

Low-Power Hvls Ventilation Integrated with Hybrid Solar Energy for Heat Stress Mitigation and Dairy Cow Welfare Improvement in Open-Housing Barns

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Abstract

Heat stress is a major constraint on dairy production in tropical regions, particularly in open-housing barns with limited environmental control. This study evaluated a low-power high-volume low-speed (HVLS) ventilation system integrated with a hybrid solar energy supply using a matched-season controlled before-and-after quasi-experimental field design. Baseline data were collected from May to August 2023, and post-installation data were collected from May to August 2024. The study was conducted in an open-housing dairy farm with 104 Holstein Friesian crossbred dairy cows. Among these animals, 48 lactating cows were included in the primary evaluation and allocated by barn-zone exposure into a control group ($n = 19$) located in the non-HVLS zone and a treatment group ($n = 29$) located under the HVLS airflow coverage area. Barn temperature and relative humidity were measured using custom-built DHT11-based sensor nodes. Respiration rate was determined by counting flank movements for one minute (60 s) before afternoon milking during the hot period, and infrared body surface temperature was measured at the lateral body region using a non-contact infrared thermometer (3CMEDICAL FI-01). In the treatment group, THI decreased from 82.6 to 78.8, average respiration rate decreased from 83.5 to 65.2 breaths/min, and infrared body surface temperature decreased by approximately 0.6 °C. Average daily milk yield increased from 12.8 to 14.3 L/cow/day, representing an approximate 12% improvement in the treatment group, whereas

the control group showed no clear change. The system consumed approximately 1.2 kWh/day, with 78% of the energy supplied by the hybrid solar subsystem. Economic estimation using cooperative milk-price records and the electricity tariff during the monitoring period indicated that the additional milk income greatly exceeded the operating electricity cost. These findings suggest that low-power HVLS ventilation integrated with hybrid solar energy is a practical and economically promising approach for improving dairy cow welfare and milk production in tropical open-housing barns.

Keywords: Heat stress mitigation, Dairy farm management, HVLS ventilation system, Hybrid solar energy, Open-housing dairy system

Introduction

Heat stress is widely recognized as a major environmental challenge affecting dairy production systems, particularly in tropical and subtropical regions (West, 2003; Collier et al., 2006). When ambient temperature and relative humidity exceed the thermoneutral zone of dairy cows, animals experience physiological strain as they attempt to dissipate excess metabolic heat. Open-housing dairy barns, which are commonly adopted due to their low construction cost and structural simplicity, are especially vulnerable to heat stress because they rely primarily on natural ventilation and lack active climate control mechanisms (Chantalakhana & Falvey, 1999; FAO, 2009).

Physiological responses to heat stress in dairy cows include increased respiration rate, elevated infrared body surface temperature, and alterations in endocrine and metabolic activity (Bernabucci et al., 2010; Collier & Gebremedhin, 2015). Respiration rate is often the earliest observable response to rising thermal load, reflecting increased evaporative heat loss through panting (Hahn, 1999). Sustained elevation of infrared body surface temperature indicates insufficient heat dissipation and has been associated with impaired immune function, reduced reproductive performance, and increased disease susceptibility (Rhoads et al., 2009; Lacetera, 2019). These physiological indicators are widely used as direct measures of compromised animal welfare under heat stress conditions (Mader et al., 2006; EFSA, 2009).

In addition to welfare concerns, heat stress has a pronounced negative impact on milk production performance. Numerous studies have demonstrated a strong inverse relationship between the temperature–humidity index (THI) and milk yield in dairy cattle (Armstrong, 1994;

Bohmanova et al., 2007). As THI exceeds critical thresholds, dairy cows reduce feed intake and redirect metabolic energy from milk synthesis toward thermoregulation, leading to measurable declines in milk yield (Rhoads et al., 2009). Large-scale field studies and meta-analyses report milk production losses ranging from 10% to over 20% during prolonged hot seasons, depending on breed, lactation stage, and management practices (St-Pierre et al., 2003; Kadzere et al., 2002).

To mitigate heat stress, various environmental modification strategies have been proposed, including shade provision, evaporative cooling, misting systems, and mechanical ventilation. While these approaches can reduce physiological stress under certain conditions, their applicability in open-housing dairy barns is often constrained by high energy consumption, substantial water requirements, and system complexity (Bucklin et al., 1991; Khongdee et al., 2006). These limitations are particularly significant for small- and medium-scale dairy farms operating under economic and infrastructure constraints.

Ventilation-based heat stress mitigation has therefore received increasing attention due to its relative simplicity and energy efficiency. By increasing air velocity at cow level, ventilation enhances convective and evaporative heat loss, thereby reducing effective thermal load even when ambient temperature remains high (Gebremedhin & Wu, 2003; Ji et al., 2020). High-volume low-speed (HVLS) fans are of particular interest because they generate large-scale, uniform airflow while consuming substantially less electrical power than conventional high-speed fans (Bucklin et al., 1991; Mondaca, 2019). However, most existing studies on HVLS ventilation have focused on enclosed or semi-enclosed barns in large-scale commercial operations, with limited empirical evidence from open-housing dairy barns commonly used in tropical regions (Ji et al., 2020; Mondaca, 2019).

Parallel to advances in ventilation technology, renewable energy integration has emerged as a promising strategy for improving the sustainability and reliability of livestock housing systems. Solar-powered and hybrid solar-grid energy systems have been explored to support ventilation and cooling in agricultural applications, reducing reliance on grid electricity and lowering operating costs (Mekhilef et al., 2011; IRENA and FAO, 2021). Despite these advances, limited research has examined the combined effects of low-power HVLS ventilation and hybrid solar energy systems on animal welfare and production outcomes in open-housing dairy barns under real-world field conditions (IRENA and FAO, 2021; Rehman et al., 2012).

In Thailand, heat stress mitigation is particularly relevant to smallholder dairy communities where open-housing barns are widely used because of their low construction cost and management simplicity. The field context of this study was linked to a dairy community in Hu Thamnop Subdistrict, Pakham District, Buriram Province, where dairy farming is an important local livelihood. Community records reported 11 dairy farms with a total of 1,068 cows and approximately 3,280 kg of raw milk production per day. Motivated by these field constraints, this study evaluated a low-power HVLS ventilation system integrated with a hybrid solar energy supply specifically designed for open-housing dairy barns in tropical smallholder conditions. The objectives were to: (i) assess changes in barn microclimate using THI as the primary heat-stress indicator, (ii) evaluate dairy cow welfare-related responses using respiration rate, infrared body surface temperature, and zone-use behavior, (iii) examine changes in milk yield and milk-quality-related economic outcomes, and (iv) estimate the practical energy and economic feasibility of the system under field operating conditions.

Methodology

Study Site and Experimental System Overview

The study was conducted at a demonstration open-housing dairy farm in Hu Thamnop Subdistrict, Pakham District, Buriram Province, Thailand. The barn had a metal-sheet roof and consisted of two sections, each approximately 8 m wide, 20 m long, and 3 m high. The barn was oriented along the north–south axis, and hot-season prevailing wind entered mainly from the southwest. The experimental system consisted of a low-power HVLS ventilation subsystem integrated with a hybrid solar energy subsystem. Two ceiling-mounted HVLS fans with a diameter of approximately 2 m were installed in the treatment zone. Each fan consumed approximately 60 W, giving a total fan power demand of approximately 120 W. The hybrid solar subsystem consisted of two 450-W photovoltaic panels, battery storage using 24-V batteries, and automatic grid backup to maintain operation when stored solar energy was insufficient.

Experimental Design, Animals, and Observation Period

A matched-season controlled before-and-after quasi-experimental field design was used. Baseline data were collected from May to August 2023, and post-installation data were collected from May to August 2024. The farm had 104 Holstein Friesian crossbred dairy cows.

Among these animals, 48 lactating cows were included as the primary observation group. Cows were allocated according to barn-zone exposure rather than random assignment. The control group (n = 19; approximately 40%) was located in a barn zone without HVLS fan installation, whereas the treatment group (n = 29; approximately 60%) was located under the HVLS fans within the airflow coverage area. Individual age, body weight, parity, and days in milk were not available in the retrospective farm records and were therefore treated as study limitations.

Microclimate, Physiological, Milk Yield, and Energy Measurements

Barn microclimate was monitored using custom-built sensor nodes equipped with DHT11 temperature-humidity sensor modules connected to an Arduino-based data acquisition system. Two sensor nodes were installed, one in the control zone and one in the HVLS treatment zone, at approximately 1.2–1.5 m above the floor to represent cow-level microclimate conditions. The recorded ambient temperature and relative humidity were used to calculate the temperature-humidity index (THI). Respiration rate was measured before afternoon milking during the hot period between 14:00 and 15:00 h. The number of flank movements was counted for one minute (60 s) and expressed as breaths/min. Body temperature was measured at the lateral body region using a non-contact infrared thermometer (3CMEDICAL FI-01). The device measures body temperature within 32.0–42.9 °C with an accuracy of ± 0.2 °C. Because the instrument was a non-contact infrared thermometer, the recorded values were interpreted as infrared body surface temperature rather than rectal core body temperature. Milk yield was obtained from farm and cooperative milk records. Energy use was estimated from the measured system operating configuration and daily operating schedule, while economic feasibility was evaluated using cooperative milk-price records and electricity tariff assumptions for the post-installation monitoring period (PEA, 2023; PEA, 2024).

Statistical Analysis

Data were analyzed descriptively because the study was conducted under real farm operating conditions and complete repeated raw observations for all variables were not available for inferential modeling. Farm-level and cow-group-level outcomes were summarized as before-and-after changes, percentage changes, and practical economic estimates. The term 'significant' was avoided unless supported by formal statistical testing. For

cow-level variables, lactating cows were considered the observational unit, whereas THI and energy outcomes were interpreted at the barn-zone or system level. The controlled matched-season design, in which the same May–August seasonal window was compared across 2023 and 2024, was used to reduce seasonal bias.

Ethical Considerations

Animal handling and field measurements were conducted under normal farm management conditions. Written permission and informed consent were obtained from the farm owner before data collection and system monitoring. No invasive animal procedures were performed; respiration rate was recorded by visual observation and body temperature was measured using a non-contact infrared thermometer.

System Configuration and Architecture

The experimental system was composed of three interconnected subsystems:

1. HVLS ventilation subsystem, responsible for enhancing air movement at cow level to promote convective and evaporative heat dissipation (Gebremedhin & Wu, 2003; Ji et al., 2020).
2. Hybrid solar energy subsystem, providing electrical power through photovoltaic generation combined with battery storage and optional grid backup to ensure uninterrupted operation during peak heat stress periods (IRENA and FAO, 2021; Rehman et al., 2012).
3. Operational control layer, coordinating system operation using predefined schedules aligned with daily heat stress patterns.

The integration of these subsystems enabled continuous ventilation support under variable environmental and energy availability conditions.

In the treatment area, cows had free access to two functional subzones: an HVLS airflow zone directly under the fans and a non-airflow zone without direct fan coverage. During fan operation, qualitative field observation showed that cows consistently congregated in the HVLS airflow zone. When the fans were not operating, cows dispersed across both subzones. This pattern was recorded as practical zone-use preference evidence and interpreted as an indirect behavioral indicator of thermal comfort. An overview of the integrated ventilation and energy system architecture is presented in Figure 1.

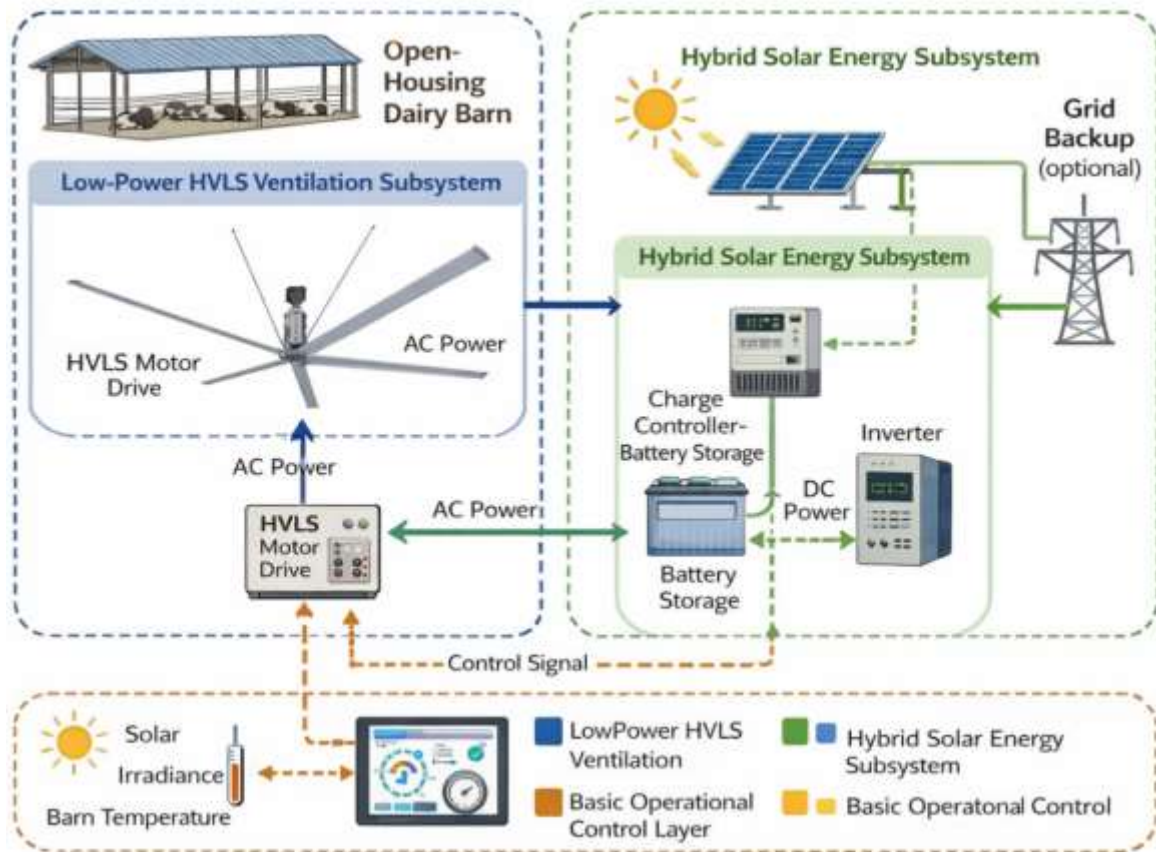


Figure 1 Overall architecture of the proposed low-power HVLS ventilation system integrated with a hybrid photovoltaic–battery energy subsystem and optional grid backup for open-housing dairy barns.

Design Objectives and System Constraints

The system design addressed practical constraints commonly observed in open-housing dairy barns, including minimal structural enclosure, limited electrical infrastructure, and sensitivity to initial investment cost (Chantalakhana & Falvey, 1999; FAO, 2009). Under tropical climate conditions, such barns experience high solar radiation and humidity, resulting in prolonged heat stress exposure (Thornton et al., 2009).

Based on these constraints, the system was designed with the following objectives:

1. To mitigate heat stress by increasing air movement at cow level without enclosing or structurally modifying the barn (Ji et al., 2020).
2. To minimize electrical power consumption to enable operation using a compact renewable energy system (IRENA and FAO, 2021).

3. To ensure continuous and reliable ventilation during peak heat periods, when system failure could exacerbate thermal stress (Rehman et al., 2012).

4. To maintain simplicity in installation, operation, and maintenance to support adoption by resource-constrained farms (Herrero et al., 2015).

HVLS Ventilation Subsystem

Fan Selection

High-volume low-speed (HVLS) fans were selected as the primary ventilation devices due to their ability to generate large-scale, uniform airflow at low rotational speeds and low electrical power consumption (Bucklin et al., 1991; Mondaca, 2019). Unlike conventional high-speed fans that produce localized airflow jets, HVLS fans move large volumes of air, resulting in more uniform air velocity distribution across the barn floor area (Mondaca, 2019).

Uniform airflow distribution is particularly important in open-housing barns, where structural openness and natural wind variability can create stagnant air zones. Consistent air velocity at cow level has been shown to improve thermal comfort and reduce physiological stress responses under heat stress conditions (Gebremedhin & Wu, 2003; Ji et al., 2020).

Fan Placement and Airflow Coverage

Two ceiling-mounted HVLS fans were installed along the treatment section of the open-housing barn to improve airflow at cow level. The control zone was maintained without HVLS fan installation, whereas the treatment zone was positioned within the airflow coverage area. Fan placement was determined from barn geometry, available mounting height, structural clearance, and observed cow movement patterns. The design emphasized uniform low-speed airflow rather than high localized air speed.

Fan mounting height and spacing were determined based on barn geometry, structural clearance, and safety considerations. The design emphasized airflow uniformity rather than high localized air speed to enhance convective and evaporative heat loss while avoiding excessive air turbulence that could disrupt normal animal behavior (Ji et al., 2020).

Hybrid Solar Energy Subsystem

Energy Architecture

The hybrid energy subsystem consisted of two 450-W photovoltaic panels, 24-V battery storage, and optional grid backup. During daytime operation, solar energy supplied the primary electrical demand of the HVLS fans. Stored energy supported operation during periods of reduced irradiance, while grid electricity served as an automatic backup source to prevent system downtime.

System Sizing and Power Matching

Total ventilation power demand was intentionally limited to approximately 120 W because the system used two 2-m HVLS fans rated at approximately 60 W each. This low-power configuration enabled operation using a compact photovoltaic array and modest battery storage, reducing operating electricity cost and supporting suitability for smallholder dairy farms.

This low-power configuration reduced initial investment cost compared to conventional cooling systems, which often require several kilowatts of electrical power and extensive electrical infrastructure (St-Pierre et al., 2003). Reduced system size also simplified installation and maintenance, enhancing practicality for small- and medium-scale dairy farms.

Operational Control Strategy

The system employed a rule-based operational schedule rather than complex sensor-based automation. Ventilation was operated primarily during midday and afternoon hours, corresponding to periods when temperature–humidity index (THI) values are typically highest (Armstrong, 1994; Ji et al., 2020). This control strategy was selected to balance effectiveness with operational simplicity. Previous studies indicate that reliability, ease of use, and low maintenance requirements are critical determinants of technology adoption in smallholder and resource-constrained farming contexts (Herrero et al., 2015; Rehman et al., 2012).

Practical Deployment Context

The real-world deployment context of the experimental system is illustrated in Figure 2. The system was installed without major structural modification to the open-housing barn and can be adapted to barns of different sizes by adjusting fan quantity and energy capacity (St-Pierre et al., 2003; Herrero et al., 2015).

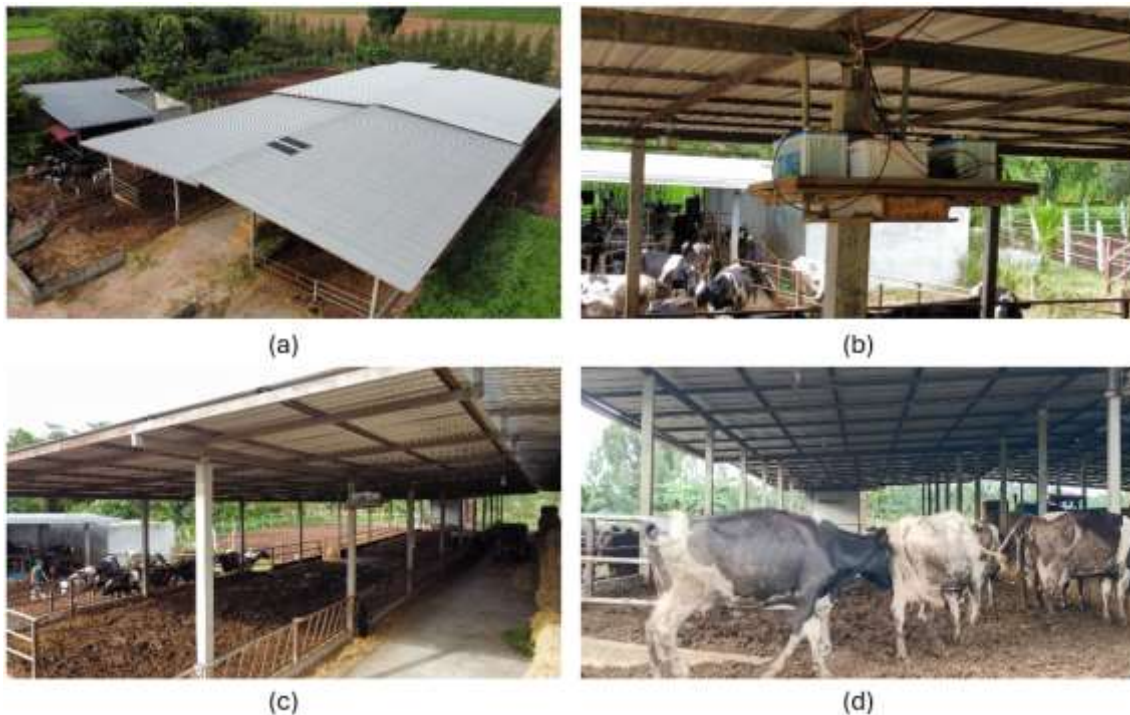


Figure 2 Field deployment context of the proposed system in an open-housing dairy barn: (a) aerial view of the barn structure, (b) installation of energy and control components, (c) interior layout of the open-housing barn, and (d) dairy cows under natural housing conditions during system operation.

By integrating low-power ventilation with renewable energy within a unified framework, the experimental system addresses environmental, energy, and economic constraints simultaneously (Thornton et al., 2009; IRENA & FAO, 2021), enabling practical evaluation of its effects on animal welfare and production performance.

Results

Microclimate Conditions

Daytime barn microclimate conditions measured during hot periods are summarized in Table 1. The control zone without HVLS installation showed no clear improvement during the matched post-installation period. In the treatment zone, THI decreased from 82.6 during the baseline period to 78.8 after HVLS-hybrid solar system deployment, representing a reduction of 3.8 THI units.

Table 1 Daytime barn microclimate conditions during peak heat hours

Parameter	Control zone (non-HVLS)	Treatment baseline May-Aug 2023	Treatment after HVLS May-Aug 2024
Temperature (°C)	No clear change	34.1 ± 1.1	31.6 ± 0.9
Relative humidity (%)	No clear change	73.2 ± 4.6	68.4 ± 4.1
THI	No clear change	82.6	78.8

Note: Values are reported descriptively from barn-zone monitoring. Inferential P-values were not calculated because complete repeated raw observations were not available.

The reduction in THI in the treatment zone indicates that the HVLS airflow reduced effective thermal load at cow level, even under open-housing barn conditions.

Physiological Welfare Outcomes

Respiration Rate

Respiration rates observed before afternoon milking during hot periods are presented in Table 2.

Table 2 Respiration rate of dairy cows before and after system deployment

Metric	Control group	Treatment baseline May-Aug 2023	Treatment after HVLS May-Aug 2024
Respiration rate (breaths/min)	No clear change	83.5 ± 7.1	65.2 ± 6.0

Note: Respiration rate was recorded by counting flank movements for one minute (60 s) before afternoon milking during 14:00–15:00 h. Results are interpreted descriptively.

Following system installation, average respiration rate in the treatment group decreased from 83.5 to 65.2 breaths/min, corresponding to a reduction of approximately 22%. The control group showed no clear change during the matched monitoring period.

Infrared Body Surface Temperature

Infrared body surface temperature data measured at the lateral body region are summarized in Table 3.

Table 3 Infrared body surface temperature of dairy cows under baseline and post-installation conditions

Metric	Control group	Treatment baseline May-Aug 2023	Treatment after HVLS May-Aug 2024
Infrared body surface temperature (°C)	No clear change	39.3 ± 0.42	38.7 ± 0.31

Note: Values were measured using a non-contact infrared thermometer and should be interpreted as infrared body surface temperature, not rectal core body temperature.

Average infrared body surface temperature in the treatment group decreased by approximately 0.6 °C after system deployment.

Milk Yield Performance

Milk yield performance before and after system deployment is presented in Table 4.

Table 4 Average daily milk yield per cow before and after system deployment

Metric	Control group	Treatment baseline May-Aug 2023	Treatment after HVLS May-Aug 2024
Milk yield (L/cow/day)	No clear change	12.8 ± 1.5	14.3 ± 1.6

Note: Milk yield was obtained from farm and cooperative milk records. The 12% improvement refers specifically to the HVLS treatment group.

Average daily milk yield in the treatment group increased from 12.8 to 14.3 L/cow/day, representing an increase of approximately 1.5 L/cow/day or 12%. The control group showed no clear change during the matched monitoring period.

Table 5 consolidates the key treatment-group outcomes to show the overall direction and magnitude of change after HVLS-hybrid solar system deployment.

Table 5 Summary of key treatment-group outcomes before and after HVLS-hybrid solar system deployment

Indicator	Baseline May-Aug 2023	After HVLS May-Aug 2024	Main change
THI during peak heat periods	82.6	78.8	-3.8 points (-4.6%)
Respiration rate (breaths/min)	83.5 ± 7.1	65.2 ± 6.0	-18.3 breaths/min (-21.9%)
Infrared body surface temperature (°C)	39.3 ± 0.42	38.7 ± 0.31	-0.6 °C (-1.5%)
Milk yield (L/cow/day)	12.8 ± 1.5	14.3 ± 1.6	+1.5 L/cow/day (+11.7%)

Note: Values are descriptive summaries from the treatment group. Error terms represent standard deviation where available. THI was reported as a descriptive index without standard deviation because complete repeated raw microclimate records were not available for inferential analysis.

Energy Performance and System Reliability

Energy performance of the ventilation system is summarized in Table 6.

Table 6 Energy performance and operational reliability of the proposed system

Metric	Value
HVLS fan configuration	2 fans × 60 W = 120 W total
PV array	2 panels × 450 W = 900 Wp
Battery storage	24-V battery system
Daily energy use	1.2 kWh/day
Solar contribution	78%
Estimated grid electricity use	0.264 kWh/day
System downtime	0 observed downtime

The system operated throughout the monitoring period without observed system downtime. Because approximately 78% of the daily energy demand was supplied by the hybrid solar subsystem, estimated grid electricity use was only approximately 0.264 kWh/day.

Economic Outcomes

Economic feasibility of the proposed system is summarized in Table 7.

Table 7 Estimated economic feasibility of the HVLS–hybrid solar ventilation system

Item	Value	Calculation/Source	Interpretation
Initial system investment	65.52k THB	Existing system cost estimate	Capital cost
Milk yield gain in treatment group	1.5 L/cow/day	14.3 - 12.8	Approximately 12% increase
Treatment cows	29 cows	HVLS airflow group	Observation group
Additional milk volume	43.5 L/day	1.5×29	Treatment group only
Milk price during post-installation period	20.70-20.80 THB/kg	Cooperative payment records	Used for revenue estimation
Estimated additional milk income	≈ 900 THB/day	43.5×20.75	Before other production costs
Estimated grid electricity cost	≈ 1.36 THB/day	$0.264 \text{ kWh/day} \times \text{tariff}$ including VAT	Very low operating cost
Estimated simple payback	≈ 73 days	$65.52k / (900 - 1.36)$	Scenario-based estimate

Based on the observed milk-yield improvement in the treatment group, additional milk volume was estimated as $1.5 \text{ L/cow/day} \times 29 \text{ cows} = 43.5 \text{ L/day}$. Using cooperative milk-price records during the post-installation period (approximately 20.70–20.80 THB/kg), the additional milk income was estimated at approximately 900 THB/day. In contrast, the estimated grid electricity cost was approximately 1.36 THB/day after accounting for the 78% solar contribution and the applicable electricity tariff during the monitoring period (PEA, 2023; PEA, 2024). These descriptive estimates indicate that the operating electricity cost was very low compared with the additional milk income.

Discussion

The results indicate that the proposed low-power HVLS ventilation system integrated with hybrid solar energy improved the thermal environment in the treatment zone of an open-housing dairy barn. The observed THI reduction from 82.6 to 78.8 occurred in the HVLS treatment zone, while the non-HVLS control zone showed no clear change during the matched seasonal monitoring period. This pattern supports the interpretation that the improvement was associated with airflow exposure rather than seasonal variation alone.

The reduction in respiration rate by approximately 22% suggests alleviation of acute heat stress in the treatment cows. The concurrent decrease in infrared body surface temperature further supports improved thermal comfort, although this measurement should not be interpreted as rectal core body temperature. The qualitative zone-use observation also strengthens the welfare interpretation: cows were free to choose between airflow and non-airflow subzones, and they consistently congregated in the HVLS airflow zone during fan operation.

Improvements in welfare-related indicators were accompanied by a 12% increase in milk yield in the treatment group. Because the control group showed no clear improvement during the same seasonal window, the increase in milk production was plausibly associated with improved heat-stress mitigation in the HVLS zone. However, the absence of random assignment and incomplete individual covariate data mean that the results should be interpreted as practical field evidence rather than confirmatory causal proof.

From an energy perspective, the system's low daily energy demand of approximately 1.2 kWh and high solar contribution of 78% demonstrate the feasibility of operating barn ventilation using a compact hybrid solar configuration. The use of two low-power HVLS fans, each consuming approximately 60 W, kept grid electricity demand low while maintaining continuous airflow support during hot periods.

The economic outcomes further support practical applicability. Cooperative milk-price records during the post-installation period showed milk prices of approximately 20.70-20.80 THB/kg. When combined with the 1.5 L/cow/day increase in milk yield among the 29 treatment cows, the estimated additional milk income was approximately 900 THB/day, whereas the estimated grid electricity cost after solar contribution was only about 1.36 THB/day based on the applicable PEA electricity tariff and Ft surcharge during May-August 2024 (PEA, 2023; PEA, 2024). This large difference between additional milk income and operating electricity cost

indicates that the system is economically promising for smallholder dairy farms, although full economic validation should include depreciation, maintenance, labor, and long-term performance.

Limitations and Practical Implications

This study has several limitations. First, it was conducted in a single demonstration farm; therefore, the findings may not represent all open-housing dairy farms. Second, cows were allocated according to barn zones rather than randomized individual assignment, so residual location-related confounding may remain. Third, individual age, body weight, parity, days in milk, feed intake, and long-term health records were not available for all cows. Fourth, zone-use behavior was recorded as qualitative field observation rather than by automated video tracking or time-budget analysis. Future studies should validate the system across multiple farms using randomized or replicated barn-zone designs, longer monitoring periods, complete individual cow records, feed intake, somatic cell count, lying behavior, and detailed economic sensitivity analysis.

Conclusion and Suggestions

This matched-season controlled before-and-after field study suggests that low-power HVLS ventilation integrated with hybrid solar energy can reduce heat load and improve welfare-related responses in open-housing dairy barns under tropical conditions. In the treatment group, THI decreased from 82.6 to 78.8, respiration rate decreased from 83.5 to 65.2 breaths/min, infrared body surface temperature decreased by approximately 0.6 °C, and milk yield increased by approximately 12%.

The system consumed approximately 1.2 kWh/day, with 78% supplied by the hybrid solar subsystem. Scenario-based economic estimation indicated that the additional milk income from the treatment group greatly exceeded the daily grid electricity cost. Therefore, the system represents a practical and economically promising heat-stress mitigation option for tropical smallholder dairy farms.

Future research should confirm these findings using multi-farm trials, replicated treatment and control zones, complete individual cow records, automated behavioral monitoring, long-term health and milk-quality outcomes, and full life-cycle cost analysis.

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