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REVIEW ARTICLE

Global Climate Change Effect on the Reproductive Efficiency of Dairy Cattle

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ABSTRACT

Global warming has a detrimental impact on the welfare and productivity of dairy cows. In many regions around the globe, farm animals experience significant material and financial losses as a result of climate change, particularly during the summer months. Dairy cattle experience heat stress (HS) when external temperatures exceed the thermo-neutral zone (comfort zone), which is defined by the range between the lower critical temperature and the higher critical temperature. The lower critical temperature is the ambient temperature at which an animal begins to produce excess metabolic heat to regulate its body temperature. The higher critical temperature refers to the temperature at which an animal raises its body temperature to make up for inadequate evaporative heat loss. Animals that are exposed to temperatures higher than their thermo-neutral zone will experience HS as a result of a confluence of environmental factors. HS represents a significant financial challenge in many dairy-producing regions around the world, as it negatively affects various reproductive traits and diminishes the milk production of dairy cows. The decline in age at puberty, estrus induction, conception rate, oocyte fertility, follicular development, embryonic development, abortions and fetal loss, pregnancy, and also male reproductive performance observed in dairy cows during the hot summer months is primarily attributed to global warming.

Key words: Climate change, dairy cattle, global warming, reproduction

INTRODUCTION

Human activities and natural sources emit greenhouse gases (GHG) into the atmosphere. Atmospheric GHG concentrations increased by around 39%, and the concentration of methane (CH_4) has more than doubled due to the industrial revolution.[1] More than 60% of GHG emissions are from the agriculture sector. The three main GHGs that cause climate change and global warming are nitrous oxide (N_2O), CH_4, and carbon dioxide (CO_2). The animal is responsible for 18% of GHG emissions, 65% N_2O, 37% methane, and 9% CO_2.[2] Methane emissions are from enteric fermentation, manure, and management of cattle. N_2O is from animal dung, while CO_2 is from changing land usage due to feed grains, grazing land, and agricultural energy. Rising GHG concentrations in the atmosphere caused an increase in environmental temperatures and, consequently, climate change. The rising average temperature of the atmosphere, or global warming, is the most evident sign of climate change. According to the Intergovernmental Panel on Climate Change[3] report, the globe's temperature has been rising by 0.20°C every 10 years. By the year 2100, the average surface temperature is expected to have climbed to 1.8–5.8°C due to global warming. The range of 21–27°C for growth rates and 24–30°C for milk production is the higher critical temperature for cattle.[4] However, cattle being homoeothermic can control their body temperature through several physiological and behavioral reactions through the

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integration of numerous organs and systems, such as the immune system, endocrine system, behavioral system, and cardiorespiratory system, and modify some physiological processes during heat exposure to support heat balance.[5] Homeostatic processes and behavioral changes, such as decreased activity, increased water intake, and decreased feed intake, can identify heat stress (HS) in dairy animals.[6] HS directly affects and damages the cellular activities of numerous bodily parts and tissues, including the respiratory alkalosis.[7] HS conditions primarily affect livestock indirectly through the quality and quantity of feed and water, as well as infections, disease outbreaks, and disease vectors. However, the direct effects of climate change can lead to even more severe consequences.[8] These consequences include altered immunological response and heightened vulnerability to illness, reduced appetite and ruminating, oxytocin release suppression, and lower fertility.[9,10] The purpose of this study was to compile previous research on the effects of global warming on the reproductive efficiency of dairy animals.

REVIEW OF LITERATURE

Deterioration Effects of Global Warming on the Reproductive Efficiency of Dairy Animals

HS impacts reproductive performance in two ways: directly through its effects on reproduction and indirectly through changes in energy balance. The effects of hot weather on reproduction may probably become increasingly noticeable in tandem with climate change. HS has detrimental effects on reproductive events because HS inhibits embryonic development, decreases the appearance of estrous behavior, grows ovarian follicles, and decreases oocyte competence.[11] Heat load also interferes with several processes related to becoming and maintaining pregnancy. These processes include modifications to follicular development and dominance patterns, regression of the corpus luteum (CL), decreased ovarian function, oocyte quality and competence, development of the embryo, elevated rates of early fetal loss and embryonic mortality, impaired endometrial function, decreased uterine blood flow, and decreased expression of estrus and behaviors linked to estrus.[12] Numerous publications have reported negative correlations between the temperature-humidity index (THI) and animal reproductive outcomes. Gaafar *et al*.[13] found that the summer HS led to a considerably longer first estrus, interval service, days open, and calving interval, more services per conception, and a lower conception rate (CR) in Friesian cows. Singh *et al*.[14] found that climate change directly affects animal reproduction and productivity, impacting these areas by approximately 63.3% and 58.3%, respectively. Mondal *et al*.[11] mentioned that HS negatively impacts reproductive events by reducing the expression of estrous behavior, changing the growth of ovarian follicles, impairing oocyte competence, and suppressing embryonic development. Reduced frequency and length of estrus, calving rate, and an increase in the number of inseminations per conception were the outcomes of HS.[15] Age at first service increases in HS, silent heat conditions, longer time to first postpartum insemination, more inseminations per conception, lower CRs, longer number of days open, and a higher incidence of reproductive issues such as dystocia, retained fetal membranes, premature abortions, and weaker calves are among the negative effects of HS.[16] The occurrence of problems such as short estrus, poor follicular development, poor oocytes and spermatozoa, decreased CRs, and poor semen quality has increased under HS.[17]

Effect of global warming on puberty and estrus induction

High ambient temperatures delay both male and female puberty onset. The delay in the recovery of complete estrous cycles in cows following calving is the primary impact of HS on reproduction. Research indicates elevated temperatures impact the reproductive process throughout several phases, such as pubertal maturation, implantation, and embryonic death.[18] According to Florida research, Bridges *et al*.[19] found that the average number of undiagnosed estrus occurrences throughout the summer months (41°C) is 76–82%, compared to 44–65% from October to May. Cows that experience high ambient temperatures are more likely to have silent heat and anestrus, which also results in a reduction in the length and intensity of estrus and a noticeable decline in the quality of produce.[20]

According to Barati *et al*.,[21] the heat-stressed cows had shorter oestrous cycles and a greater duration of noncyclic reproductive phases. The duration of the cattle's oestrus cycle at day 21 was 88.6% under thermoneutral conditions and drastically dropped to 62.5% in heat-stressed settings. HS shortens the length and intensity of estrus, which makes it harder to reproduce because of thsilent heat or weak estrus expression results.[22] Silent ovulation and anoestrus, which reduce estrus expression, are linked to some of the reproductive losses in heat-stressed cattle. HS lengthens the follicular wave and delays follicle selection, which may have a negative impact on the quality of oocytes and follicular steroidogenesis. The summer estrous cycle in Japanese cattle was longer (23.4 days vs. 21.5 days), and the cattle exhibited less roaming behavior during estrus than in the winter.[23] Identifying estrus becomes more difficult in dairy cows with fewer symptoms and shorter estrus durations during HS.[24] HS has a major impact on cows' expression of estrus by shortening and intensifying estrus in animals and increasing the frequency of anestrous and silent heat.[25] The summer estrus cycle of non-lactating cows was found to be much longer than the winter cycle, and the rates of estrus and conception decreased when the THI exceeded 72.[26] Inadequate identification of estrous cycles and losses of embryos are the main reasons for subpar reproductive outcomes. Approximately 50% of standing periods of estrus go unnoticed during the postpartum period. This inability to detect estrus can result in an average interval of 40–50 days between successive inseminations.[27] Cattle that experience HS may silently heat up, and their estrus may be shorter and less intense, which may result in less mounting activity. HS has a direct impact on the estrous behavior of dairy cows, as observed by Gupta *et al*.[28] The calving season influences the length of service for cattle in India, as noted by Dash *et al*.,[29] with summer-calving cows exhibiting the longest service periods. The most significant sexual activity in these animals is observed in the morning and at midnight, whereas the least activity takes place around midday when temperatures are elevated. Dash *et al*.[30] showed that HS reduces the intensity and duration of behavioral estrus, making it less common to see cows in estrus under these circumstances. The later authors reported that the expression of estrus at the first ovulation, the time between calving and conception, and the chance of conception and pregnancy were all strongly correlated with HS. HS changes follicular development and shortens and weakens estrus.[31] Parikh *et al*.[32] showed that compared to heifers born during the winter and rainy seasons, those born during the summer had noticeably longer ages at sexual maturity, first conception, and first calving.

The synthesis and release of glucocorticoids are stimulated by the adrenocorticotropic hormone in response to stress, which can negatively impact the hypothalamic–pituitary–gonadal axis and estrous cyclicity.[33] The hormone that causes the expression of estrus is estradiol. Estrus is impacted by the decrease in estradiol production, which is low in females in warmer climates.[34] HS inhibits estradiol-induced sexual behavior by increasing the release of adrenocorticotropic hormone (ACTH) and cortisol.[35] Low estradiol production inhibits gonadotropin surge, ovulation, gamete transport, and indications of estrus.[29] In addition, silent heat issues in cows or heifers are caused by low progesterone (P_4) along with low estrogen levels.[36] Moreover, Patel *et al*.[15] found that HS influences the production of follicle-stimulating hormone (FSH), luteinizing hormone (LH), and gonadotropins from the anterior pituitary gland in addition to gonadotropin-releasing hormone from the hypothalamus. The production of LH and gonadotropin-releasing hormone is reduced in response to HS, which inhibits ovulation and the manifestation of estrus activity.[37] Lower amounts of estradiol-17α and LH secretion may cause dairy cows to be less anestrous and have a longer summer estrous cycle, and the hormone estradiol is found in lower concentrations when HS results in a reduction in the production of 17-hydroxylases.[38] HS affects the synthesis of gonadotropin-releasing and LH hormones, which are essential for ovulation and the display of estrus behavior.[26] HS is associated with a reduced ovarian response to FSH and LH, which leads to hot seasonal anoestrus. HS also increases the ACTH/cortisol ratio, which alters endocrine secretion and results in anoestrus.[39] Infertility and the cessation of estrous cycles are caused by elevated circulating prolactin under HS.[24] HS also raises the level of prolactin in the blood, which has anti-gonadotrophic properties and is the main reason for postpartum anoestrus in lactating animals.[40,41] Long-term stress reduces the amount of estradiol released by follicles, which has an immediate impact on the animal's ovaries; estrous behaviors may become unclear or nonexistent.[42]

Effect of global warming on CR

The percentage of services that produce lactating dairy cows pregnant is known as the CR. Elevated ambient temperatures can potentially impact the CR and pregnancy. In lactating dairy cows, summertime records revealed a 20–27% drop in CR.[43] Compared to findings from the winter, there might be a 20–30% drop in CR during the summer season.[20] When THI = 78.0, only 39.4% of dairy cows were pregnant, and the CR of dairy cows drops by 1.03% for every unit rise in THI when it exceeds 72.0.[44] Reduced CR was consistently linked to HS in the lead-up to breeding day.[45] Garcia-Ispierto *et al*.[46] observed that HS reduces the CR of lactating dairy cows by about 30.6% compared to breeding days. The latter authors revealed that when THI is higher than 80 for 3 to 1 day before artificial insemination (AI), the CR drops from 30.6% to 23.0%. Morton *et al*.[45] noted that the nursing dairy cows' CR was substantially lower during the hot season (July to September) at 29.5% than it was during the cold period (October to June), when it was 38.2%. Dairy cows have much lower summertime CR than in other seasons.[47] CR was adversely correlated with the maximum ambient temperature on the day following insemination.[48] Compared to other seasons, cows that calved in the summer had lower CR and more services per conception.[49] Summer HS has a detrimental impact on dairy cows' reproductive performance, according to Ghavi *et al*.,[50] who found that summer-calved cows had lower CR and more services per conception than cows calved in other seasons. The linear regression of CR percentage on THI is $y = 0.70x^2 - 3.95x + 72.57$ ($R^2 = 0.75$), where x is THI and y is CR %. The authors concluded that compared to other seasons, cows that calved in the summer had lower CR and more services per conception. HSs before and after the breeding day had a detrimental effect on the CR of nursing dairy cows. The highest detrimental effect of HS on the CR was shown 21 to 1 day before breeding, and the rate of CR dropped from 31% to 12% when the mean THI was 73 or higher.[51] According to Boni *et al*.,[52] a noteworthy drop in CR among Holstein Friesian cows was assessed monthly on an annual basis throughout the summer months; moreover, this parameter declined in tandem with a rise in THI. In Egypt, the CR in purebred Holstein cows dropped dramatically from 31.6 at the lower THI to 11.5% at the higher THI.[27] Gaafar *et al*.[13] found that as THI grew from 57.98 in January to 80.40 in July, the number of services per conception rose from 2.44 to 3.02, and the CR dropped from 78.69 to 63.29%. Lacerda and Loureiro[53] found that during the months with high and low temperatures and humidity, the AI CR ranges from 55% to <10%. Dash *et al*.[29] indicated that, while the reproductive performance of buffaloes significantly declined at a threshold of THI 75, the CR and pregnancy rates in dairy cattle in India experienced a decline above THI 72. Schüller *et al*.[12] discovered a correlation between the mean THI on the day of breeding and the subsequent CR and determined that 73 was the THI threshold for the impact of HS on the CR. According to Polsky and Keyserling,[54] there are clear seasonal variations in the CR, and the drop in CR during summer months might range from 20% to 30%. In contrast to 40–50% at the ideal temperature, the likelihood of effective fertilization might decrease to 10% during the hottest months of the year. Krishnan *et al*.[55] discovered that when the THI was over 70, a one-unit rise in THI led to a 4.6% drop in the CR. During the mild HS phase (THI 73–78), the highest rates of CR were seen in inseminated cows (41.7%), while during severe HS (THI above 90), the CR decreased to 32.5%.[56] The latter authors mentioned that the percentage of CR dropped from around 40–60% in the colder months to 10–20% or less in the summer, according to the intensity of HS. Wolfensen and Roth[57] reported that CR dropped from 40–50% in months with higher ambient temperatures to fewer than 10% in months with lower temperatures. The authors reported that, in the summer months, lactating cows' CR was 27.7%, but in the cold winter months, it was 42.6%. Reduced levels of gonadotropins, estrogen, and LH brought on by HS disrupt the regular cycle of estrus and suppress follicular growth, which accounts for the decline in the CR.[58]

Effect of global warming on Oocytes

HS affects both the oocyte quality and the embryo development, and hence affects the fertility of cows. HS also impairs oocyte competence, oocyte maturation, and developing oocytes throughout the later stages to become fertilized.[57] Poor oocyte quality in Holstein cows has been associated with reduced fertility due to the adverse effect of HS.[59] The damaging consequences of HS start when the egg is still growing and continue through subsequent stages, affecting the egg's ability to fertilize, the development and implantation of the embryo, and even the fetal calf.[60] Summer Holstein cow oocytes through *in vitro* fertilization were less competent than winter cow oocytes to grow into the blastocyst stage.[61] Oocyte competence is lower in summer than in winter, as indicated by the developmental rate following fertilization.[62] One of the best strategies to reduce the severity of HS is embryo transfer, which shields the egg and early embryo from its effects.[35] HS modifies follicular development by decreasing the synthesis of steroid hormones, and these modifications in follicular steroid concentration may cause problems for oocyte formation.[63] HS has the potential to inhibit oocyte formation through several different methods. The first is the depression in LH and estradiol production during the pre-ovulatory surge.[60] A tenfold increase in cortisol levels in heat-stressed cows inhibits oxytocin, resulting in a decrease in milk supply and an increase in leftover milk after milking. Cortisol also inhibits immunity, delays ovulation, and interferes with the estrous cycle.[64] Lower levels of LH were observed in cows under HS, and the decrease in LH led to several reproductively related problems, such as oocyte maturation and ovulation.[49]

Effect of global warming on fertility and follicular development

The animal's capacity to become pregnant and keep it pregnant if inseminated at the right time for ovulation is known as fertility in farm animals. One of the main elements influencing the performance of any dairy herd is fertility. Numerous elements, including heredity, diet, hormones, pathophysiology, management, physiological, managerial, and climate, affect the fertility of cows.[31] Summer HS is a key cause of decreased fertility in dairy cattle, according to Wolfenson and Roth.[57] The reproductive features of dairy animals have a relatively low heritability value, indicating that environmental influence or non-genetic variables affect fertility.[46] The latter authors reported that HS causes oocytes to grow less, leading to acyclicity and infertility in animals. The main cause of the decreased fertility in farm animals is higher ambient temperatures. Cattle under HS have lower fertility rates (FRs), which lowers reproductive efficiency. High-yielding dairy cows have a lower FR in the summer than in the winter, and nursing cows are more adversely affected than heifers due to their noticeably higher internal heat production.[65] HS is a major source of economic loss for dairy cows in tropical climates and causes infertility.[38] According to Boni *et al*.,[52] the primary cause of decreased fertility in Holstein Friesian cows due to HS was the number of heats detected, which changed in proportion to the number of CR assessed monthly on an annual basis. HS on fertility results in a larger percentage of cows having various kinds of anestrus, a decrease in the incidence of CR, and an increase in days open. HS affects the ovary, uterus, gametes, embryo, and early fetus after pregnancy, which lowers the cow's capacity to procreate.[66] The fertilization rate in nursing cows bred using AI dropped from 88% in the winter to 55% in the summer.[67] Cows experiencing HS show reduced motor activity and various symptoms associated with estrus. In addition, there is an increased occurrence of anoestrus and silent ovulation, which ultimately leads to declines in fertility.[38] The fertilization rate falls when the uterine temperature rises by 0.5°C on a hot day.[68] HS has been linked to lower fertility in animals due to its detrimental effects on early embryo development and oocyte maturation.[30] In a subtropical region, buffaloes are particularly susceptible to HS fertility loss over the THI threshold of 75.[69] According to Biani *et al*.,[70] HS influences the poor fertility of dairy cows conceived in the late summer, with low fertility during the months with high temperatures and humidity. The extremely low heritability value of reproductive variables in dairy cows indicates that environmental or non-genetic factors are primarily responsible for the majority of fertility variability.[71] In India, the critical HS zone (May and June) and HS zone (April to September) have lower reproductive rates for dairy cattle and buffaloes. However, for the best reproductive results, the non-HS zone (October to March) is ideal. Reduced fertility in animals has been associated with the detrimental effects of HS on oocyte maturation and the early stages of embryo development.[29] The reduction in fertility is the most notable consequence for dairy farmers.[72] HS reduces the quality of an ovarian cell that may go through meiotic division to generate an ovum, alters hormonal balance, disturbs reproductive tract activities, and ultimately decreases embryo development and survival, all of which affect dairy cattle fertility.[31] The release and activity of LH and FSH hormones are decreased by HS.[31] HS reduces fertility by preventing the production of LH hormone and gonadotropin-releasing hormone, which are necessary for ovulation and the expression of estrous activity.[26,73]

Concerning follicular development, dairy cow's follicular growth has been demonstrated to be directly impacted by HS. The quantity of dominant ovarian follicles in dairy cows under HS started to decrease earlier during the first follicular wave than in the animals that were cooled, as demonstrated by Wolfenson and Roth.[57] The disruption of gonadotropin secretion under HS causes a reduction in plasma P_4 levels, steroid production, and follicle formation.[74] HS in lactating cows has been demonstrated to lower blood estradiol levels and follicular development, which in turn leads to a reduction in follicular size or dominant follicle function.[38] Furthermore, alterations in P_4 levels and a reduction in ovarian follicles' generation of estradiol are linked to reproductive abnormalities under HS.[75]

Effect of global warming on embryonic development

The vulnerability of lactating cows to HS reduced the growth of embryos to the blastocyst stage after the 1st day of estrus. The percentage of embryos that reached the blastocyst stage was lowered in lactating cows exposed to HS on the 1st day after estrus.[76] Holstein heifers exposed to HS from the start of estrus had a higher percentage of abnormal and developmentally disturbed embryos.[77] Impaired reproductive success is mostly caused by low estrous signs and embryonic losses.[78] Furthermore, a cow may experience HS shortly after fertilization and hinder the embryo's growth.[79] The direct impact of high temperatures on the embryo is one factor contributing to the high rate of early embryonic death in cows subjected to HS.[38] Cattle's exposure to high temperatures during the first 3 or 7 days of pregnancy, or ovulation and oocyte maturation, reduced the viability and growth of the embryo.[80] Embryos on the 1st day are more susceptible to maternal HS than those on days three through seven.[81] Numerous pieces of evidence suggest that the bovine embryo is susceptible to thermal stress from the mother, especially in the first 2 weeks following conception.[53] HS, however, negatively affects ova quality, which may affect the viability of developing embryos.[82] Heat-stressed cows have altered intrauterine environments, reduced blood flow, and elevated uterine temperatures. These modifications will lower the percentage of successful inseminations in the summer and increase early embryonic loss.[25] According to Roth,[83] HS affects embryonic development, lowers the appearance of estrous behavior, changes follicular development, and increases the roles of the dominant follicle. HS also affects embryo development and implantation in the uterus.[42] The development of embryos and endometrial function is restricted by low P_4 levels in heat-stressed cows. The increased endometrial prostaglandin (GF_2^{α}) production in response to HS results in early CL regression and embryo loss. Fewer animals are visible in estrus in heat-stressed habitats, which negatively impacts embryonic mortality.[84]

Effect of global warming on abortions and fetal loss

In normal bovine populations, abortions denote a harm to reproductive efficiency. Spontaneous abortion of dairy cows is a progressively significant issue that significantly adds to low herd viability and production.[85] In dairy cattle, HS during pre-implantation was strongly correlated with early fetal death by López-Gatius *et al*.[86] Moreover, heat load has been linked to early fetal death between days 21 and 30 of gestation, which is known to compromise gestation during the per-implantation phase.[46] Cow embryos exposed to high temperatures at day 42 of gestation had greater rates of embryonic loss, and the greatest pregnancy loss occurs between days 8 and 17 in cows exposed to high temperatures during the early embryonic period.[76] The rate of embryonic loss dramatically increased from 11.5%

at the lower THI to 22.2% at the higher THI.[27] Elevated body temperature in animals under HS raises the temperature in the uterus because blood flow is restricted in the uterus and is diverted to the body's periphery to aid in heat removal. As a result of the uterus receiving less blood, there is a reduction in the rate of gestation, loss of the embryo, and availability of nutrients and hormones.[87] HS lowers the P_4 level in the blood, slows down follicle selection, and decreases the dominant follicle's degree of dominance. These results imply that HS is a major factor in early embryonic mortality in dairy cattle.[77] Furthermore, HS causes the endometrium to produce more GF_2^{α} secretion, which might cause the embryos to die.[25] In heat-stressed cattle, a negative energy balance can also lead to abnormalities in steroid concentration, alter the development of germinal vesicles, encourage the creation of ovarian cysts, and perhaps cause embryonic death.[88]

Effect of global warming on pregnancy

Pregnancy rates are significantly impacted by HS. HS lowered the pregnancy rate in dairy cows and increased its impact when it lasted longer and was more intense. The pregnancy rates of Holstein cows and the monthly THI means recorded throughout the year have a negative linear ratio. This meaning that pregnancy rates dropped by 0.7% for every unit increase in THI.[89] HS during late gestation significantly lowers the chances of CR and pregnancy on the day of AI.[90] HS diminishes the intensity and duration of oestrus, which subsequently leads to a decrease in both the number of inseminations and the rates of pregnancy. HS was one of the main causes of the notable drop in the pregnancy rate of crossbred cows in India.[91] The latter authors revealed that pregnancy rates in the HS group were significantly lower (20.5%) than in the thermo-neutral group. Pregnancy by AI reduced from 47% to 26% when THI increased from <70 to ≥ 95 units.[92] Moreover, under HS, less standing heat is recorded, which might eventually result in a lower pregnancy rate.[26] In Holstein Friesian cows, the season significantly influenced the mean number of AI s and pregnancies related to the calving date.[52] The pregnancy rate of buffalo significantly declined at the threshold of THI 75, while the pregnancy rate in dairy cattle was shown to drop above THI of 72.[30] In cows that were exposed to the sun and those that were not, Alves *et al*.[87] found that HS affected the pregnancy rate in cows that were exposed to the sun by 51.85% and 70.37%, respectively. The imported cows in Sri-Lanka, which were subjected to moderate HS for most of the day, had a pregnancy rate of 6% with THI greater than 78, and when the THI was below 78, the detected pregnancy rate was higher than 20%.[93] HS was linked to lower levels of glucocorticoids, prolactin, growth hormone, and thyroxin (T_4) in the blood, which lowered the CR and pregnancy rate in dairy cows.[94] HS alters the concentration of circulating hormones by increasing the circulating concentration of corticosteroids and reducing P_4 concentration.[95] Reduced CR, reduced estrus length and intensity, significantly worse oocyte quality, and decreased pregnancy rates. Oocyte quality and oviduct functions decline in response to HS, causing a drop in the pregnancy rate.[96]

Effect of global warming on the pre- and post-partum periods

During pre-partum time, HS may have an impact on endocrine responses that might lead to an increase in fetal abortions, a shorter gestational period, a decrease in calf birth weight, and a reduction in the maturation of follicles and oocytes related to the postpartum reproductive cycle.[9] Pre-partum HS may raise blood levels of non-esterified fatty acids while lowering thyroid hormones and placental estrogen levels. These changes may impact the development of the placenta and udder, the nutrition provided to the developing calf, and the subsequent milk supply.[97,98] HS during the dry season has a detrimental impact on dairy farm profitability. HS at any time during the dry period shortened both the length of the dry period and the gestation period.[99] Dry animals are mistakenly believed to be less susceptible to HS; therefore, dry cows receive little protection from HS. Abrupt physiological, dietary, and environmental changes occur during the dry period, adding to the stresses.[62] These alterations may make the cows more vulnerable to HS and impact their fertility, milk supply, and postpartum health. The dry phase is important since it is associated with fast fetal growth, induction of milk, and mammary gland involution and subsequent development.[72] Reisi-Vanani *et al*.[100] found a significant impact of HS on productive life among the reproductive traits of Holstein dairy cows, which is defined as the number of days from the first calving to the last milk record.

Radioisotopes are used in the radioimmunoassay (RIA) procedure to assess the levels of the hormones. The RIA method was used to determine the amounts of steroid hormones in the blood plasma and the seminal plasma in animals. Iodine-125 was used to identify the tracer in the RIA procedure. Steroid hormones in the blood of male and female animals are estimated by RIA, which affects sexual behavior and alterations in the oestrus cycle and puberty. Sexual hormone synthesis, particularly testosterone in males, is essential for reproductive function and can be inhibited by stresses that interfere with sexual hormone production. The RIA method was also used to determine the amounts of the hormones in the blood plasma and the seminal plasma of semen. Habeeb *et al*.[101] revealed that, in comparison to moderate circumstances, Friesian crossover calves' levels of T_4, triiodothyronine, and parathormone were considerably lower under hotter settings by 20.0, 22.0, and 22.0%, respectively. Cortisol levels showed the opposite trend, with a 30.0% rise.

Effects of global warming on male reproductive performance

The side effects of HS on reproductive function compromise the fertility of both males and females. The fertility of a bull is just as important as that of an egg in fertilizing it to create a viable, healthy, and genetically potential conception because males make up over half of the herd.[102] Bull testes are known to require a temperature 2–6°C lower than the body's core temperature to produce viable sperm. Therefore, high testicular temperatures caused by HS may change seminal and biochemical properties, potentially leading to reproductive problems in bulls.[103] Seasonal differences in semen quality, sexual behavior, hormone profiles, and testicular volume impact male reproductive success.[104] High temperatures often interfere with the oxidative metabolism of glucose in sperm cells due to mitochondrial malfunction, the accumulation of reactive oxygen species, and increased lipid peroxidation, which leads to a rise in primary defects in sperm.[105] Balic *et al*.[106] found that Simmental bulls revealed deterioration in semen quality due to summer HS and the younger bulls are more vulnerable to the high air temperatures in the summer. Mishra *et al*.[107] found significant differences in the membrane integrity status of fresh spermatozoa between four different breeds of bulls compared to spermatozoa that were not subjected to HS. Bhakat *et al.*[108] revealed a noteworthy seasonal variation in the properties of semen. The authors noted that semen quality was best in the winter, bad in the summer, and intermediate during the rainy season. Therefore, HS dramatically affects male conception and FRs per insemination, which in turn lowers male fitness. The same authors revealed that the season had a substantial impact on sperm concentration, sperm abnormalities, and osmolality in the semen of Karan Fries bulls, as well as crossbred bulls, but no discernible influence on ejaculation volume, mass activity, or total sperm production. In Africa, Chauhan and Ghosh[109] reported that the quantity, concentration, total number, and percentage of normal sperm cells decreased in bulls during the hot season. In addition, subtropical summers cause identical kinds of animals to lose weight, size, tone, scrotal circumference, and testicular consistency. HS causes sperm concentrations to drop, motility to decrease, and sperm abnormalities to increase.[110] The most evident effects of HS on male animal reproductive systems include alterations in the size, libido, texture, and shape of the testicles; decreased sperm production in terms of both quantity and quality; and diminished fertility.[87] Concerning the effects of HS on bulls, Habeeb *et al*.[103] noted a reduction in ejaculate concentration, motility, vigor, and the count of viable spermatozoa, alongside a decline in overall semen quality. During hot-humid seasons, there was a substantial decrease in sperm viability, membrane integrity, and acrosome integrity. Seasonal fluctuations have a major impact on bulls' ejaculate volume, concentration, total sperm, and motility.[111] The sperm mass activity was lowest in the humid summer and highest in the dry, humid spring. The Sahiwal bulls produced better-quality semen during the dry summer and spring; however, the humid summer and autumn adversely affected the quality of the semen.[112] However, Cheng *et al*.[113] noted that there is no severe decline in sperm count and semen quality in male animals exposed to HS. Finally, alterations in the processes of spermatogenesis and steroidogenesis result in testicular degeneration and fibrosis, which in turn cause a loss in fertility, sperm mutation, sterility, and germinal epithelium degradation.[5,102]

HIGHLIGHTS OF OUR REVIEW RESEARCH

Our paper intends to analyze and summarize current research on the effects of HS brought on by global warming on dairy cows' reproductive efficiency, with a particular emphasis on the following points:

1. Our analysis clearly reveals that the GHG comprise carbon dioxide, methane, nitrous oxide, and numerous other chemicals. Because they absorb infrared radiation from the Earth's surface, these gases increase the amount of energy that reaches the lower atmosphere and contribute to global climate change. Global temperatures are expected to rise by 1.8–5.8°C by the year 2100 due to this trend, which is occurring at a pace of 0.20°C per decade. Global warming poses a severe threat to dairy cow welfare and production, resulting in significant economic losses for dairy farms worldwide
2. Our research shows that when ambient temperatures climb over their thermoneutral zone during hot weather, dairy cattle suffer from HS. This stress has a dramatic, detrimental influence on the reproductive efficiency of males and females. Finally, HS throughout the summer months lowers both reproductive function and milk supply, posing a huge financial issue to dairy-producing countries
3. The impact of global warming on dairy cattle efficiency, including puberty, estrus induction, CR, oocyte quality, embryonic development, fertility and follicular development, abortions and fetal loss, pregnancy rate, and the pre- and post-partum periods, is explained in our review
4. Our study clearly reveals that HS circumstances during the hot summer season are a serious concern that inhibits farm animals' capacity to breed nearly anywhere on the planet. Global warming increases the number of inseminations per conception, the number of days open, the age at first service, silent heat conditions, and the incidence of reproductive issues such as dystocia, retained fetal membranes, early abortions, weaker calves, and lower CRs. Regarding the implications of HS on bulls, it harms the volume and quality of semen as well as semen's physical and chemical qualities
5. Our study illustrates the use of radioisotopes in an *in vivo* RIA to evaluate hormone levels in animals.

CONCLUSION

HS conditions during the hot summer season are a significant issue that impacts farm animals' ability to reproduce virtually everywhere on the globe. The age at first service, silent heat conditions, the number of inseminations per conception, the number of days open, and the incidence of reproductive problems such as dystocia, retained fetal membranes, premature abortions, weaker calves, and lower CRs are all increased by global warming. Regarding the consequences of HS on bulls, it has a detrimental impact on the amount and quality of semen as well as semen physical and chemical properties.

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DATA AVAILABILITY

The authors confirmed that the availability of data and materials supports their published claims and complies with field standards.

DECLARATIONS

Our work submitted for publication does not have any implications for public health or general welfare.

CONSENT FOR PUBLICATION

The authors were accepted for publication of this manuscript, and the content of this manuscript will not be copyrighted, submitted, or published elsewhere, while acceptance by the journal is under review.

CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

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