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HEAT STRESS CHALLENGES AND MITIGATION STRATEGIES IN INDONESIAN SMALLHOLDER DAIRY FARMS: A BRIEF REVIEW

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ABSTRACT

This review synthesizes the impacts of heat stress and assesses viable mitigation strategies for smallholder dairy farms in Indonesia. In such systems, heat stress can be detected early through observable physiological and behavioral alterations. Clinical indicators such as an increased respiratory rate (exceeding 60 breaths per minute), reduced feed intake, and restless behavior serve as early warning signs that are recognizable by farmers. The effects of heat stress are complex and detrimental, including reductions in milk production by 10–20% or more, increased reproductive disorders with conception rates below 20%, as well as heightened disease susceptibility and elevated production costs. Mitigation strategies for heat stress in smallholder dairy systems encompass three principal aspects: (1) housing and environmental management via barn orientation, roof design and height, natural ventilation, suitable building materials, and shade vegetation as passive cooling methods; (2) feed and water management through increased dietary energy density and provision of drinking water *ad libitum*; and (3) daily activity management by scheduling feeding and milking during cooler periods. Building upon these approaches, pragmatic and cost-effective strategies are vital for maintaining productivity in smallholder dairy systems, while targeted empowerment of farmers through practical support can enhance production by up to 16% and markedly diminish the impacts of heat stress. According to this review, context-specific mitigation of heat stress, supported by farmer empowerment and practical assistance, is crucial for ensuring sustained productivity and resilience in smallholder dairy farming systems within tropical regions.

Keywords: Heat stress, smallholder farming, housing management, livestock productivity, tropical climate

INTRODUCTION

Dairy farming in Indonesia faces significant challenges in maintaining animal welfare and milk productivity, primarily due to the country's tropical climate characterized by high ambient temperatures (24–34 °C) and relative humidity levels of 60–90%. These environmental conditions exceed the thermal comfort zone for Friesian Holstein (FH) dairy cows, which physiologically perform optimally at temperatures between 13 and 25 °C. Prolonged exposure to such climatic conditions disrupts the ability of dairy cows to maintain thermal homeostasis, thereby triggering heat stress and compromising their physiological balance (Marumo et al., 2022; Patriani et al., 2019; Tuwaidan, 2022).

Heat stress is widely recognized as a major limiting factor in dairy production systems, particularly because it increases the metabolic heat load during lactation. Dairy cows are more susceptible to heat stress than other ruminants due to their high metabolic activity associated with intensive milk synthesis. When heat dissipation mechanisms are insufficient to counteract excessive environmental heat, cows experience physiological disturbances, including reduced feed intake, altered metabolism, reproductive disorders, impaired immune function, and decreased milk production. As a consequence, heat stress has been reported to cause substantial economic losses, affecting more than 60% of dairy farms worldwide (Atrian & Shahryar, 2012; Cartwright et al., 2023; Habeeb, 2020; Habimana et al., 2023).

Heat stress is particularly critical in Indonesia, where approximately 80% of the national milk production is produced by smallholder dairy farms (Aranguiz et al., 2024). These farming systems are typically characterized by small herd sizes (1–5 cows), limited capital and land resources, semi-permanent housing, and traditional management practices with minimal access to modern technology (Setianto et al., 2025; Sutawi et al., 2022). Such constraints contribute to relatively low milk productivity, with average yields of only 10–12 liters per cow per day (Hartanto et al., 2020). Limited resources also increase smallholder farmers' vulnerability to climate variability and restrict their capacity to adapt effectively to heat stress.

Previous literature reviews have primarily focused on heat-stress mitigation strategies in Indonesia, often emphasizing technically complex approaches that are difficult to implement and not specifically designed for smallholder dairy farms (Asmarasari et al. 2023). Many of the recommended strategies are capital-intensive and insufficiently adapted to the practical realities of smallholder farming systems. In contrast, smallholder farmers require mitigation measures that are simple, low-cost, easy to implement, and capable of delivering immediate improvements in animal comfort and productivity (Aisyah et al., 2020). To date, only a limited number of review studies have systematically synthesized practical, context-appropriate heat-stress mitigation strategies tailored to smallholder dairy farms in tropical regions.

Therefore, this article aims to briefly review the impacts of heat stress on smallholder dairy farming systems in Indonesia and to evaluate mitigation strategies that are applicable, cost-effective, and readily adoptable by small-scale farmers. The review focuses on housing and environmental engineering, feed and drinking water management, and the scheduling of daily farm activities as adaptive measures to reduce the adverse effects of high ambient temperatures on dairy cow productivity and welfare.

HEAT STRESS AND ITS IMPACT ON SMALLHOLDER DAIRY FARMING

Heat Stress and Its Signs

Stress is a condition in which livestock experience pressure due to sudden environmental changes. One of the most common types of stress in dairy cattle is heat stress, which happens when the animal's body absorbs more heat than it can release. Scientifically, the potential for heat stress can be measured using the Temperature-Humidity Index (THI), which combines the effects of air temperature and humidity. This index is calculated using the formula THI = (0.8 × DBT) + [(RH/100) × (DBT - 14.4)] + 46.4, where DBT is the dry-bulb temperature (°C) and RH is the relative humidity (%). Based on the resulting THI value, the level of heat stress can be categorized as follows: safe or no stress if below 70, mild stress at 70-75, semi-moderate stress at 76-80, moderate stress at 81-85, and severe stress if above 85 (Kulkarni et al., 2017). Although THI offers a solid scientific basis for assessing heat stress risk, its use at smallholder farms is often limited by a lack of measuring tools and technical knowledge. Therefore, direct observation of clinical signs in cattle can be a more practical method that farmers can perform daily.

Signs of heat stress typically show up when a cow's body temperature rises above normal levels. The normal body temperature for adult cows ranges from 37.8-39.2°C, while for calves it is between 38.5-39.8°C (Abdisa, 2017). If the body temperature exceeds these ranges, the cow may be experiencing heat stress. Although not measured directly, an increase in body temperature can lead to several visible signs in the cow, both behavioral and physical, that the farmer can notice. Changes in behavior in cows under heat stress include increased respiratory rate, panting, standing more often, increased water intake, and decreased appetite. This decrease in feed intake is a natural response to limit heat production, as the digestive process generates additional metabolic heat in the cow's body. Consequently, dry matter intake decreases, rumen activity slows down, and nutrient absorption declines, which ultimately lowers the cow's energy and productivity (Atrian & Shahryar, 2012; Divekar & Dhami, 2016).

Table 1. Respiratory rate in cattle

Respiratory Rate (times/minute)	Explanation and action
40-60	The respiratory rate remains within the normal range for cattle.
>60	This frequency indicates that the cow's body temperature has reached approximately 39°C. At this point, the farmer needs to take immediate action to cool the cow's body temperature.
>70	The cow begins to have difficulty breathing and shows signs of heat stress. If it reaches the 80s, it indicates severe heat stress. And if it exceeds 90-100 per minute, the cow is in a hazardous condition and at risk of heat exhaustion.

Source: Dairy Australia (2023)

Practically, the clearest sign that farmers can recognize when cattle begin to overheat is a change in respiratory rate. Mohammed (2023) emphasized that an increase in breathing frequency is the earliest and most accurate indicator of heat stress, as it can rise immediately after cattle feel hot. Normally, adult dairy cattle breathe about 40-60 times per minute. As shown in Table 1, a respiratory rate above 60 breaths per minute indicates that the cattle's body temperature has reached approximately 39°C, and farmers should act. Besides increased breathing, there are several other physical signs that are also easy to notice without specialized equipment. Cattle might start producing excessive saliva, sweating more, and appearing restless (Divekar & Dhami, 2016). These symptoms occur because the cattle are working to lower their body temperature. By paying attention to small changes, such as respiratory rate and behavior, farmers can recognize heat stress sooner, allowing them to take preventive measures before the condition worsens.

Impact of Heat Stress

Heat stress, or heat strain, is a major challenge in dairy cow management in tropical regions because it significantly affects physiological, metabolic, and reproductive aspects (Atrian & Shahryar, 2012; Iqbal et al., 2021; Tuwaidan, 2022). After the initial body

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response, such as increased respiration rate and behavioral changes, ongoing heat stress can disrupt digestive functions. Reduced feed intake decreases rumination activity and saliva production, weakening the rumen's buffering capacity. Simultaneously, cows tend to select more easily fermentable feeds, which can lead to acid buildup and a decrease in rumen pH. This condition hampers the activity of fiber-degrading bacteria and can trigger ruminal acidosis, which then affects milk production and quality, metabolic health, and reproductive performance (Iqbal et al., 2021; Tuwaidan, 2022).

One tangible effect of heat stress on dairy cattle farming is a decrease in milk production. According to Divekar & Dhami (2016), heat stress can reduce milk output from dairy cows by 10-20%, depending on management practices. This aligns with research by Hossain et al. (2023), which shows that a 17% rise in THI during summer can reduce milk production by up to 24.4%, while lowering milk fat and protein content by 14.5% and 15.2%, respectively. Other studies also report that an increase in THI causes milk production to decline by 4.16-14.42% (Ekine-dzivenu et al., 2020). Tessalonika et al. (2024) explain that the reduction in milk production due to heat stress primarily results from decreased feed intake and impaired nutrient absorption in the digestive system. During high temperatures, the cow's body shunts more blood to the skin to help dissipate heat. Although this process is vital for cooling, it disrupts nutrient metabolism. Consequently, fewer nutrients are available for milk synthesis, leading to a notable decrease in milk output during hot weather.

The impact of heat stress on dairy cows varies across regions because each altitude zone has a different combination of temperature and humidity. This pattern is supported by the findings of Setyorini et al. (2020) and Mariana et al. (2019), summarized in Table 2, which indicates that lower altitudes are associated with higher ambient temperatures and Temperature–Humidity Index (THI) values. Consequently, dairy cows in lowland areas experience greater heat stress, resulting in reduced milk production. These findings confirm that elevated environmental temperatures directly impair dairy cow productivity. For smallholder farms, this condition represents a major challenge, as feed costs remain high while milk yields tend to decline.

Table 2. Environmental and milk production parameters of dairy cows in three elevation zones

Parameter	Highland		Midland		Lowland	
	Setyorini et al. (2020)	Mariana et al. (2019)	Setyorini et al. (2020)	Mariana et al. (2019)	Setyorini et al. (2020)	Mariana et al. (2019)
Elevation (meters above sea level)	1065	1241	789	574	449	97
Temperature (˚C)	23,2-26,1	25,7±4,41	23,6-26,9	28,9±9,01	26,1-30,5	33,1±3,91
Moisture (%)	78,75-85,75	56,7±14,82	64-85	57,2±14,02	60-81,5	61,8±15,4
THI	72-77	73,8±5,1	74-78	78,3±9,33	77-79	83,5±4,19
Milk production (l/head/day)	13,36	13,1±3,52	14,1	11,3±4,73	10,48	7±3,36

Under heat stress, dairy cows experience increased physiological pressure because milk production demand remains high while body temperature regulation mechanisms are disrupted. This situation causes a series of endocrine changes that directly impact the reproductive system. An elevated body temperature reduces hypothalamic release of gonadotropin-releasing hormone (GnRH), leading to reduced secretion of follicle-stimulating hormone (FSH) and luteinising hormone (LH) by the pituitary gland. These hormones are key drivers of ovarian follicle development. When the dominant follicle fails to develop, and estrogen production falls, signs of heat become silent (silent heat), and ovulation does not occur. This condition results in fertilization failure and lowers the chances of conception in dairy cows (Susilawati et al., 2023).

Reproductive disturbances caused by heat stress can lead to various physiological and management challenges. This condition not only increases the risk of fertilization failure but also extends reproductive intervals such as postpartum estrus >90 days, days open >85-110 days, calving interval >12-15 months, conception rate <60%, services per conception >1.5, and a decline in calf birth rates (Jatmiko, 2020). Field evidence supports this pattern: Yusuf et al. (2020) reported that reproductive disorders cause many cows to be artificially inseminated more than three times, yet their conception rate remains only 20%, with an average calving interval of 550 days. Meanwhile, a study by Lestari (2022) shows that reproductive disturbances result in an inter-calving period of 14.44±0.5 days, days open of 154.5±61.4 days, and a services-per-conception rate of 3.0±0.5 times. The occurrence of these conditions can increase the costs of maintaining unproductive breeding stock and reduce reproductive efficiency, hindering population growth and causing a decline in milk production.

Not only reproduction but also excessive heat can impair cows' immune systems. Oliveira et al. (2025) explains that this occurs because the nervous system, hormones, and immune response are interconnected and work together bidirectionally. When livestock experience heat stress, the body releases hormones such as cortisol and catecholamines. These hormones can affect the functioning of cells, such as white blood cells, disrupting the immune response and making livestock more vulnerable to various illnesses. One disease that can result from decreased immunity is mastitis. If heat stress occurs alongside mastitis, the effects can be even more severe: milk production declines, milk quality worsens, treatment costs increase, and cow fertility is affected (Wang et al., 2021). For small-scale farms that keep only a few cows, losing production from just one animal has a significant economic impact. The decline in milk output, reproductive issues, and higher disease risks directly reduce income, especially when facilities and infrastructure for animal health and comfort are limited.

HEAT STRESS MITIGATION STRATEGY IN SMALLHOLDER DAIRY FARMING

Housing and Environmental Management

The occurrence of heat stress is closely linked to the microclimate inside the shed and the physiological capacity of each individual livestock animal. Dairy cattle are among the most vulnerable to heat stress due to their high metabolic heat production. The intensive metabolic processes involved in milk production generate substantial body heat, which hampers cattle's ability to dissipate it as environmental temperatures rise (Cartwright et al., 2023). For animal welfare, managing the shed's microclimate is essential to ensure comfort and optimize productivity. THI, a key indicator for evaluating heat stress potential, is affected not only by external environmental factors but also by the shed's physical design, including building orientation, roof height, ventilation area, and the materials used for the roof and walls (Lovarelli et al., 2021).

The orientation of the shed (its long axis) is a key factor in creating a comfortable environment, especially in tropical regions like Indonesia. According to Ashokbabu et al. (2024), positioning the shed with its long axis running east-west is most beneficial in tropical climates. This orientation provides extensive shade throughout the day, shielding livestock from direct sunlight and excessive heat. However, Sugiharto (2021) emphasized that adjusting the shed's orientation should account for local topography. In lowland areas with generally high temperatures, an east-west orientation (Figure 1) is recommended because it reduces direct sunlight on walls and roofs, helping maintain stable indoor temperatures. Proper ventilation is also essential to ensure good air circulation and prevent excess humidity. In medium- to highland areas, a north-south orientation might be more suitable, as the environment tends to be cooler and morning sunlight enters the area optimally from the east, which helps inhibit microbial growth and keep the area around livestock clean. Adequate ventilation remains critical to prevent heat buildup during the day and afternoon (Sugiharto, 2021).

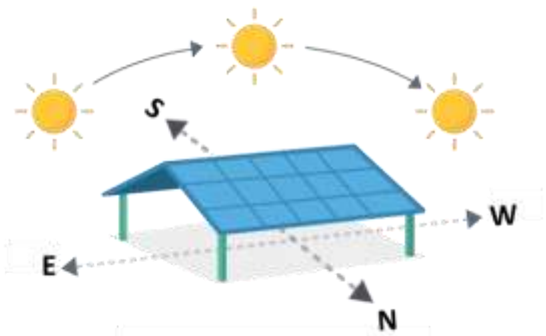

Figure 1. East-west orientation shed

Along with shed orientation, roof design significantly influences temperature control and airflow inside the shed. A well-designed roof helps naturally release heat and reduces moisture buildup. For sheds in highland regions, a gable roof is recommended, whereas a monopitched roof is better suited for lowland areas (Manafe, 2019). Nonetheless, most small-scale farms in Indonesia primarily use saddle or gable roofs (Prabowo et al., 2025). Apriyani et al. (2023) observed that this type of roof offers practical benefits, including ease of manufacture, relatively low construction costs, and simple maintenance. These advantages make the gable roof the preferred choice of many farmers. However, airflow in gable roofs is limited because air tends to move mostly at the lower part of the roof. When ridge ventilation is not installed, hot air rising to the top can become trapped, reducing overall airflow circulation. Adjusting the roof height is crucial for optimizing natural airflow inside the shed. Research by Suherman et al. (2017) indicates that roof height influences reductions in air temperature and increases in humidity within the shed environment. In lowland areas with relatively high air temperatures, the shed roof should be higher, at around 3.5 to 4.5 meters above the floor, to improve air circulation and support natural cooling. Conversely, in highland areas with cooler temperatures, the roof should be lower, approximately 2.5 to 3.5 meters, to trap heat effectively and keep the interior warm and comfortable for the cattle (Manafe, 2019; Susana et al., 2024). In addition to its shape and height, the materials used can also affect the shed's microclimate.

Roofing materials can include asbestos, tiles, and other materials, each with a different ideal slope angle. Tiles are recommended to have a slope of 30-45%, asbestos or zinc 15-20%, and palm-leaf or cogon-grass thatch 25-30%. Among these roofing materials, tile is most recommended for pens in lowland areas (Manafe, 2019). According to research by Maylinda and Riskila (2023), dairy cows kept in tiled-roof pens have lower body temperatures and higher milk production than those in asbestos-roofed pens. However, heat-tolerance capacity (HTC) and

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respiration frequency are not affected by roof type. Generally, tiled roofs provide a more comfortable microclimate and help reduce heat stress effects, making them more suitable for smallholder farms in tropical regions.

Nevertheless, passive protection provided by roof materials alone is often insufficient when environmental temperatures fall outside the comfortable range for dairy cows. Therefore, temperature control can be improved through passive cooling design. This involves combining the selection of roof and wall colors, building orientation, and natural ventilation. Light colors have high reflectivity, which reduces the amount of solar radiation absorbed by the surface. The heat load can also be reduced by choosing light or white-painted walls (Sugiharto, 2021).

Research by Patil et al. (2025) showed that an east-west orientation of the shed with a gable roof made of asbestos, equipped with four wind-powered roof ventilators and a combination of white exterior paint and black interior paint, can form an affordable passive cooling system that does not require electricity but effectively maintains the shed's temperature. Similar results were reported by Tikul & Prachum (2022), who found that passive design lowered the shed's internal temperature by up to 5°C relative to the outside temperature and reduced humidity to 60–70%, demonstrating the effectiveness of passive strategies in tropical regions.

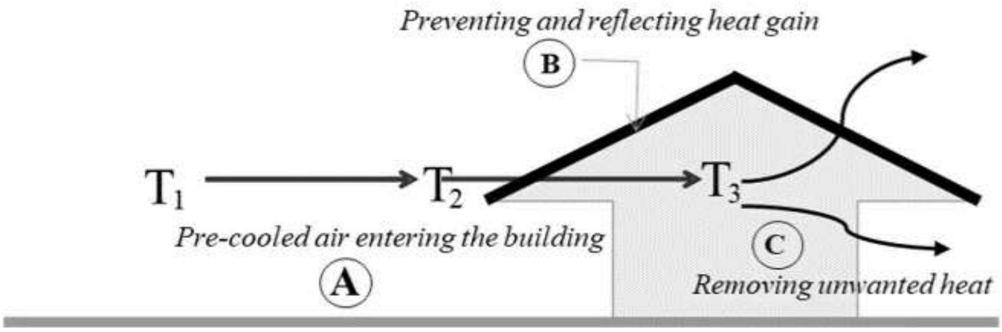

Figure 2. Passive cooling design (Tikul & Prachum, 2022)

As a complement to the passive cooling design strategy, vegetation around the pen also plays a vital role. The shade provided by trees helps lower ambient temperatures and shields livestock from heat stress caused by direct sunlight. Vegetation acts as a natural barrier that reduces the amount of heat reaching the ground and pen walls, creating a cooler, more stable, and comfortable microclimate—especially during extreme heat due to climate change (Sugiharto, 2021; Widiawati et al., 2023). In addition to reducing heat, trees also improve environmental comfort for both livestock and farmers. According to Das et al. (2016), trees produce a cooling effect through evaporation of moisture from their leaves. The choice of tree species should match the tropical climate and local seasonal patterns; ideally, they should have dense foliage during the dry season for maximum shade, but not be too dense or shed leaves excessively during the rainy season so that morning sunlight can still enter the pen (Li et al., 2025). The research by Li et al. (2025) shows that planting poplar trees on the west side of the pen, oriented east-west, effectively reduces heat stress, lowers cattle respiration rates, increases milk production, boosts antioxidant activity, and enhances immune function in cattle. Therefore, vegetation is a key component of the passive cooling, which should be plural, since there are many options to reduce the heat stress effect

If passive strategies alone are insufficient to mitigate heat stress, active cooling methods using water and air may be applied as supplementary measures. Sprinkler systems, fans, or a combination of both have been shown to effectively lower barn and cattle body temperatures. Badali et al. (2023) reported that the combined sprinkler-fan system could reduce barn temperature by 3°C, body temperature by 1°C, and respiration rate by 8 breaths per minute. Research by Liu et al. (2024) also indicated that water-spraying treatments and the combined sprayer-fan approach could significantly reduce heart rate, rectal temperature, and Heat Tolerance Coefficient (HCT) in dairy cows. Meanwhile, Kartiko et al. (2019) observed that the combination of fans and nozzles could lower air temperature by 1°C, though it did not have a significant physiological effect on cattle. Based on these studies, active cooling systems using water and air have proven effective for maintaining barn temperatures in tropical regions. However, the application of active cooling systems generally requires higher capital investment, continuous water and electricity supply, and greater technical management, which may limit their feasibility for smallholder dairy farms.

Feed and Drinking Water Management

Adjusting feed ingredients is a crucial step to reduce the negative effects of heat stress on dairy cows. Improving feeding practices and adding mineral and vitamin supplements are known to help livestock adapt to hot conditions. To offset decreased feed intake and increased heat production due to forage fermentation, the diet needs to be supplemented with energy sources, such as additional concentrates (Sammad et al., 2020). During hot weather, energy becomes the most limited nutrient for lactating dairy cows. Therefore, managing the diet by lowering the proportion of forage and increasing the proportion of concentrate can help, as lower fiber levels can boost feed intake, while concentrates provide a quick energy source. However, maintaining fiber balance is essential to prevent rumen function issues (Divekar & Dhami, 2016). Adequate fiber supports optimal fermentation; concentrate levels should not exceed 60% of the diet's total dry matter (Ventura et al., 2021).

The diet for lactating dairy cows should ideally contain at least 40-45% dry matter from forage. An imbalance between energy and fiber can change milk composition: too much energy with low fiber can lower fat content, while too little energy with high fiber can decrease protein levels (Garamu, 2019). It is recommended that concentrates given to dairy cows should not exceed 2% of their body weight. The ideal amount ranges from about 6.5 to 10.5 kg per cow per day, depending on the forage quantity and quality and the milk production goal (Krasniqi et al., 2018). On smallholder farms, this approach can be difficult to implement due to limited access to quality concentrates. As a result, high-energy local materials such as rice husks, bran, or polard can serve as practical and more affordable alternatives Syamsi et al., 2020).

On the other hand, water becomes a vital factor when livestock experience heat stress. As environmental temperatures rise, cattle naturally lose significant amounts of body fluids through evaporation and respiration to lower their body temperature. This increases their need for drinking water. Water plays a key role in transferring heat from the body to the environment, helping to reduce body temperature. The water needs of cattle can vary depending on factors such as body size, milk production, the amount of dry matter they consume, environmental temperature and humidity, the temperature of the drinking water, water quality and availability, and the water content in their feed (Schroeder, 2015). According to Monteiro et al. (2023), average daily water intake requirements vary across physiological groups of cattle. Calves require approximately 10 L per day, young cattle about 25 L, heifers 35–45 L, dry cows 40–60 L, and lactating cows 50–100 L per day. However, to meet their water needs properly, dairy cows should have constant access to water, also known as water ad libitum. This method allows cows unrestricted access, enabling them to drink according to their natural needs. Generally, this approach best supports the health, digestion, and metabolism of the livestock (Nizzi et al., 2025).

Daily Activity Management

In hot tropical environments, managing daily activities is essential for reducing heat stress in dairy cows. Tasks such as feeding, milking, and grooming should be scheduled based on the daily temperature patterns, as increases in temperature and solar radiation during the day can worsen heat stress. Between 10:00 and 15:00, air temperature, THI values, and radiation intensity peak, with the peak around 13:00, putting cows at the greatest risk of increased body temperature (Enos The, 2018; Suherman, 2014). To minimize heat exposure during this critical time, feeding schedules should be arranged at cooler parts of the day. Cows tend to eat more when temperatures are lower, so it is recommended to offer a small portion of feed during the day and a larger portion in the evening, or to concentrate feeding in the morning and evening (Divekar & Dhami, 2016; Suherman & Purwanto, 2020). Research by Suherman (2014) showed that feeding at 05:00 and 18:00 helps maintain lower rectal and skin temperatures in dairy cows during the hottest part of the day.

Adjusting milking activities is an important step. It is recommended to perform milking before 10:00 am, and evening milking should be delayed until the environment cools. These recommendations follow the Dairy Australia (2023) guidelines and are supported by the findings of Schütz et al. (2023), which showed that cows whose milking and feeding are delayed from hot to cooler periods have more stable body temperatures and are less likely to become overheated. Additionally, physical care, such as bathing and regular grooming, is also beneficial, especially in lowland areas. These simple practices have been shown to reduce heat stress and improve cow comfort. Research by Verma et al. (2017) indicated that twice-daily bathing and grooming in crossbred FH cows can effectively reduce heat stress, enhance livestock comfort, and positively influence milk yield and quality during the summer season.

EMPOWERING FARMERS FOR HEAT STRESS MITIGATION

The various heat stress mitigation strategies previously described can, in principle, be applied to smallholder farms. However, implementing them in the field is not always easy. Many farmers still face challenges, especially related to limited technical knowledge, management skills, and access to adequate information (Hlatshwayo et al., 2021). In fact, efforts to reduce heat impacts are inherently part of Good Dairy Farming Practices (GDFP), particularly concerning animal welfare and environmental management. These two aspects are interconnected and form a vital foundation for developing a dairy cattle system that can adapt to tropical climates. According to the FAO & IDF (2011) guidelines, animal welfare emphasizes that cattle must be protected from discomfort, including exposure to excessively high environmental temperatures. Its implementation involves meeting several basic conditions, such as adequate barn ventilation, protection from direct sunlight, and continuous access to fresh water. In other words, heat stress mitigation is not a separate activity but an essential part of good barn environment management within the framework of GDFP.

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In field practice, the introduction of GDFP to smallholder farmers, as conducted by Asminaya et al. (2024), among dairy cattle farmers in Wesalo Village, Lalolae Subdistrict, East Kolaka Regency, emphasized five main aspects: breeding and reproduction, provision of feed and drinking water, management, housing and equipment, as well as animal health and welfare. Although several principles related to heat stress control were addressed, the empowerment material did not yet position heat stress as a primary issue requiring specific attention. This highlights the need for training activities that directly address heat stress risks and symptoms, and provide practical measures smallholder farmers can use to mitigate heat stress. A similar empowerment model was used by Mariana et al. (2021) through socialization and training programs for dairy goat farmers in Gampong Lamlumpu, Aceh, focusing on environmental modification and feed management to reduce heat stress risks. The program led to increased milk production and reduced heat stress levels by up to 16%. These results show that education based on practical mentoring, tailored to local conditions, can significantly improve farmers' understanding and livestock performance. Therefore, empowering farmers with a specific focus on heat stress mitigation can be a strategic step toward improving the sustainability of the smallholder dairy sector and supporting the goal of national self-sufficiency in milk.

CONCLUSION

This review highlights that heat stress is a major limiting factor affecting productivity, reproductive performance, and health of dairy cows in smallholder farming systems in Indonesia under tropical climatic conditions. Elevated ambient temperature and humidity disrupt feed intake, rumen function, milk yield and quality, reproductive efficiency, and immune responses, with more severe impacts observed in lowland areas and resource-limited farms. Given that smallholder dairy farms account for most of the national milk production, the negative effects of heat stress pose a significant challenge to the sustainability of the Indonesian dairy sector.

Effective mitigation of heat stress in smallholder dairy systems should prioritize passive cooling strategies, including appropriate barn orientation, roof design and height, natural ventilation, reflective materials, and shade vegetation, as these approaches are practical, cost-effective, and compatible with limited farm resources. Nutritional management through improved energy balance, continuous access to drinking water, and adjustments to daily feeding and milking schedules further supports animal comfort and productivity. Although active cooling technologies have demonstrated effectiveness in reducing heat load, their adoption remains constrained by higher costs and infrastructure requirements, making them more suitable as complementary options. Future research should focus on evaluating the long-term effectiveness and economic feasibility of passive cooling strategies and strengthening farmer-centered extension programs to enhance the adoption and resilience of smallholder dairy farming systems in tropical regions.

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