingdom of *Euryarchaeota* and are found in a wide range of other anaerobic environments [48]. Through a series of biochemical reduction of carbon dioxide (CO_2) with hydrogen (H_2), and some methanogens use acetate and methyl group-containing compounds to produce methane (CH_4) (methanogenesis). Usually, CH_4 is produced by two types of methanogens, the slow-growing methanogens (regeneration time about 130 h) that produces CH_4 from acetate (*Methanosarcina*) and fast growing methanogens (generation time 4–12 h) that reduce CO_2 with H_2. In the rumen, methanogenesis occurs mostly by the fast-growing methanogens as ruminal retention time is too short to permit establishment of the slow growing species. Methane emissions in ruminants also account for a 2% to 12% of gross energy loss of feeds depending upon the type of diets [49]. Methane is one of the by-products formed from the degradation of carbohydrates during enteric fermentation in feed and anaerobic digestion in manure. The rumen is the most important part of methane production in ruminants like cattle, while methane is mainly produced in the large intestines for monogastric animals like pigs. Enteric fermentation accounts for about 80% of methane in dairy cow [50]. Methane production from enteric fermentation is a function of the rate of organic matter fermentation, the type of volatile fatty acid produced and the efficiency of microbial biosynthesis [51,52]. The major factors that affect methane production in the ruminants are pH, volatile fatty acids, diet, feeding strategy, animal species and environmental stresses. The optimum pH for methane production is 7.0–7.2, but the gas production can occur in the pH range of 6.6–7.6. However, beyond this range, the activity of fiber degraders reduces [53,54].

The emission rates of CH_4 showed significant diurnal variations with two peaks which were probably related to the feeding routine [55]. Daily CH_4 emissions increased significantly with the activity of the cows ($r = 0.61$) while daily CH_4 emissions were negatively correlated to the indoor air temperature ($r = -0.84$). This suggests that increased daily indoor air temperatures due to seasonal changes may bring about decreased animal activity which may decrease the release of CH_4 from dairy cows [55]. The methane production was found to be correlated with DMI [56] whereas the forage portion of the diet has also been used to predict the methane production [57]. The effect of different thermal exposure on methane emission were studied [58] and found that methane emission per kg DMI was reduced during 35°C and as compared to exposure at 25 and 30°C, then increased at 40°C. The lowest methane emission at 35°C might be due to higher digestibility whereas methane production at 25 and 30^{0}C was higher as digestibility was lower at respective temperatures than at 35°C temperature exposure and therefore, more organic matter was available for microbes to convert them into methane and so methane production was comparatively higher at 25 and 30^{0}C temperature. The highest methane emission per kg DMI at 40°C might be attributed to lower organic matter digestibility and shift in methane producing microbes and other microbial fermentation, due to change in rumen environment because of higher environmental temperature [58]. An increase in methane emission was observed during higher ruminal temperature [33]. Methane production from enteric fermentation was a function of the rate of organic matter fermentation, the type of volatile fatty acid produced and the efficiency of microbial biosynthesis [51,52].

Conclusion and future action plan

The effect of heat stress has been well established on digestibility and production of volatile fatty acids but there had been a few studies related to effect of heat stress on alteration of the molar concentration of volatile fatty acids, methane production and population of flora and fauna in the rumen. There are only few studies related to the change in the ruminal microbial population in response to heat stress. Methane is one of the main products of ruminal fermentation which might also be affected by heat stress. In the scenario of climate change, methane emission from livestock animals is of paramount importance. Therefore, it necessitates a comprehensive study relating to the microbial population being affected by heat stress especially the methane producing bacteria. In order to mitigate and formulate successful strategies to combat the negative effects of increased environmental temperature on rumen function, it is highly pertinent to carry out studies to ascertain the physiological and microbiological basis of alteration in rumen function during heat stress.

References

1. Thornton, P. K. (2010) Livestock production: recent trends, future prospects. *Philos. Trans. R. Soc. Lond., B. 365*(1554): 2853-2867.
2. Delgado, C.L. (2003) Rising consumption of meat and milk in developing countries has created a new food revolution. *J. Nutr.* 133: 3907S-3910S (Supplement 2 on Animal Source Foods).
3. FAOSTAT. Agricultural production database. Food and Agricultural Organization. http://faostat.fao.org/site/339/default.aspx Accessed on August 8, 2013.
4. Lonergan, S. (1998) Climate warming and India. In: *Dinar, A. et al (eds) Measuring the Impact of Climate Change on Indian Agriculture. World Bank Technical Paper No. 402, Washington DC,* pp 33–67.
5. Gaughan, J.B., Mader, T.L., Holt, S.M., Sullivan, M.L. and Hahn, G.L. (2009) Assessing the heat tolerance of 17 beef cattle genotypes. *Int. J. Biometeorol*. 54: 617–627.
6. Baumgard, L.H. and Rhoads, R.P. (2012) Ruminant Nutrition Symposium: ruminant production and metabolic responses to heat stress. *J. Anim. Sci.* 90(6): 1855-1865.
7. National Research Council. (1989) Nutrient Requirements of Dairy Cattle (6th Revised Edition Update). National Academy Press, Washington, DC.
8. Rhoads, R.P., Baumgard, L.H., Suagee, J.K., & Sanders, S.R. (2013) Nutritional Interventions to Alleviate the Negative Consequences of Heat Stress. *Adv.Nutr. 4*(3): 267-276.
9. Wheelock, J.B., Rhoads, R.P., VanBaale, M.J., Sanders, S.R. and Baumgard, L.H. (2010) Effects of heat stress on energetic metabolism in lactating Holstein cows. *J. Dairy Sci.* 93: 644–655.
10. Albright, J.L. and Alliston, C.W. (1972) Effects of varying the environment upon performance of dairy cattle. *J. Anim. Sci.* 32: 566–577.
11. Rhoads, M.L., Rhoads, R.P., VanBaale, M.J., Collier, R.J., Sanders, S.R., Weber, W.J., Crooker, B.A. and Baumgard, L.H. (2009) Effects of heat stress and plane of nutrition on lactating Holstein cows: I. Production, metabolism, and aspects of circulating somatotropin. *J. Dairy Sci.* 9(5):986-997.
12. Smith, D.L., Smith, T., Rude, B.J. and Ward, S.H. (2013) Comparison of the effects of heat stress on milk and component yields and somatic cell score in Holstein and Jersey cows. *J. Dairy Sci*. 96(5): 3028-3033.
13. Nonaka, I., Takusari, N., Tajima, K., Suzuki Higuchi, T. and Kurihara, K.M. (2008) Effects of high environmental temperatures on physiological and nutritional status of prepubertal Holstein heifers. *Livest. Sci.* 113: 14–23.
14. Pereira, A.M.F., Baccari Jr. F., Titto, E.A.L. and Almeida, J.A.A. (2008) Effect of thermal stress on physiological parameters, feed intake and plasma thyroid hormones concentration in Alentejana, Mertolenga, Frisian and Limousine cattle breeds. *Int. J. Biometeorol.* 52: 199–208.
15. Yadav, B., Singh, G., Wankar, A., Dutta, N., Verma, A.K. and Chaturvedi, V.B. (2012a) Effect of heat stress on digestibility in crossbred cattle. VIIIth Biennial Conference of ANAC and symposium on Animal Nutrition Research Strategies for Food Security. pp 138.
16. Hall, M. B. (2009) Heat Stress Alters Ruminal Fermentation and Digesta Characteristics, and Behavior in Lactating Dairy Cattle. In *Proceeding of 11th International Symoosium on Ruminant Physiology, Y. Chilliard, F. Glasser, Y. Faulconnier, F. Bocquier, I. Veissier, and M. Doreau, ed. Wageningen Academic Publ., Wageningen, the Netherlands* pp. 204.
17. Hamzaoui, S., Salama, A.A.K., Albanell, E., Such, X. and Caja, G. (2013) Physiological responses and lactational performances of late-lactation dairy goats under heat stress conditions. *J. Dairy Sci.* 96(10): 6355-6365.
18. Chaiyabutr, N., Chanpongsang, S. and Suadsong, S. (2008) Effects of evaporative cooling on the regulation of body water and milk production in crossbred Holstein cattle in a tropical environment. *Int. J. Biometeorol.* 52: 575–585.
19. Korde, J.P., Jadhao, S.V., Varshney, V.P., Singh, G and Shukla, D.C. (2006) Longterm effects of heat exposure on nutrient digestibility and digesta flow rate in buffalo calves. *Buffalo Bulletin* 22(1): 25-32.
20. Sejian, V., Valtorta, S., Gallardo, M. and Singh, A. K. (2012) Ameliorative Measures to Counteract Environmental Stresses. In *Environmental Stress and Amelioration in Livestock Production.* Springer Berlin Heidelberg. pp. 153-180.
21. Soriani, N., Panella, G. and Calamari, L. (2013) Rumination time during the summer season and its relationships with metabolic conditions and milk production. *J. Dairy Sci.* 96(8): 5082-5094.
22. Dikmen, S., Ustuner, H. and Orman, A. (2012) The effect of body weight on some welfare indicators in feedlot cattle in a hot environment. *Int. J. Biometeorol. 56*(2): 297-303.
23. Baile, C.A. and Forbes, J.M. (1974) Control of feed intake and regulation of energy balance in ruminants. *Physiol. Rev.* 54: 160.
24. Aganga, A.H., Umna, N.N., Oyendipe, E.O., Okoh, P.N. and Aduku, A.O. (1990) Response to water deprivation by Yankasa ewes under different physiological states. *Small Rumin. Res.* 3: 109–115.
25. Silanikove, N. (1985) Effect of dehydration on feed intake and dry matter digestibility in desert (black Bedouin) and non-desert (Swiss Saanen) goats fed on lucerne hay. *Comp. Biochem. Physiol.* 80A: 449–452.
26. Marai, I.F.M. and Haeeb, A.A.M. (2010) Buffalo's biological functions as affected by heat stress-A review.

Livest. Sci. 127(2): 89-109.

27. Mishra, M., Martz, F.A., Stanley, R.W., Johnson, H.D., Campbell, J.R., Hildebrand. E. (1970) Effect of diet and ambient temperature–humidity and ruminal pH, oxidation –reduction potential, ammonia and lactic acid in lactating cows. *J. Anim. Sci.* 31: 1023–1028.
28. Grovum, W.L. (1981) Factors affecting the voluntary intake of food by sheep. 3. The effect of intravenous infusions of gastrin, cholecystokinin and secretin on motility of the reticulo-rumen intake. *Br. J. Nutr.* 45: 183–201.
29. Bloom, S. R. (1978) Gut hormones. *Proc. Nutr. Soc.* 37: 259–271.
30. Kelly, R.O., Martz, F.A. and Johnson, H.D. (1967) Effect of environmental temperature on ruminal VFA levels with controlled feed intake. *J. Dairy Sci.* 50: 531–533.
31. Tajima, K., Nonaka, I., Higuchi, K., Takusari, N., Kurihara, M., Takenaka, A. and Aminov, R.I. (2007) Influence of high temperature and humidity on rumen bacterial diversity in Holstein heifers. *Anaerobe 13*(2): 57-64.
32. Salles, M.S.V., Zanetti, M.A., Salles, F.A., Titto, E.A.L. and Conti, R.M.C. (2010) Changes in ruminal fermentation and mineral serum level in animals kept in high temperature environments. *Revista Brasileira de Zootecnia,* 39(4): 883-890.
33. King, C.C., Dschaak, C.M., Eun, J.S., Fellner, V. and Young, A.J. (2011) Quantitative analysis of microbial fermentation under normal or high ruminal temperature in continuous cultures. *The Professional Animal Scientist* 27(4): 319-327.
34. Uyeno, Y., Sekiguchi, Y., Tajima, K., Takenaka, A., Kurihara, M. and Kamagata, Y. (2010) An rRNA-based analysis for evaluating the effect of heat stress on the rumen microbial composition of Holstein heifers. *Anaerobe* 16(1): 27-33.
35. Christopherson, R.J. (1985) The thermal environment and the ruminant digestive system. In: *Yousef, M.K. (Ed.), Stress Physiology in Livestock. CRC Press, Boca Raton, Florida,* pp. 163–180.
36. National Research Council. (1981) Effects of environment on nutrient requirements of domestic animals. National Academies Press, Washington, DC.
37. Weniger, J.H. and Stein, M. (1992) Einfluss von Ungebungstemperatur und Luftfeuchte auf die Nahrstoffverdaulichkeit beim Schaf. 1. Problemstellung, *Durchfuhrung der Untersuchungen, Verdaulichkeit. Zuchtungs-kunde* 64: 148 –155.
38. Mathers, J.C., Baber, R.P., Archibald, R.F., (1989) Intake, digestion and gastro-intestinal mean retention time in Asiatic Buffaloes and Ayrshire cattle given two contrasting diets and housed at 20 °C and 33 °C. *J. Agric. Sci.* 113: 211–222.
39. McDowell, R.E., Moody, E.G., Van Soest, P.J. and Lehmann, R.P. (1969) Effect of heat stress on energy and water utilization of lactating cows. *J. Dairy Sci*. 52: 188–194.
40. Christopherson, R.J. and Kennedy, P.M. (1983) Effect of the thermal environment on digestion in ruminants. *Can. J. Anim. Sci.* 63: 477–496.
41. Korde, J.P., Singh, G., Varshney, V.P. and Shukla, D.C. (2007) Effects of Long-term Heat Exposure on Adaptive Mechanism of Blood Acid-base in Buffalo Calves. *Asian-Aust. J. Anim. Sci*. 13: 329–332.
42. Bernabucci, U. (2011) Impact of Hot Environment on Nutrient Requirements. *Environmental Physiology of Livestock*, 101-128.
43. Nonaka, I., Takusari, N., Higuchi, K., Enishi, O. and Kurihara, M. (2012) Effects of a Hot and Humid Environment on the Performance of Holstein Heifers. *Jpn. Agric. Res. Q. 46*(3): 221-226.
44. Bernabucci, U., Bani, P., Ronchi, B., Lacetera, N. and Nardone, A. (1999) Influence of short and long-term exposure to hot environment on rumen passage rate and diet digestibility by Friesian heifers. *J. Dairy Sci.* 82: 967–973.
45. Lu, C.D. (1989) Effect of heat stress on goat production. *Small Rumin. Res.* 2: 151–162.
46. McDowell, R.E., Hooven, N.W. and Camoens J.K. (1976) Effects of climate on performance of Holsteins in first lactation. *J. Dairy Sci.* 59: 965–973.
47. Bernabucci, U., Lacetera, N., Danieli, P.P., Bani, P., Nardone, A. and Ronchi, B. (2009) Influence of different periods of exposure to hot environment on rumen function and diet digestibility in sheep. *Int. J. Biometeorol.* 53: 387–395.
48. Liu, Y. and Whitman, W.B. (2008) Metabolic, phylogenetic, and ecological diversity of the methanogenic archaea. *Annals New York Acad. Sci.* 1125: 171–189.
49. Johnson, K.A. and Johnson, D.E. (1995) Methane emissions from cattle. *J. Anim. Sci.* 73: 2483–2492.
50. Monteny, G.J., Groenestein, C.M. and Hilhorst, M.A. (2001) Interactions and coupling between emissions of methane and nitrous oxide from animal husbandry. *Nutr. Cycl. Agroecosys.* 60(1/3): 123-132.
51. Monteny, G.J., Bannink, A. and Chadwick, D. (2006) Greenhouse gas abatement strategies for animal husbandry. *Agric. Ecosyst. Environ.* 112(2-3): 163-170.
52. Shibata, M. and Terada, F. (2010) Factors affecting methane production and mitigation in ruminants. *Anim. Sci. J.* 81(1): 2-10.
53. Morvay, Y., Bannink, A., France, J., Kebreab, E. and Dijkstra, J. (2011) Evaluation of models to predict the stoichiometry of volatile fatty acid profiles in rumen fluid of lactating Holstein cows. *J. Dairy Sci.* 94(6): 3063-3080.
54. Dijkstra, J., Ellis, J.L., Kebreab, E., Strathe, A.B., López, S., France, J. and Bannink, A. (2012) Ruminal pH regulation and nutritional consequences of low pH. *Anim. Feed Sci. Tech.* 172(1): 22-33.
55. Ngwabie, N.M., Jeppsson, K.H., Gustafsson, G. and Nimmermark, S. (2011) Effects of animal activity and air temperature on methane and ammonia emissions from a naturally ventilated building for dairy cows. *Atmos. Environ.* 45(37): 6760-6768.
56. Ramin, M. and Huhtanen, P. (2012) Development of non-linear models for predicting enteric methane production. *Acta. Agric. Scand. A.* 62(4): 254-258.
57. Hippenstiel, F., Pries, M., Büscher, W. and Südekum, K.H. (2013) Comparative evaluation of equations predicting methane production of dairy cattle from feed characteristics. *Arch. Anim. Nutr.* 67(4): 279-288.
58. Yadav, B., Singh, G., Wankar, A., Dutta, N., Verma, A.K. and Chaturvedi, V.B. (2012b). Effect of thermal stress on Methane emission in crossbred cattle. VIII[th] Biennial Conference of ANAC and symposium on Animal Nutrition Research Strategies for Food Security. pp 144.

****