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Impact of heat stress on buffalo production trend and reproductive efficiency in tropical climate and mitigation strategies: A review

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ABSTRACT

Increasing environmental temperatures is one of the extreme conditions resulting from climate change. Temperatures exceeding the thermoneutral zone in livestock can trigger heat stress. This review provides information regarding the effects of heat stress on the productivity and reproduction of buffalo. In tropical countries such as Indonesia, the buffalo species include swamp buffalo (*Bubalus bubalis*) and river buffalo (Murrah buffalo). Buffalo can tolerate environmental temperatures up to 27.6°C, with an ideal environmental temperature range of 16-24°C. The tropical climate data showed that over the past decade, the temperature increased by approximately 0.8°C annually. If this condition continues it will disrupt the thermoregulatory mechanisms of buffalo, triggering hormonal changes, decreasing milk and meat production, and decreasing reproductive efficiency. Mitigation strategies through cooling methods, the use of sensor-based technology and artificial intelligence, also feed supplementation have shown positive results. Genetic selection and assisted reproductive technology (ART) techniques are promising approaches for increasing the resilience and productivity of buffalo to heat stress. A comprehensive and solution-based scientific approach is essential to achieving sustainable buffalo farming despite the challenges of global climate change.

Introduction

The right to food is one of the Sustainable Development Goals (SDGs), point 2, as expressed by the United Nations (UN). Every individual has the right to access high-quality food to ensure their survival. One effort to support food security is the availability of meat. In 2024, Indonesia still cannot meet its demand for beef and buffalo. Beef and buffalo meat consumption in 2024 reached 759,670 tons (BPS, 2024), an increase of 11.71% compared to 2023. Meanwhile, beef and buffalo meat production in the same year only reached 496,250 tons. As a result, Indonesia experienced a meat deficit of 263.42 thousand tons, reflecting a shortfall of 34.67% of national needs.

Indonesia imports feeder cattle, and feeder buffalo, as well as frozen meat, including buffalo meat to meet the national demand. This import activity possesses the ability impact the development of the livestock sector, which tends to move downstream, oriented more toward the meat trade than livestock farming (Daryanto *et al*., 2020). Continued reliance on imports could create a disincentive to domestic buffalo farming activities. If this situation persists, buffalo farming risks experiencing a sharp decline, threatening the sustainability of the buffalo farming business in Indonesia. The interest of livestock farmers in raising livestock will decrease because they cannot compete with the price of imported meat.

One way to increase food self-sufficiency is to optimize the potential of local livestock, such as buffalo. Buffalo have many advantages, including the ability to use low-quality forage more efficiently than cattle (Rostini *et al*., 2018). In addition, buffalo milk contains higher levels of fat than cow's milk (Priyashantha *et al*., 2024). Buffalo is also known to have good adaptability to diverse geographical and agroecological zones (Rafiepour *et al*., 2021). These advantages make buffalo a potential livestock for sustainable development.

In Indonesia, the buffalo are swamp buffalo (*Bubalus bubalis*) and river buffalo (Murrah buffalo) (Prihandini *et al*., 2023). Swamp buffalo are more commonly found in rural areas and are used as a food source, work animal and tourist attraction. (Tatipikalawan *et al*., 2019). Meanwhile, river buffalo are commonly used for milk production. Some local buffalo species found throughout Indonesia include the Anoa, Gayo, Kuntu, Moa, Murrah, Pampangan, Tedong, Kalang, Simeulue, Java, West Sumatra, North Sumatra, and Sumbawa (Prihandini *et al*., 2023). In addition to its economic function, the buffalo also has high social and cultural value. In Toraja society, buffalo are used in the traditional Rambu Solo ceremony as a symbol of respect for ancestors (Paranoan, 2015) and markers of socio-economic status (Patadungan *et al*., 2020). Among the Batak people, buffalo are also used at weddings and funeral ceremonies called saur matua (Rahman, 2019).

However, due to climate change, buffalo farming in Indonesia faces serious challenges, which negatively impacts population decline. According to data from the Central Statistics Agency (BPS) (2024), the buffalo population has drastically decreased by 50.89% in the last five years (BPS, 2024).

The survival of buffaloes is highly dependent on the availability of water, forage, and feed sources. Climate plays a very important role in the provision of buffalo feed. Changes in temperature will have a very significant impact on the survival of buffaloes. If temperatures are high and rainfall is low and prolonged, water availability will be limited, land will dry up, and forage and feed sources for buffaloes will be limited. Additionally, climate change directly impacts buffalo, causing heat stress, which negatively affects buffalo production (Napolitano *et al*., 2023). Therefore, to address climate change, a comprehensive investigation into the effects of heat stress on buffalo is necessary to develop mitigation strategies and future measures to cope with heat stress.

Heat Stress and Thermoregulatory Challenges in Buffalo

Heat stress poses significant issues for buffalo. They are particularly susceptible to high environmental temperatures because to physiological traits such dark skin, thin fur, and a lack of sweat glands (Gonçalves *et al*., 2021). Buffalo prefers temperatures between 16°C and 24°C, but they can withstand temperatures as high as 27.6°C (Matondang and Talib, 2015). Within this temperature range, buffalo may maintain their core body temperature without using extra energy for thermoregulation. But according to climate statistics, most parts of Indonesia have seen a notable rise in temperature during the last ten years. According to the annual report of Meteorology, Climatology Agency (BMKG, 2024), the hottest year in Indonesia was 27.5°C, with an average air temperature anomaly of 0.8°C. The rise in global temperatures is caused by human activities that produce greenhouse gases. Emissions from fossil fuel combustion, industry, and deforestation have increased the temperature of the atmosphere (Forster *et al*., 2024). This temperature is projected to increase, Indonesia's average temperature was previously in the range of 22.5-27.5°C in the period 1971-2000, it is projected to increase to 25.5-29.5°C in the period 2040-2069 (Toersilowati *et al*., 2022).

This extreme climate change is a serious concern in the livestock sector because environmental temperatures that exceed the thermoneutral zone for livestock can trigger heat stress (Collier *et al*., 2019). In tropical climate, buffalo able to maintain their homeothermy with ranged temperatures between 31.1 and 31.8°C and humidity index ranged from 79.7 to 80.6% (Barros *et al*., 2016). Suboptimal climate conditions can disrupt the buffalo's body heat balance, which will have a long-term impact on reduced performance (Khongdee *et al*., 2011). Several studies have shown the impact of increasing environmental temperatures on plant growth (Chikkagoudara *et al*., 2022), milk production (Seerapu *et al*., 2015), meat production (Marai and Haeeb, 2010), reproductive ability (Vale, 2007; Bayr, 2023), and immune response (Sihag *et al*., 2021).

Water buffalo exposed to intense heat (>35°C) spent 4.06 h immersed in water/mud pools as a cooling mechanism. This condition caused changes in the buffalo's eating patterns and feed consumption (Galloso-Hernández *et al*., 2021). High feed consumption in hot environmental temperatures increases body heat production due to the metabolic process of energy burning (Belhadj Slimen *et al*., 2016). Changes in hormonal activity occur in response to heat stress. Heat stress in buffalo can also be identified through increased body surface temperature, respiratory rate, and rectal temperature (Yadav *et al*., 2025). Buffalo experiencing moderate heat stress show a respiratory rate between 40–60 breaths per minute, increasing to 60–80 breaths per minute at moderate-severe stress levels, 80–120 breaths per minute at high levels, and more than 150 breaths per minute at severe stress condition (Silanikove, 2000). Rectal temperature is an important marker in addition to respiratory rate

If a buffalo has a rectal temperature of 39–43°C, it will experience heat stress. Buffaloes will exhibit signs of heat stress if their rectal temperature increases by 3.2–2.4% from the normal temperature (Aggarwal and Upadhyay, 2013). If the rectal temperature rises, it is evident that buffaloes experience a decrease in performance, especially with an increase in rectal temperature of 10°C (Manica *et al*., 2022). Rectal temperature is influenced by the topographical conditions where buffaloes are kept. Buffaloes in coastal areas exhibit higher rectal temperatures than those kept in lowland areas (Rahmatullah *et al*., 2024). When rectal temperature rises, buffaloes exhibit heat stress behaviors such as panting, reduced movement, decreased feed intake, increased drinking frequency, and seeking shade (Hussain *et al*., 2024). These behaviors significantly impact buffalo performance.

Impact of heat stress on reproductive performance

Previous studies have reported the negative effects of heat stress on buffalo reproduction. . Heat stress can reduce calf birth weight, damage embryos, reduce fertility, and decrease pregnancy rates, delayed estrus, silent heat and lower oocyte quality (Gantner *et al*., 2011; Khan *et al*., 2023). This problem is closely related to changes in the hormonal system. When livestock experience heat stress, luteinizing hormone (LH) levels decrease, while prolactin and adrenocorticotropic hormone (ACTH) levels increase, thereby reducing aromatase enzyme activity in ovarian follicles, which inhibits the conversion of androgens to estradiol. Low estradiol levels result in the absence of estrus behavior (Jan *et al*., 2015). Normally, buffalo experience a 21-day estrus cycle. However, this hormonal imbalance can cause the reproductive cycle to worsen (Gonçalves *et al*., 2021). As a result, it is difficult for breeders to determine the right time for mating their animals. This can result in low pregnancy rates and long calving intervals (Bayr, 2023).

Study Rahmatullah *et al*. (2024) reports indicate that buffalo reared in higher temperature environments have lower reproductive efficiency. Generally, buffalo reproductive performance in Indonesia remains below optimal standards for ruminants. For example, swamp buffalo in West Sumatra have an age at first mating of 33–39 months, an age at first calving of 45–51 months, a calving interval of 24–27 months, and a service per conception rate of 1.55–1.82 months (Reswati *et al*., 2021). Other data shows that the reproductive performance of buffaloes during puberty occurs at the age of 2.60 years, with an estrus duration of approximately 1.5 days, the age of first mating is 3 years, the gestation duration is 10.3 months, the calf crop is 74%, post-partum estrus is 4.21 months, and post-partum mating is 5.18 months (Utomo *et al*., 2023). Meanwhile, Alifia *et al*. (2023) reported an average gestation period of 324.2 days, an age at first calving of 3.7 years, 1.1 services per conception, a calving interval of 467.1 days, and a postpartum mating time of 128.5 days. Thus far, few studies have been conducted specifically examining the impact of heat stress on buffalo reproductive performance, particularly in a tropical climate like Indonesia.

In male buffalo, testicular degeneration has an impact on reducing sperm count, sperm motility, increasing the number of abnormal sperm, and reducing the buffalo's sexual libido (Vale, 2007; Al Amaz and Mishra, 2024)). Increased environmental temperature results in increased temperature in the testicles, disrupting spermatogenesis. Furthermore, heat stress also triggers increased free radical production, which can damage sperm cells. This damage occurs through lipid peroxidation in the sperm membrane, peaking approximately 21 days following heat stress exposure (Garcia-Oliveros *et al*., 2020). As a result, damage to nitrogen bases and DNA strand breaks can occur. DNA methylation patterns have also been reported to be disrupted by heat stress (Kumar *et al*., 2024).

Environmental temperature levels can also be influenced by the type of land where livestock are raised. According to research, Reswati *et al*., (2021). There was no significant effect on serum testosterone levels in male buffaloes raised in lowland, medium, and highland areas, with levels ranging between 1.71–2.29 ng/mL. However, there were significant differences between seasons in semen characteristics. During the dry season in Indonesia, which lasts from May to September, sperm concentration, total sperm output, and straw production in Murrah buffalo were reported to be lower compared to the rainy season (Isnaini *et al*., 2019). This decline is thought to be due to higher environmental temperatures and longer exposure to sunlight during the dry season, which increases testicular temperature and disrupts spermatogenesis (Golher *et al*., 2018). During the dry season, sperm concentration was recorded at 0.91 billion/ml, total sperm output at 3.89 billion, and straw production at 151 units. Meanwhile, during the rainy season, these values increased to 1.22 billion/mL for sperm concentration, 5.20 billion for total sperm output, and 209 straws for semen production (Isnaini *et al*., 2019).

Impact of heat stress on milk

Heat stress in buffalo is a condition of temperature changes that can affect milk production performance. Increasing environmental temperatures beyond the thermoneutral zone in dairy buffaloes reduces forage consumption and the production of Volatile Fatty Acids (VFA) in the rumen. VFA synthesis is broken down into acetic, propionic, and butyric acids, which affect milk production volume, particularly milk fat precursors. The decrease in milk quantity and nutritional quality due to heat stress in buffaloes will affect their selling value and public acceptance. The effects of heat stress on buffalo milk production and composition are presented in Table 1.

Daily milk production in buffaloes affected by heat stress has been shown to experience a significant decrease (Fernandez, 2020; Kalyan *et al.*, 2022; Hussain *et al.*, 2023; Behera *et al.*, 2023; Darji *et al.*, 2024), between 0.03 to 1.90 depending on the breed type. Murrah dairy buffaloes affected by heat stress will experience a decrease in appetite, resulting in a decrease in daily milk production of 0.083 kg/day (Seerapu *et al.*, 2015) to detect a decrease in milk production, the THI (temperature humidity index) value can be used (Zhang *et al.*, 2022). The higher the THI value, the more daily milk production will decrease (Kalyan *et al*, 2022)

The nutritional composition of buffalo milk reviewed in this article includes the percentage of fat, protein, lactose, and total milk solids. The fat percentage of buffalo milk varies from 0.03% to 1%. Dairy buffalo raised in tropical climates experience the highest decline in milk fat percentage in August and September. The period from August 15th to September 14th was identified as a period of decreased milk production and decreased nutritional components in Murrah buffalo milk (Behera *et al.*, 2023). The percentage of fat, protein, and lactose in milk from buffalo exposed to heat stress tends to decrease slightly. When heat stress occurs, energy requirements increase for thermoregulation. However, buffalo experience a decrease in feed consumption, which encourages fat hydrogenation by rumen microbes. Consequently, there is an increase in short-chain fatty acids (SFCAs), which impacts the milk fat profile (Hussain *et al.*, 2023) reported that heat stress also has a direct impact on fat synthesis in the mammary glands.

The buffalo's physiological response to heat stress is to utilize glucogenic amino acids through gluconeogenesis. Gluconeogenesis is the process of glucose synthesis to maintain balanced blood glucose levels (Albenzio *et al.*, 2024) reported that there was no effect of heat stress on buffalo exposed to heat stress, but essential amino acids such as lysine, leucine, and methionine decreased significantly. The solid, non-fat nutritional components of milk are a combination of protein, lactose, minerals, and vitamins.

Murrah buffalo exposed to heat experience a decline in milk nutritional quality, which also affects the reduction in milk non-fat solids. The indicator of changes in milk fatty acids is an increase in short-chain fatty acids (SCFA) and a decrease in monounsaturated fatty acids (MUFA), leading to a reduction in SNF levels. In addition to changes in milk fatty acid profiles, there are also alterations in other nutritional components, including changes in essential amino acid profiles, calcium, copper, and selenium.

Impact of heat stress on meat

Several studies have reported the effects of heat stress on beef buffalo production (Maheswarappa *et al.*, 2022; Chauhan *et al.*, 2023). Buffalo will experience a significant decrease in feed intake when exposed to heat stress (Yadav *et al.*, 2025). The decrease in consumption is due to the reduced duration of feeding, which drops to 364 minutes per day, compared to the normal feeding time of 425 minutes per day. This reduction in feeding time reflects a behavioral adaptation to avoid heat buildup during periods of high ambient temperatures. The combined impact of these physiological and behavioral changes directly contributes to reduced growth rates and the attainment of optimal body weight. It will impact on reducing meat production.

In addition to impacting meat production, heat stress has also been reported to affect the characteristics of buffalo meat. The effects of heat stress on buffalo meat quality can be seen in Table 2. When livestock experience heat stress, body temperature will increase beyond the thermoneutral zone threshold. This increase in body temperature will trigger a physiological response thermoregulatory mechanism characterized by increased respiratory frequency (panting) accompanied by excessive salivation. If the environmental temperature exceeds the heat tolerance threshold, it will impact the carcass quality of livestock. Oxygen supply to the blood will be limited, thereby lowering blood pH. This decrease in blood pH will affect muscle metabolism by breaking down glycogen reserves during life (Gonzalez-Rivas *et al.*, 2020; Chauhan *et al.*, 2023). Muscle glycogen is drastically reduced at low pH, halting glycolysis, resulting in dark meat with a pH >5.7. A relatively high pH in meat causes post-mortem myofibril shrinkage, resulting in changes in structure and water-holding capacity.

Heat stress triggers increased oxidative stress and the accumulation

Table 1. Effect of heat stress on milk production and composition.

Parameter	Effect of Heat Stress	Breed	Average		Average Diff.	References
			Before HS	After HS		
Milk Yield (kg/d)	↓*	River Buffalo (Murrah Buffalo)	7.55	7.47	-0.08	(Behera *et al*., 2023)
	↓*		7.63	7.6	-0.03	(Fernandez, 2020)
	↓*		6.33	5.67	-0.66	(Yadav *et al*.,2022)
	↓*		8.37	7.17	-1.2	(Aarif *et al*., 2023)
	↓*	*Bubalus bubalis*	7.49	5.59	-1.9	(Kalyan *et al*, 2022)
	↓**		6.9	5.3	-1.6	(Hussain *et al*., 2023)
Fat (%)	↓*	River Buffalo (Murrah Buffalo)	7.82	7.79	-0.03	(Behera *et al*., 2023)
	ne		7.62	7.71	0.09	(Aarif *et al*., 2023)
	↓**	*Bubalus bubalis*	6.1	5.1	-1	(Hussain *et al*., 2023)
	↓**		8.78	8.67	-0.11	(Matera *et al*., 2022)
	↓**		8	7.7	-0.3	(Costa *et al*., 2020)
Protein (%)	↓*	River Buffalo (Murrah Buffalo)	3.67	3.64	-0.03	(Aarif *et al*., 2023)
	ne	*Bubalus bubalis*	4.26	4.13	-0.13	(Albenzio *et al*., 2024)
	ne		4.76	4.47	-0.29	(Wang *et al*., 2022)
Lactose (%)	↓*	River Buffalo (Murrah Buffalo)	5.53	5.46	-0.07	(Aarif *et al*., 2023)
	↓*	*Bubalus bubalis*	4.8	4.73	-0.07	(Costa *et al*., 2020)
Solid Non-Fat (%)	↓*	River Buffalo (Murrah Buffalo)	9.63	9.62	-0.01	(Behera *et al*., 2023)
	↓*		9.86	9.74	-0.12	(Aarif *et al*., 2023)

Despite limited direct research, the Indonesian local buffalo is physiologically related to the *Bubalus bubalis* species. Heat stress mechanisms and thermoregulatory responses (eg, panting and wallowing) are very similar. ne = no effect; ↓ = decrease; *p<0.05; **p<0.01

Table 2. Effect of heat stress on meat composition.

Impact Area	Mechanism	Effect on Meat Composition	Physiological Consequences	References
Structural Changes	Reduced oxygen and blood supply because pyruvate cannot enter the mitochondria	Increased pH of meat due to low muscle glycogen	Darker colored meat (DFD meat)	(Chauhan *et al.*, 2023)
	Decreased feed consumption reduces body metabolic heat, glucose precursors	Fat deposition (low intramuscular fat)	Low carcass percentage	
			Low water holding capacity	
Lipid oxidation	Damage to cell function and failure of antioxidant defense mechanisms in neutralizing reactive oxygen species (ROS)	Unsaturated fatty acids increase	Short shelf life of meat	(Xing *et al.*, 2019)
	PUFAs oxidation	Loss of nutritional value of meat	Sensory qualities (juiciness, tenderness, flavor) decrease	
			Rancidity	
Protein content and amino acids	Proteolysis		The texture of the meat is tougher	(Gonzalez-Rivas *et al.*, 2020; Maheswarappa *et al.*, 2022)
	Metabolic stress triggers muscle apoptosis	Decreased amino acid content in meat	Consumer acceptance is decreasing	
	Decreased plasma triiodothyronine (T3) and tetraiodothyronine (T4)			
Sensory characteristics (colour, tenderness, juiceness)	Decreased glycogen reserves and myofibril shrinkage	Increased pH value (>5.7)	Dark Firm Dry (DFD) meat	(Gonzalez-Rivas *et al.*, 2020)
	Proteolysis	The isoelectric point of the muscle decreases	Low cooking loss	
	Aldehydes and ketones from lipid oxidation	Changes in the nutritional value of meat		

of reactive oxygen species (ROS), which accelerate the oxidation of lipids and proteins in muscle tissue. Lipid and protein oxidation can be measured by calculating the amount of malondialdehyde (MDA), protein sulfhydryl, and carbonyl groups. Lipid oxidation occurs when ROS interact with unsaturated fatty acids (PUFAs), producing simpler secondary fatty acid compounds such as aldehydes and ketones. Secondary compounds resulting from fat oxidation cause changes in sensory properties such as juiciness, tenderness, and meat flavor, causing meat to spoil quickly and develop a rancid odor (off-flavor). Meanwhile, protein oxidation in meat causes several changes in conformation, aggregation, bioavailability, and susceptibility to proteolysis (Xing *et al*., 2019). Proteolysis occurs due to an increase in the rate of breakdown of myofibrillar proteins in skeletal muscle mediated by Ca^{2+} and the autophagy-lysosome system (Gonzalez-Rivas *et al*., 2020). Bell *et al*., (2016) reported that proteolysis was the process of breaking down and forming muscle fibers. Heat stress in buffalo results in suboptimal muscle cell differentiation. This results in changes in muscle structure, resulting in meat with a tougher texture.

Mitigation Strategies

Heat stress can be overcome by implementing several cooling strategies, including creating wallows for buffalo to bathe in and spraying water on their bodies. These cooling strategies have a significant impact on increasing buffalo milk production (Yadav *et al*., 2016). Additionally, Petrocchi *et al*. (2023) reported a combination of cooling strategies, namely the use of sprinklers and fans. This combination aims to reduce heat in the buffalo's body through water spraying and air circulation. With air circulation, heat on the buffalo's body can evaporate. Cooling strategies implemented on buffaloes more than three times a day have been proven to increase milk production (Hussain *et al*., 2023). If buffaloes are grazing in pastures, providing shade such as trees or artificial shade can also be a way to protect them from sunlight (Fournel *et al*., 2017).

Currently, artificial intelligence (AI) technology is widely used in buffalo farming. AI can also be used to reduce heat stress in buffalo. One such technology is a cooling system that uses sensors. The sensors detect the buffalo's body temperature, and if the buffalo's body temperature is above normal, the sensors will activate the cooling system so that the buffalo can avoid heat stress (Levit *et al*., 2021). In addition to easily detecting body temperature, the advantages of using AI or the Internet of Things (IoT) also include real-time monitoring of the buffalo's body, making it more efficient for the sustainability of buffalo farming. Feed management can also be a strategy for coping with heat stress. According to research by Petrocchi Jasinski *et al*. (2023), feed containing polyphenols and tannins can increase antioxidants in buffaloes, thereby reducing heat stress. Conte *et al*. (2018) further explain that antioxidants in buffaloes' bodies can be sustained with supplementation of vitamin E, zinc (Zn), and selenium (Se). Feed management for heat stress is also important for buffalo reproduction. Research by Maddahi *et al*. (2024) reported that buffalo experiencing heat stress during embryo development and oocyte maturation can have their heat stress reduced through supplementation of vitamin E, C, and coenzyme Q10 in feed. Natural antioxidants can also be used to mitigate the negative effects of heat stress. One such antioxidant is curcumin, which has been proven to alleviate heat stress in pregnant buffalo.

A heat stress mitigation strategy that can be implemented at the molecular level is to modify gene expression to adapt to extreme temperatures. According to Ashraf *et al*. (2014), buffalo experiencing heat stress will activate cellular defense mechanisms to prevent disruption of reproduction. When buffaloes experience heat stress, they activate the HSF-1 gene to protect cells. If this gene is active, buffaloes produce HSP-70 and HSP-90 (proteins that protect cells at high temperatures) to prevent disruption of oocyte maturation. Another molecular finding reported by Liu *et al*. (2020) indicates that there are genes in buffaloes that can withstand high temperatures. This discovery can serve as a basis for genetic selection to produce buffaloes that can adapt to high temperatures.

Future directions

The development of the water buffalo population in Indonesia over the past 10 years (Fig. 1) shows a significant decline. According to data from the Central Statistics Agency (BPS, 2024), the buffalo population in 2015 was 1,346,917 head, while in 2024 it was 556,794 head. This figure indicates that the buffalo population in Indonesia has decreased by 41.34%.

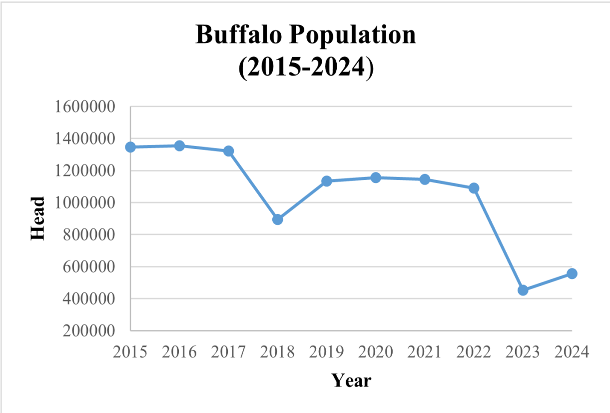

Fig. 1. The Indonesian buffalo population (Murrah and Swamp buffalo) produce milk and meat. Source: Central Statistics Agency 2015-2024s (BPS, 2024)

As was mentioned in the preceding section, the effects of heat stress make this scenario much worse. This suggests that maintaining Indonesia's buffalo population and raising production will be extremely difficult. Genetic selection and altering gene expression in native buffalo should be the main goals of future advancements. Genetic selection has been conducted on the local Toraja buffalo, which is now widespread throughout South Sulawesi Province, Indonesia, due to its superior adaptability and quantitative traits as a meat producer (Maulana *et al.*, 2023). Hufana-Duran *et al.* (2025) reported that wild buffalo breeds such as the Anoa have the potential to be crossbred with wild Tamaraw buffalo in the Philippines for the conservation and propagation of germplasm. It is hoped that this crossbreeding activity will also be carried out for the types of buffalo found in various regions in Indonesia in order to produce buffalo that can withstand heat stress and have good productivity.

The buffalo population in Indonesia must be increased through various comprehensive measures to achieve optimal buffalo growth performance and productivity. Improved reproductive management can be achieved through the application of assisted reproductive technology (ART) techniques. Utilization of reproductive technologies, such as artificial insemination (AI), sperm cryopreservation, and embryo technologies (cloning and in vitro embryo production) have been applied for the buffalo species *Bubalus bubalis* (Baruselli *et al.*, 2023). The identified superior genetics of Indonesian buffalo can be used to increase the number of local buffalo through ART techniques. The use of this technology aligns with adaptation efforts to the challenges of climate change in tropical regions and supports strategies to increase the population and genetic quality of buffalo in Indonesia.

Conclusion

Heat stress in buffalo is a serious challenge because it negatively impacts physiological function, production performance, reproduction, and meat and milk quality. If this continues, the buffalo population in Indonesia will further decline. The implementation of sustainable mitigation strategies is essential to maintain the sustainability of buffalo farming businesses. This sustainability needs to be supported by further research focused on adaptive solutions to address heat stress. Through an integrated scientific approach, it is hoped that the buffalo population in Indonesia can increase.

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Conflict of interest

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

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