JAST (Journal of Animal Science and Technology) TITLE PAGE

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ARTICLE INFORMATION	Fill in information in each box below
Article Type	Review Article
Article Title (within 20 words without abbreviations)	Meat quality and safety issues during high temperatures and cutting-edge technologies to mitigate the scenario
Running Title (within 10 words)	Mitigate meat quality and safety issues during high temperatures
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Competing interests	
Funding sources State funding sources (grants, funding sources, equipment, and supplies). Include name and number of grant if available.	This research was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2020R1I1A206937911), and the Korean Institute of Planning and Evaluation for Technology in Food, Agriculture, Forestry and Fisheries (IPET) through the Agri-Bioindustry Technology Development Program, funded by the Ministry of Agriculture, Food, and Rural Affairs (MAFRA) (Project No. 321028-5), Korea.
Acknowledgements	
Availability of data and material	
Authors' contributions Please specify the authors’ role using this form.	Conceptualization: Alam AN, Joo ST Data curation: Alam AN Formal analysis: Alam AN, Joo ST Methodology: Alam AN Software: Samad A, Hwang YH, Joo ST Validation: Lee EY, Hossain MJ, Samad A, Kim SH, Hwang YH, Joo ST Writing - original draft: Alam AN Writing - review & editing: Alam AN, Lee EY, Hossain MJ, Samad A, Kim SH, Hwang YH, Joo ST
Ethics approval and consent to participate	

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Meat quality and safety issues during high temperatures and cutting-edge technologies to mitigate the scenario

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Abstract

Climate change, driven by the natural process of global warming, is a worldwide issue of significant concern because of its adverse effects on livestock output. The increasing trend of environmental temperature surging has drastically affected meat production and meat product quality, hence result in economic losses for the worldwide livestock business. Due to the increasing greenhouse gas emissions, the situation would get prolonged, and heat exposure-related stress is expected to worsen. Heat exposure causes metabolic and physiological disruptions in livestock. Ruminants and monogastric animals are very sensitive to heat stress due to their rate of metabolism, development, and higher production levels. Before slaughter, intense hot weather triggers muscle glycogen breakdown, producing pale, mushy, and exudative meat with less water-holding capacity. Animals exposed to prolonged high temperatures experience a decrease in their muscle glycogen reserves, producing dry, dark, and complex meat with elevated final pH and increased water-holding capacity. Furthermore, heat stress also causes oxidative stresses, especially secondary metabolites from lipid oxidation, severely affects the functionality of proteins, oxidation of proteins, decreasing shelf life, and food safety by promoting exfoliation and bacterial growth. Addressing the heat-related issues to retain the sustainability of the meat sector is an essential task that deserves an inclusive and comprehensive approach. Considering the intensity of the heat stress effects, this review has been designed primarily to examine the consequences of hot environment temperatures and related stresses on the quality and safety of meat and secondarily focus on cutting edge technology to reduce or alleviate the situational impact.

Keywords:, Heat stress, Meat quality, Muscle glycogen, Dry meat, Food safety, Cutting edge technology.

Introduction

In the 21st century, Global warming is a significant peril confronting the world, resulting in recurrent episodes of extreme heat and increasing global temperature (NASA, 2021). The rise in human-caused greenhouse gas (GHG) levels has contributed to the unprecedented warming of the Earth in recent years (Stocker et al., 2013). This, in turn, has resulted in more frequent and protracted periods of severe heat, which have an enormous impact on both living and working conditions (Baccini et al., 2008). In addition to the human population, this hot and humid global weather throughout the summer results in economic losses for the worldwide livestock and meat business due to decreased animal output and increased mortality rates (Zhang et al., 2020). Heat stress is a highly demanding and costly occurrence in the lives of livestock animals, resulting in deleterious effects on animal productivity, welfare and the quality of meat products. Heat stress affects the live animal's growth and performance and can undermine meat quality attributes such as pH, water-holding capacity (WHC), and meat color (Ma et al., 2015). This can lead to financial losses for producers and reduced customer acceptance (Čobanović et al., 2020). Heat stress is a critical obstacle in worldwide farm animal production, particularly in warmer climates (Rhoads et al., 2013). Rising heat waves caused by climate change (IPCC, 2018), and the shifting of animal production to comparatively warmer regions to address rising requirements for global meat demand, which have increased livestock susceptibility to heat stress (Mannuthy et al., 2017).

With the increasing global meat demand, more emphasis and pressure are coming on intensively farmed animals; treating livestock as meat machines has led to additional stress to the animals along with heat stress (Kumar et al., 2022). Due to continuous genetic improvement broiler chicken finishing weight rise to 2.5 kg in approximately 30days in present days, which used to take 112 days in 1925 (Dennehy 2022) These boosted broiler growth patterns have increased metabolic rates (Tallentire et al., 2016). They are distinctly vulnerable to heat stress because of their elevated rate of metabolism, which outturn in higher body heat production. Increasing avian population density, paired with high atmospheric temperature, increases the likelihood of heat stress (Goo et al., 2019). However, in recent studies, it was observed that wild animals are less prone to extreme temperate weather. One similar study indicates that the Iberian pig can withstand elevated ambient temperatures, unlike lean pigs and other native breeds that see a decline in the quality of their meat (Pardo et al., 2021). So, it can be said that high-yielding poultry breeds, ruminants, and pigs are more prone to heat stress due to their higher rate of metabolism, generation of metabolic heat, fast growth rate, and higher productivity. Poultry and pigs are extremely prone to heat stress as they lack sweat glands. They also have subcutaneous fat (in the case of pigs) or feathers (in the case of poultry) that offer insulation to their skin. For ruminants, the heat generated when their feed ferments in the rumen raises their metabolic heat output and impairs their ability to regulate the temperature of the body. (Kadzere et al., 2002; Tajima et al., 2007).

Pre-slaughter exposure to intense heat causes a rapid breakdown of muscle glycogen, leading to an increased lactic acid content and a fast increase in muscle pH after death, which makes the carcass is warm (Matarneh et al., 2013) The consecutive outcome is the production of soft, exudative and pale meat, known for its reduced WHC, which is commonly observed in monogastric farm animals like poultry and pigs (Freitas et al., 2017). However similar observations have also been revealed in cattle (Kim et al., 2014). In contrast, animals who endure continuous hot temperature exposure have lesser muscle glycogen reserves, thus restricting lactic acid formation. This results in hardened, dry, dark meat forming, with a higher pH and greater WHC. Typically, ruminants show this phenomenon more often than other farm animals (Adzitey & Nurul, 2011). Furthermore, research has revealed that in different species, hot seasons lead to an increase in the oxidation of lipids and protein, meaning that the keeping quality and safety of meat decreases due to microbial shedding and development (Wang et al., 2009). Hot climates may be more prone to high-yielding animals than wild animals. Figure 1 shows an indication of the effect of heat stress on biological, chemical, and biochemical parameters of animals that affect meat quality.

It is imperative to have an in-depth knowledge of the impacts of heat stress on animal productivity and meat quality to develop successful approaches for sustainable meat production and quality assurance. This study examines the existing understanding and advancements in research regarding the impact of heat stress on meat quality. Additionally, it emphasizes actions that can potentially reduce the adverse effects of heat stress and improve meat quality.

Effect of heat streas on homeostasis and meat quality parametersThe thermoneutral zone is the range of temperatures that pigs, poultry, and ruminants inhabit (Asseng et al., 2021). The comfortable temperature zone for all these species is between 17°C to 24°C and above this range, there are changes in thermoregulation and risk of heat stress. Furthermore, when these animals exposed to a temperature over 35°C or more with elevated humidity might result in fatality. However, extended exposure to temperatures above 25°C with high humidity can cause heat stress in many organisms and continued exposures to temperatures above 35°C with high humidity, or above 40°C with low humidity, can be lethal (Hansen 2009; Mignon-Grasteau et al., 2015; Morignat et al., 2014; Schauberger et al., 2019).

The body's internal temperature rises when external factors—such as outside temperature, sun radiation, airflow, and humidity—exceed the thermoneutral zone, inevitably developing hyperthermia and heat stress (Renaudeau et al., 2012). Feeding habit is also related to the extent of heat stress. It was observed that during heat exposure, ruminants with grain-based diets can easily break down and produce volatile fatty acids, for rumen microbes are more susceptible to heat exposer related stress (Gonzalez-Rivas et al., 2017).

High-yielding poultry breeds genetically improved for faster muscle growth have successfully altered their ability to respond to and adapt to environmental cues based on different climates but to a certain extent. According to Lara and Rostagno (2013), heat stress is an important aspect of the environment that greatly impacts the yield and wellness of chickens in intensive and extensive farming conditions around the globe. Commercial broiler strains exhibit reduced adaptability to severe temperatures compared to native chicken breeds due to their higher metabolic response temperatures and accelerated growth rate. Slow-growing breeds of chicken outperform commercial kinds in terms of feed efficiency, survival rates, body weights, and growth rates when exposed to heat stress. Furthermore, the rectal temperatures of slow-growing breeds are lower (Deeb et al., 2002).

Thyroid hormones regulate the skeletal muscles' calcium content, related to bone strength and body growth (Chiang et al., 2008). Warm-blooded farm animals alter their thyroid hormone secretion rate according to ambient temperature fluctuationsFor example, when the temperature increases, the secretion of thyroid hormone rate decreases, and vice versa (Silva, 2003). Chickens have been found to exhibit a negative association between their plasma T3 concentration and the surrounding temperature, as reported by Tao et al. (2006). It was evident that exposure to one day in the heat commercially bred turkeys reduced T3 levels, and there was an imbalance in T3:T4 ratio (Chiang et al., 2008).

Controlled housing where temperature and humidity are controlled is found to be better regarding growth and meat quality. When broilers are housed at a controlled temperature of 22–24 °C, their breast meat is lighter (L* 41.8 vs. 37.5), their pHu is higher (more than 6), and their weight loss during cooking is reduced (32.4 vs. 35.8%), compared to broilers kept over 25°C temperature in open house (Dai et al., 2012). In an experiment at 22±1 °C, 60% relative humidity and 32±1 °C, 80-90% relative humidity, there was no difference in drip loss between meat from two groups of birds (Akter et al., 2017). A different study (Imik et al., 2012) revealed comparable results regarding the exposer of high temperature on weight loss and meat shelf life. In addition, there was evidence of protein and lipid oxidation in meat, alongside reduced keeping quality of the product, when compared to broilers kept at an average temperature of approximately 24-25 °C.

Long-term high temperatures (32 °C for a period of 14 days) and subsequent heat stress up to harvesting in broilers increase the skeletal muscle of chickens' generation of mitochondrial reactive oxygen species (ROS), which leads to protein oxidation and lipid peroxidation (Lu et al., 2017). The pectoral muscle of broilers in this study had increased levels of lactic acid, intramuscular fat, lactate dehydrogenase and pyruvate kinase. These data suggest that prolonged exposure to high temperatures causes mitochondrial dysfunction, which reduces the animal's ability to perform aerobic metabolism. As a result, there is an increase in glycolysis and a build-up of fat in the muscles, which may deteriorate the meat's quality in prolonged heat stress due to oxidation. To compare the results if looked into another study where in control group broiler chicks housed in controlled temperature conditions (25 °C) and treatment groups exposed to cyclical heat exposure (33 °C and 25 °C in day and night respectively) saw a 16% drop in breast muscle weight during the 42-day raising period (Shakeri et al., 2018). The higher weight of the breast muscles after extended heat stress exposure suggests that chicken use their energy resources more for maintaining body temperature regulation than for muscular building. In a separate study carried out on broiler chickens, it was observed that rearing them in long-term heat stress (34-36 °C) preslaughter triggered an increase in muscle glycolysis in the pectoral and thigh muscles. This was confirmed by increased lactate production, decreased meat pHu by 13 points from 5.88 to 5.75, lighter meat, almost two percent increase in cooking loss, and increased shear force value (27.59 and 22.68 N) in comparison to chickens reared at 23°C (Zhang et al., 2012). These results confer with another study exposing commercial broilers to cyclical chronic heat stress, involving of 8 hours at 32°C with a maximum of 90% relative humidity resulted in lower pHu from 6.0 to 5.8, lightness & b* value increased, a* value decreased, and the shear force of the pectoralis muscle was almost doubled (Akter et al., 2017).

The combined stress of heat and temperature was found to be harmful to chickens. In an experiment by Sandercock et al. (2001) and his group imposed high temperature and humidity at 32 °C and 75%, respectively, for two hours in chicken and found reduced levels of alkaline phosphatase but increased planes of creatine kinase, lipase, and aspartate aminotransferase, and alanine aminotransferase. In this study post slaughter observations were hemorrhages in the muscle and lower pH. Elevated pH levels and dark pigmentation of the meat are indicators of stress caused by heat exposure, which is associated with darker and dry meat in fattening cattle, sheep, and goats (Gregory, 2010). Pre-slaughter stress is responsible for the depletion of muscle glycogen reserves, making the meat dark, complex, and dry. The main element responsible for darker meat is deoxymyoglobin, and the mechanism is increased oxygen consumption by mitochondria at high pH exposures (Suman & Joseph, 2013). In addition, the elevated pH of the meat inhibits the contraction of myofibrils and muscle cells after death, resulting in reduced light scattering properties (low L* values) of the meat (Hughes et al., 2018).

There are more physiological consequences of heat stress in farm animals. A common disease in cattle, buffalo, camels, sheep, goats, and pigs is acute hemorrhagic septicemia caused during heat stress and is typified by high fever, which causes death in a few hours to days. The causative organism of acute septicaemic disease is an anaerobic bacteria *Multicoid pasteurella* (Dubey et al., 2021). Research has shown a greater prevalence of mortality due to stomach abnormalities and indigestion in ruminant animals during high rearing temperatures compared to low rearing temperatures, according to a study conducted by McPhail et al. in 2014. An observable surge in the prevalence of dark and arid conditions is also observed throughout late spring and autumn as a result of abrupt weather fluctuations or temperature variances, with frigid evenings and scorching days serving as the primary catalysts. According to Boykin et al. (2017), there is a greater occurrence of dark and dry meat cases recorded in the north hemisphere between the months of September and October. Pighin et al. (2014) found that sheep have elevated rectal temperatures and reduced glycogen levels during times of stress. This indicates a correlation between increased body temperature and subsequent physiological reaction to glycolytic stress, and the potential for higher muscle pH and darker meat color. A concise review of the impact of heat exposure on meat quality is presented in Table 1.

Due to hot and high temperatures, there are many significant alterations in muscle tissue pre-slaughter and meat post-slaughter. There is changes in muscle pH before and after slaughter of animals. During post slaughter rigor mortis, there is a drop of energy store in muscle that results in a drop of pH and muscle temperature (Strydom et al., 2016) and a low muscle pH (5.2-6.9) evaluated to produce high quality meat (England et al., 2013). Elevated body temperatures are linked to a higher threshold rigor mortis, resulting in earlier and more prominent muscle stiffness, leading to meat stiffness (Warner et al., 2014).

Archana et al. (2018) conducted a recent study to examine the impact of heat stress on the body weight and carcass characteristics of two goat breeds (Osmanabadi and Salem). The scientists observed that heat stress did not affect the meat color in both breeds. Osmanabadi goats exposed to heat stress decreased body weight by 3 kilograms and increased pHu at 24 hours (6.03 compared to 5.74) in the vertebral muscle, when compared to goats housed in shaded pens. These findings imply that the depletion of glycogen reserves may have occurred due to heat stress, however the study did not directly assess this. The consistent meat pHu and body weight stability observed in the Salem breed suggests the breed's exceptional ability to acclimate to hot and moist weather (Archana et al., 2018).

A Korean study revealed that Hanwoo carcasses of varying genders, slaughtered throughout the summer, exhibited significantly reduced ribeye area and marbling scores compared to those slaughtered during different seasons. Nevertheless, the maturity score held greater importance in the carcasses butchered throughout the summer (Panjono et al., 2009). Another investigation on Hanwoo cattle revealed that the meat obtained from animals slaughtered during the summer season exhibited a greater pH level in the longissimus thoracic muscle 48 hours post-slaughter, compared to meat obtained from animals slaughtered during the winter. The variation was ascribed to the elevated temperature and excessive humidity characteristic of the Korean weather during summer (Kang et al., 2011).

There needs to be more research available on the effects of dehydration on the quality of meat. Nevertheless, Jacob et al. (2006a), in a different study, revealed that subjecting lambs to a 48-hour water deprivation period resulted in a significant increase in both live weight loss and muscle dry matter loss. Significantly, this dehydration did not impact the dressing yield or post slaughter carcass weight. The researchers demonstrated that the meat of lambs with dehydration exhibits a deeper hue as a result of the myofibrils contracting. This darkening phenomenon is not always correlated with pH levels (Jacob et al., 2006a). However, these characteristics did not have an effect on the quality of meat intake (Jacob et al., 2006b).

Heat stress and meat safety

Mounting data indicates that stress has a substantial detrimental impact on the taste, flavor, and safety of meat. Although there are reports associating stress with the presence and release of pathogens in farm animals, the exact processes behind this relationship have not been completely understood. Acute *Multicoid pasteurella* infection in animals under heat stress (Dubey et al., 2021) should be considered for further studies on whether it infects meat. The presence of enteric infections caused by pathogenic bacteria such as *Salmonella enterica*, *Escherichia coli*, and *Campylobacter* spp. in farm animals and subsequent exposure to human food is an important threat to financial stability and human health (EFSA, 2022; Mkangara 2023; Rostagno, 2009). Amongst these *Salmonella* is a highly significant meat born pathogen that is responsible for around 93.8 million cases of gastroenteritis and 0.15 million fatalities globally every year (Galán-Relaño et al., 2023). Stress caused by elevated environmental temperature is associated with gut disorders in animals (Gabler & Pearce, 2015), and increase the risk of meat contamination from unhealthy animals. Healthy animals usually maintain a state of equilibrium between flora (beneficial bacteria) and fauna (pathogenic bacteria). Nevertheless, the equilibrium of hazardous bacteria excretion is distributed when external variables like feed withdrawal, transit, hot and humid temperatures, and high animal density come into play, shifting from sporadic to continuous patterns (Mulder, 1995). An elevation in pH in the stomach especially in monogastric animals like pig and poultry, raises the risk of foodborne diseases caused by *Salmonella*, *E. coli*, and *Campylobacter* (Firrman et al., 2022), surviving the transit through the stomach, colonizing the lower gastrointestinal tract, and is discharged into the environment (Rostagno, 2009). Studies have shown that heat stress can decrease blood circulation to the intestines and cause damage to the intestinal lining through oxidative stress. This can lead to disruption of the intestinal barrier and an increased probability of endotoxemia in chickens and swine (Alhenaky et al., 2017; Shakeri et al., 2018). Furthermore, this situation can easily contaminate meat and pose health risk for meat consumers.

Usually meat contamination at slaughterhouse is impacted by heat stress to animals during their farming, so special attention and more study required in this segment, which found inadequate during searching literatures for this review. The animals themselves are the source of bacterial contamination in meat processing plants. Salmonella and other detrimental microbes can propagate horizontally inside the lairage area via feces and polluted drinking water; a recent study in pig abbatoir has confirmed in favor of the statement (Buder et al., 2023). Meat, particularly in processing factories, is often associated with the presence of foodborne pathogens, including Listeria monocytogenes, Bacillus cereus, Clostridium perfringens, and C. botulinum. Foodborne infections exhibit greater resilience and propensity for propagation in correlation with rising ambient heat (Hellberg & Chu, 2016). Changes in housing conditions and good farming practices are anticipated to impact the transmission of foodborne diseases. Elevated levels of pathogenic microorganism carriage, environmental contamination will heighten the likelihood of contaminated meat during processing, and further processing of meat in slaughterhouse.

From 1998 to 2015, the majority of outbreaks associated to pork in the USA took place during the summer months, representing 84.3% of the cases. Salmonella was the most commonly recognized cause of these outbreaks (Self et al., 2017). Salmonella and C. perfringens were the main pathogens that caused foodborne outbreaks in the chicken sector in the United States between 1998 and 2012. These outbreaks were primarily caused by the increased intake of turkey and poultry during certain seasons (Chai et al., 2017). Elevated temperature and related stressors in poultry can promote the penetration of salmonella into the muscle fibers of heat-exposed birds (Alhenaky et al., 2017). This increases the likelihood of contracting a foodborne illness if the meat is not cooked completely before to ingestion. The summer season has been associated with a rise in the occurrence and release of *Campylobacter* bacteria in poultry, resulting in an increase in Campylobacter infections (Skarp et al., 2016). Contrary to this, multiple studies have shown that provision of shed to fattening cattle, with the intension of reducing their exposure to heat does not effectively eradicate E.coli infection (Wells et al., 2017).

Improvement in animal welfare during heat stress to maintain meat quality

It is a proven fact that animal welfare is directly related to the production of premium quality meat for the consumers (Marchewka et al., 2023). To address the heat stress, the welfare of the animals we farm for meat production should be intensively taken care of, especially during hot, humid weather. Furthermore, rearing stresses are responsible for insufficient glycogen and lactic acid in the blood (Matarneh et al., 20230), changing the pH to higher than normal after slaughter (Terlouw et al., 2021) and as per physiological terms this changes can affect meat color, texture and keeping quality. Good husbandry practices are essential tools to obtain gold standard of animal welfare. Usually, changes in the housing system, temperature control, and use of nutraceuticals have been used to maintain optimum feed intake and reduce heat loss. A graphical representation of good farming practices is shown in figure 3. Management techniques evaluated to minimize heat stress and improve animal welfare during rearing are discussed in this section.

Rearing conditions are most important to protect the animals from heat and other possible stresses. Housing techniques are essential in protecting animals from exposure to outside temperatures. Condensation cooling is an efficient method of dissipating heat from the animal's body. It can chill animals on the farm and during their stay at the processing plant by providing air circulation and water cooling systems. Nevertheless, the effects of water cooling are less noticeable or nonexistent in areas with high humidity (Renaudeau et al., 2012).

Integrating a well-designed and constructed shed with natural airflow and insulation may be helpful for the welfare of the animals. As we know, in many places, open shades are used in cattle farming, but providing a better housing system can protect them from the effects of heat (Moons et al., 2014). Only a few studies have examined the impact of shade on meat quality. These studies found that sheep meat under shed had lower pHu levels and improved WHC (Liu et al., 2012). Nevertheless, there were no discernible disparities in meat quality from cattle provided in constructed sheds compared to open-rearing conditions (DiGiacomo et al., 2014). Although shade can effectively mitigate many adverse effects of extreme hot circumstances, its effectiveness may be reduced in hot and humid conditions due to physiological differences in ruminants (Renaudeau et al., 2012). It was observed that the provision of electric fans and water sprinklers aided in the elevated feed intake, reduced respiration rate, and body temperature in dairy cattle (Aggarwal & Upadhyay, 2013). An application of water spray for ten minutes during the transportation of the broiler was found helpful in reducing heat stress in the hot season. Subsequently, it improved the meat quality after slaughter (Xing et al., 2016). Research studies have proven that well-natural ventilation coupled with controlled humidity and temperature can significantly improve pork meat quality regarding drip loss and pH (Driessen et al., 2020). Pork meat quality usually deteriorates more than other species during heat stress, especially when the protein content in the muscle is lower and drip loss is higher (Albert et al., 2024). Better transportation facility in hot weather with sufficient space, ventilation from farm to abattoir found to produce better quality pork meat in terms of color and tenderness (Pasquale, 2022).

Dietary strategies

Adopting dietary practices that prioritize improving energy metabolism could effectively reduce the adverse effects of hot weather and preserve meat quality. The administration of electrolytes is the predominant method used to address heat stress in animals on the farm and in processing facilities before slaughter. Heat stress induces oxidative stress in farmed livestock (Liu et al., 2018; Garner et al., 2017). To alleviate this, adding vitamin C and electrolytes has effectively reduced stress and enhanced immunity in buffaloes under hot conditions (Kumar et al., 2010). Vitamin E aids in the mitigation of oxidative damage to lipids and proteins. Guerra-Rivas et al. (2016) demonstrated that adding Vitamin E reduced the oxidation of beef products and improved their color stability. The inclusion of selenium and vitamin E supplementation in pigs (Liu et al., 201) resulted in a significant reduction in oxidative stress. Nevertheless, research is scarce regarding the influence of Vitamin E and Selenium supplementation on meat quality. In their study, Baldi et al. (2019) found that supplementing vitamin E had a beneficial effect on the color and stability of lamb meat. Betaine is a compound containing a quaternary ammonium group, and when added to the diet, it aids in mitigating the adverse effects of heat stress in livestock. The administration of betaine enhanced body weight in Ross broiler chickens under hot weather circumstances, as reported by Shakeri et al. (2019). A study conducted by Fu et al. (2016) found that including betaine in broiler chickens' diet improved the meat's pH and its ability to hold water. A separate investigation conducted by He et al. (2015) shows evidence that including betaine of a specific quality in broiler feed helped to diminish the harmful effects of heat stress on both body weight and fat storage. An investigation was carried by Shahin et al. (2002) out to examine the physiological effects of chromium supplementation, specifically chromium picolinate, on broiler chickens during high heat exposure. The results revealed a positive correlation between higher chromium supplementation and carcass quality. Resveratrol is a specific type of phenol derived from plants and it was effectively improved meat quality in broiler chicken during heat stress. This was attained through boosting the general ability of the muscle to counteract oxidative stress and increasing the potency of specific antioxidant enzymes, such as catalase (Zhang et al., 2017).

Observing the improvements in animal welfare and meat characteristics achieved by the management of the above strategies and feed nutraceuticals suggests that these techniques may provide significant benefits regarding meat quality for animals in hot climate related stress conditions. However, further investigation is necessary to examine the correlation between heat stress, animal well-being, and characteristics of meat quality in order to promote sustainable livestock production and the meat business.

Additional stressor need to be taken care of to minimize the animal's stress due to the hot climate. To manage the farming environment, heat stress and sustainability in meat production efficiency of nitrogen use needs to be measured and taken care to reduce at the farm level (Hutchings et al., 2020). Efficient and mechanized removal of feces and urine from farms may improve the overall ambient and subsequent liveweight achievement. Smart industrial-scale recycling of this waste into nitrogen and phosphorus for plants could be a sustainable solution to animal welfare (Adegbeye et al., 2020). In addition, achieving sustainability in meat production requires enhancing nutrient use efficiency and strategies to reduce losses of nutrients per unit of meat produced would improve the heat emission in the flock and have positive impacts on the environment and public health (Gerber et al., 2014). To address the deleterious consequences of heat stress, meat processing industries are modernizing transportation systems, slaughter techniques, packaging materials, and deliquiate product handling measures (Ponnampalam and Holman 2023).

Cutting edge technologies to address heat stress

The changing global warming situation and pressure on livestock production demand the application of novel approaches in animal husbandry practices and meat processing systems. Use of digital instruments, and remote sensing in the farms may reduce environmental impact and greenhouse gas emissions bring sustainability in the livestock and meat industry (Kumar et al., 2022). Furthermore, the Internet of Things (IoT), computer vision, and artificial intelligence (AI) have facilitated the automation of farming practices to reduce stressors and improve animal welfare methodologies (Morota et al., 2018; Singh et al., 2020). Machine and deep learning algorithms are a subset of AI and assist in evaluating physiological alterations in animals under stress conditions more precisely. Thus, prompt actions can be taken to alleviate the stresses and improve productivity and superior meat quality (Neethirajan and Kemp). Currently, meat proteomics is used to assess heat shock proteins, texture, and tenderness biomarkers, which helps predict the quality of meat and stress levels in animals before slaughtering. It can be corrected in advance (Kumar et al., 2023). Deep learning techniques (Cowton et al., 2018) and computer vision approach (Jorquera-Chavez et al., 2020). In pigs, an elevating concentration of acute phase protein (APP) is observed during stress and suggested for use as a promising biomarker to identify stress conditions rapidly (Čobanović et al., 2020).

Conclusion

Relevant research revealed that heat stress causes physiological, hormonal, neurological and metabolic reactions and changes in ruminants, pigs, and poultry significantly which is highly connected with meat quality. A significant observation during heat stress is a decrease in muscle glycogen and protein levels and additional reposition of fat stores. In contrast, dehydration diminishes the overall body weight and the amount of dry muscle tissue. Furthermore, heat stress exacerbates oxidative and cellular damage, linked to diminished meat quality and product deterioration. Additionally, summer production has been associated with an increased hazard of foodborne outbreaks compared to winter production. With increased animal productivity, exposure should be given to animal welfare issues regarding better housing, ventilation, and heat management to avoid the detrimental effects of heat stress on animal health and productivity. Nevertheless, it is crucial to acknowledge the special attention on the handling and transporting meat type animals from farms to processing plants to maintain optimum physiological parameters and welfare to maintain product quality in the context of heat stress conditions.

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Table 1. Effect of high temperature on meat quality

Type of Study	Species	Experimental condition	Observations	Reference
Exposed to prolonged heat stress	Pig	MXT 33°C MNT 23°C MXRH 68% MNRH 58%	Heat stress resulted in soft fat in the belly region and was challenging to handle and process.	Seibert et al., 2018
Rearing temperature	Pig	MXT 35°C MNT 22°C MXRH 81% MNRH 78%	Heat stress decreased feed intake without any change in meat quality	Shi et al. (2017)
2 hours of prolonged heat stress	Pig	MXT 37°C MNT 21°C	A quality decrease in muscle structure and the final product were observed.	Cruzen et al., 2017
Exposer to prolonged high temperature	Pig	MXT 30°C MNT 22°C	High temperature reduces meat pH, redness, yellowness, and antioxidant activity.	Yang et al., 2014
Variation in rearing temperatures	Broiler	MXT ranges 36°C/38°C/40°C; MNT: 25°C	A temperature exposure of 36°C increased meat lightness and cooking loss.	Zhang et al. (2019)
Chronic heat stress during rearing	Broiler	MXT 32 ± 1 °C MNT 22 ± 1 °C MXRH 89-90% MNRH 60%	Heat stress reduces pHu, increases lightness, and almost doubles the shear force value in breast meat.	Akter et al., 2017
Summer heat stress on farm	Broiler	MXT 32 °C	Increased reactive oxygen species (ROS) generation in breast meat was observed.	Lu et al., 2017
Transportation in summer	Broiler	Heat exposure 0-4 hours	The impact of summer transpiration on lightness, cooking loss, and drip loss was negative.	Xing et al. (2015)
Feeding environment	Goat	MXT 40 °C MNT 28 °C MXRH 58% MNRH 29%	High temperature significantly increased meat pH and hardness, resulting in pale meat.	Archana et al. (2018)
Housing condition	Lamb	Open house MXT 40°C MNT 28°C controlled shade MXT 21°C MNT 18°C	Housing temperature had no significant influence on pH, TBARS of meat, and carcass weight.	Ponnampalam et al. (2016)
Transportation in summer	Goat	MXT- 42 °C	Preslaughter transportation during high ambient temperatures increases meat pH and hardness, decreasing meat lightness and water-holding capacity.	Kadim et al. (2014)
Seasonal effect	Goat/sheep	MXT 35°C RH-47% Cool season MNT 21°C RH 59%	The summer heat resulted in pale meat and increased meat pH.	Kadim et al. (2008)

MXT=Maximum temperature, MNT=Minimum temperature, Relative humidity= RH, Maximum Relative humidity= MXRH, Minimum Relative humidity= MNRH, TBARS= thiobarbituric acid reactive substances

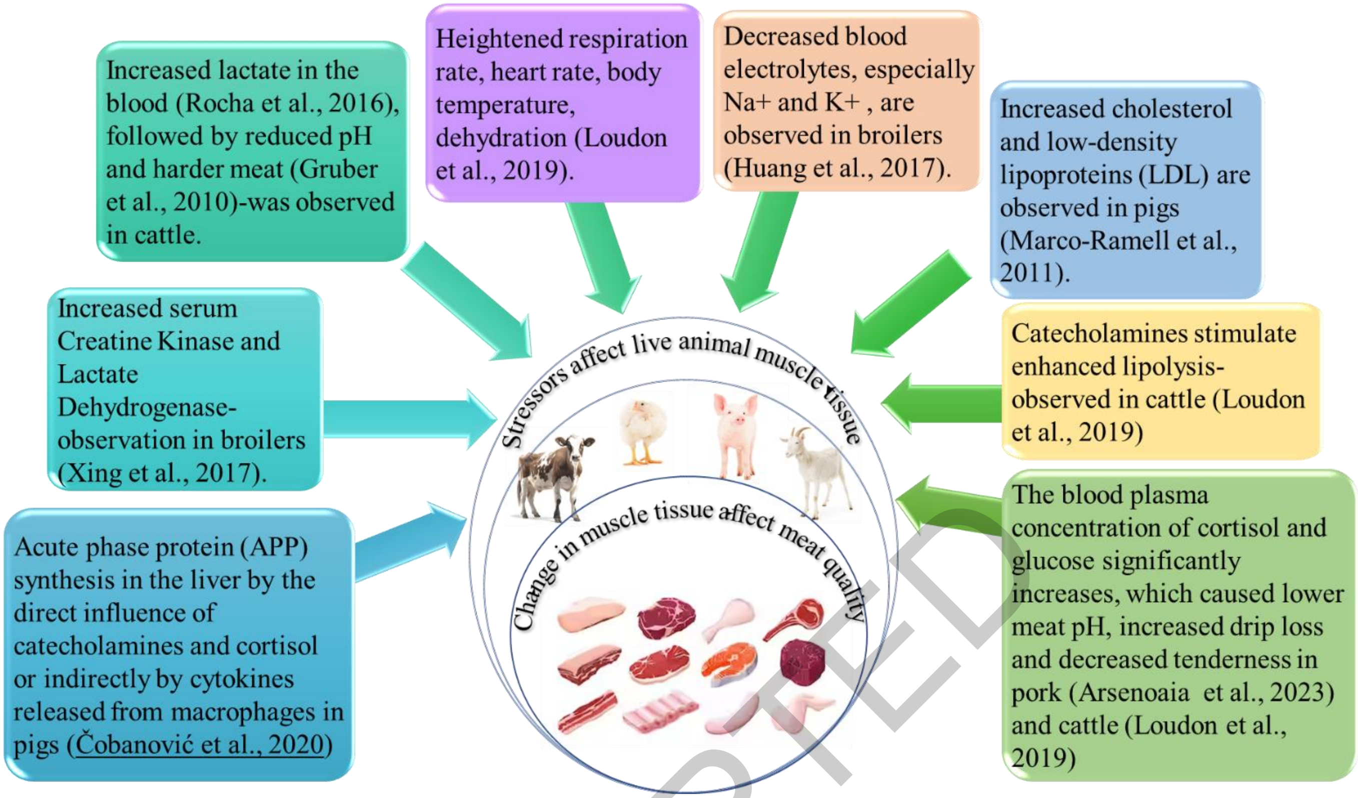
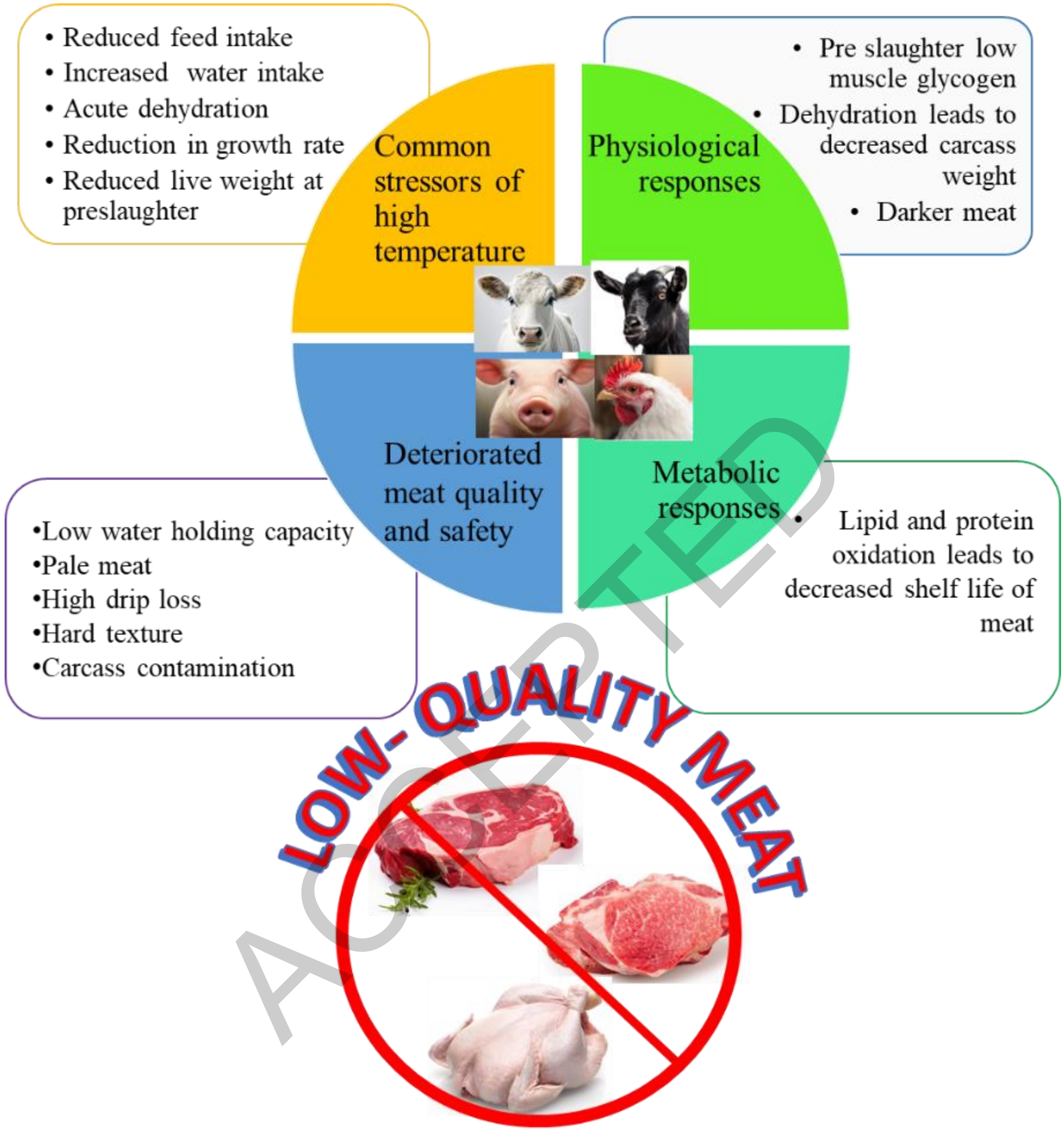


Figure 1. Biological, biochemical, and chemical molecules change during heat stress in farmed animals



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682 **Figure 2. Relationship between heat stress and physiological response of the meat animals.**

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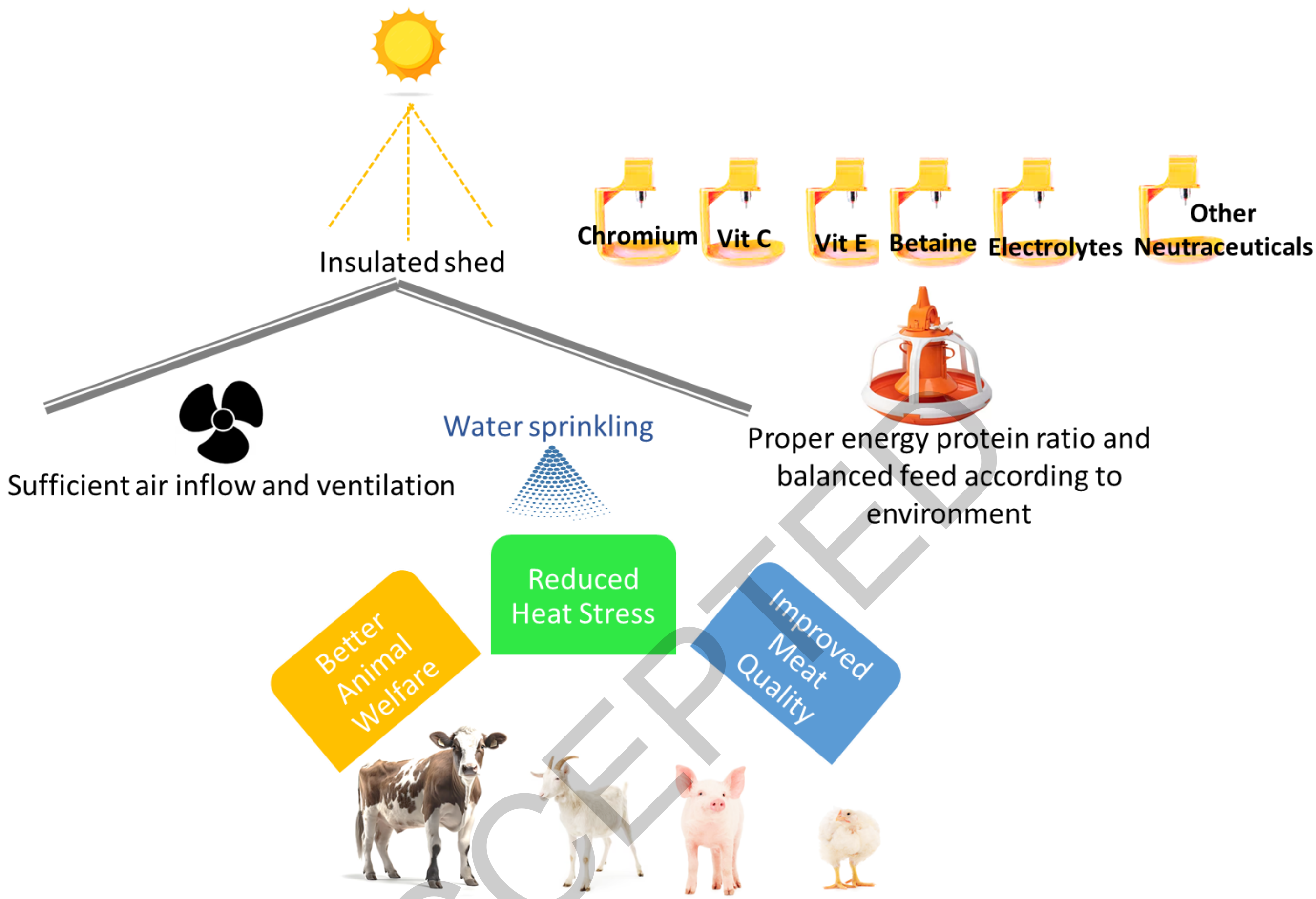

Figure 3. Good farming practices to address heat stress