

AN INNOVATIVE VENTILATION AND COOLING STRATEGY BASED ON THE THERMAL COMFORT OF GROWING-FINISHING PIGS



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HIGHLIGHTS

- Nine treatments of a ventilation and cooling strategy based on the HS2I index were developed.
- The treatments were tested with pigs (45-120 kg) exposed to artificial heatwaves in experimental rooms.
- Zootechnical performance showed no advantage in using larger sprinkling water volumes.
- The combination of an HS2I of 3.0 and reduced sprinkling water volumes may not avoid heat stress for heavier pigs.

ABSTRACT. During the growing-finishing phase of pig production, mitigating heat stress is essential to maximize growth performance, improve feed efficiency, and minimize risks of deteriorating animal welfare and farm profitability. Housed Swine Heat Stress Index (HS2I) assesses pigs' thermal comfort into a dimensionless metric scored from 0 (no heat stress) to 10 (severe heat stress), where 3 marks the beginning of heat stress along the range. Focusing on thermal comfort, a ventilation and cooling strategy based on the HS2I was implemented through precise control of air velocity and cooling using water sprinklers. The objective of this study was to optimize this strategy by adjusting two main parameters: the HS2I setpoints (2.0, 2.5, or 3.0) and the water sprinkling volumes (partial, gradual, or complete). Experiments were conducted in laboratory rooms housing 14 pigs under simulated summer-like conditions to test nine functional treatments of the strategy. The results showed that reduced water use through partial sprinkling was generally adequate to maintain pig performance, regardless of the selected HS2I setpoint. However, the combination of an HS2I setpoint of 3.0 with a reduced sprinkling strategy may expose heavier pigs (>100 kg) to heat stress. These findings offer practical insights for optimizing cooling strategies in pig production systems that face heat stress challenges.

Keywords. Animal index, Direct cooling, Heat stress mitigation, Recirculation fans, Sprinkling systems, Swine production, Zootechnical performance.

Over the past six decades, the frequency, intensity, and duration of heatwaves have steadily increased under a changing climate, with projections indicating further deterioration (IPCC, 2023; US EPA, 2024). This trend poses major economic challenges for environmental control in animal production

systems (St-Pierre et al., 2003). In pig farming, animals in the finishing phase are especially vulnerable to heat stress due to higher heat production and limited ability to dissipate heat, as pigs lack functional sweat glands (Renaudeau et al., 2012). The consequences include reduced average daily gain (ADG), poorer feed conversion ratio (FCR), impaired health and welfare (Vitt et al., 2017), and higher mortality near market weight, when pigs have the highest economic value (Rivest et al., 2009).

Mechanical ventilation is the main strategy to mitigate heat stress in confined housing (Vitt et al., 2017; Mikovits et al., 2019). In summer, its primary role is to increase air-flow and limit temperature rise (Vitt et al., 2017). However, design standards from ASABE and CIGR are based on studies from the mid-20th century and do not reflect current production conditions (Ramirez et al., 2022; Brown-Brandl

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et al., 2004). Modern pigs are marketed at heavier weights (≈ 130 vs. 100 kg) and selected for productivity, which increases metabolic heat production and reduces tolerance to heat stress (Brown-Brandl et al., 2004; Renaudeau et al., 2012). Conventional ventilation control strategies typically rely solely on ambient temperature, neglecting humidity and air velocity in the animal zone, both of which are critical for thermal comfort (Hahn et al., 2009). This limitation reduces their capacity to optimize conditions and efficiency (Fournel et al., 2017). A more comprehensive evaluation of pigs' thermal comfort is required.

Animal comfort indices (ACIs) provide such an approach by modeling heat exchange between pigs and their environment using both environmental and physiological data (Fournel et al., 2017). They quantify impacts on animal performance, health, and welfare (Hahn et al., 2009). Early examples include the Wet-and-Dry-Bulb Temperature Index (WDTI) and Effective Environmental Temperature (Ingram, 1965; Roller and Goldman, 1969; Baker, 2004). More recently, studies have summarized ACI applications in livestock (Fournel et al., 2017) and developed pig-specific indices (Bjerg et al., 2018; Ramirez et al., 2018). Two principles emerge for advancing thermal control in pig housing: (i) integration of updated bioenergetic models of heat and moisture production, and (ii) use of ACIs that combine environmental and physiological parameters. Brown-Brandl et al. (2014) proposed modern bioenergetic models, while Ramirez et al. (2018) introduced the Housed Swine Heat Stress Index (HS2I), which accounts for pig weight, air temperature, humidity, air velocity, and sprinkling systems.

Building on this, researchers in Québec developed a novel control strategy based on HS2I to improve thermal management in growing-finishing pigs (Godbout et al., 2023). Compared with a conventional temperature-based strategy (CTBS) using the same cooling equipment (recirculation fan and sprinklers), the HS2I approach yielded slight improvements in zootechnical performance (ADG: 1.27 vs. 1.29 kg d^{-1} pig $^{-1}$). Importantly, water consumption per pig was lower under HS2I (7.54 vs. 10.39 L d^{-1}), though sprinkler water use was higher (1.42 L d^{-1} vs. negligible in CTBS). These results highlighted the need to refine both the sprinkling strategy and the HS2I setpoints, as setpoints determine sprinkler activation timing (Godbout et al., 2023).

The objective of this study was to refine the HS2I-based comfort strategy by optimizing thermal control for growing pigs under heat stress. Specifically, the study aimed to determine the sprinkler water volumes required for effective cooling and to identify optimal HS2I setpoints to improve assessment of the pigs' thermal environment. This knowledge could then enhance control logic for regulating air speed, sprinkling volumes, and activation timing.

MATERIALS AND METHODS

EXPERIMENTAL SETUP

The experiment was carried out in a research facility (Laboratory for the Agri-Environmental Assessment of Livestock Buildings 2.0, Deschambault, QC, Canada; fig. 1) with three small-scale rearing rooms (3.05×3.66 m) designed to

replicate commercial swine production conditions with heat-stress mitigation equipment. In each room, a 350-mm (13.8 in.) diameter exhaust fan (Ziehl-Abegg, Germany, distributed by IEL Technologie Agricole, QC, Canada) generated negative pressure, facilitating continuous air exchange while preventing cross-contamination between chambers. Available ventilation rates range from ~ 130 L s^{-1} pig $^{-1}$ to ~ 550 L s^{-1} pig $^{-1}$ per room (a maximum of 33 air changes per hour). As illustrated in figure 1, fresh outdoor air was drawn in through air intake #1 into a conditioning chamber. It was equipped with a 5-kW electric heater, a 30-kW propane heater with a chimney (i.e., air outlet) for exhaust of combustion gases, and a misting unit to humidify heated, dry air. The conditioned air was then drawn into the rearing rooms via air intake #2, maintaining uniform environmental conditions. Air circulation was ensured by a 310-mm (12.2-in.) recirculation fan (Ziehl-Abegg, Germany, distributed by IEL Technologie Agricole, QC, Canada) positioned to face the rearing area with a $\sim 20^\circ$ angle to the floor. Cooling water was delivered via a low-pressure sprinkler system (Netafim VibroNet model 050; 47 L h^{-1} , distributed by Groupe Horticole Ledoux, Québec, QC, Canada), similar to pre-soaking sprinklers used for soaking pig houses. The environmental control system was primarily managed by an automated system controller (Maximus Solutions, St-Bruno-de-Montarville, QC, Canada), which regulated fans, heating units, drinkers' water meters, and environmental sensors. Figure 2 presents a photograph of Room 3, illustrating the scale of the experimental setup for 14 pigs housed in the pen. The setup includes an exhaust fan, a recirculation fan, a sprinkler, and an air inlet. The wet feeder is not visible in the image, as it was positioned to the near left of the camera's viewpoint.

At both air inlet and outlet of each room, thermistors measured ambient temperature (T_{db}) and hygrometers (Model CS500, Campbell Scientific Inc., Edmonton, AB, Canada, or Model DOL104, Dol-Sensors A/S, Aarhus, Denmark) recorded relative humidity (RH). An additional ceiling-mounted thermistor, secured with aluminum tape, was used to estimate surface temperature (estimated mean radiant temperature; T_{mr}). Figure 2 shows the sensors installed at the exhaust fan opening (right side), consisting of a thermistor and a hygrometer. Identical sensors were also placed inside the air inlet, though they are not visible in the photograph. Similarly, the thermistor is affixed to the ceiling with aluminum tape, which is not shown in the image. A data logger (Model CR1000, Campbell Scientific Inc., Edmonton, AB, Canada) was also used to collect complementary sensor measurements not integrated into the central controller (static pressure and exhaust fan speed). Sprinkling water volumes were measured using 0.019 L contact $^{-1}$ resolution water meters (model RCDL 25, BadgerMeter Inc., Milwaukee, Wis.).

For data aggregation, calculations, and decision-making, the comfort strategy was designed as a custom program (Python 3.4, Python Software Foundation, Beaverton, Ore.) running on a PC connected to an analog-to-digital converter (CAN-T7 Pro, LabJack, Colo.). This program controlled the activation of the sprinkling system in the rearing room and the misting unit in the conditioning room. An analog-to-digital converter was also connected to the environmental

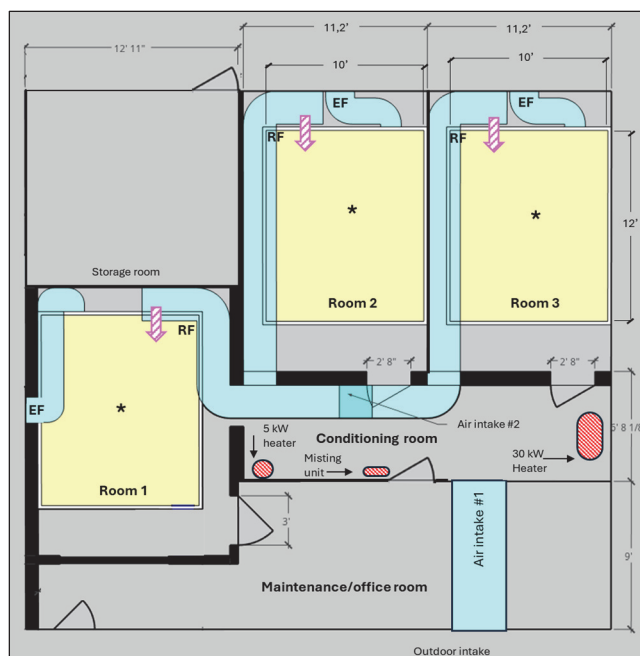


Figure 1. Schematic plan of the laboratory illustrating the three rearing rooms (light yellow) and air ducts (blue). Hatched purple arrows identify air inlets in each room. Exhaust fans (EF) and recirculation fans (RF) in each room are identified by their abbreviations. The asterisk at the center of each room identifies the approximate location of the low-pressure sprinklers mounted on the ceiling.

sensors, the drinkers' water meters, and the sprinklers' water meters, thereby providing access to data for the program. The latter was connected to the automated system to control exhaust and recirculation. The computerized system controller functioned as a fail-safe mechanism, ensuring system reliability in the event of issues with the custom program. Finally, the custom program limited airflow rates at 70% of exhaust fan speed, accounting for less than $30 \text{ L s}^{-1} \text{ pig}^{-1}$ (~ 25 air changes per hour and ~ 64 cubic feet per minute per pig [CFM pig^{-1}]), in each room according to previous studies on heat stress mitigation in Québec through cooling strategies (Godbout et al., 2023; Pouliot et al., 2012). Temperature and humidity compensation were incorporated into the

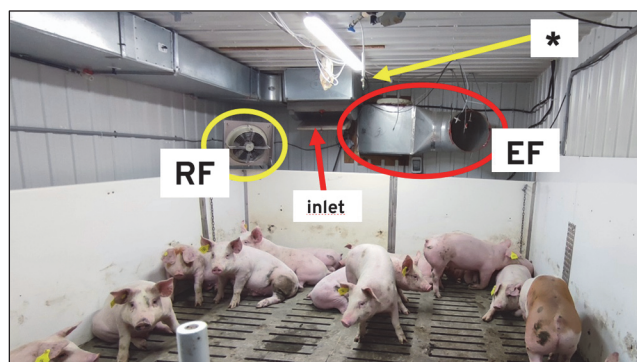


Figure 2. Photograph of Room 3 during period 1 of the experiment. Exhaust fans (EF) and recirculation fans (RF) in each room are identified by red and yellow circles, respectively. The sprinkler is located at the center of the ceiling, pointed by the yellow arrow (*). The air inlet is pointed by the red arrow.

program to enhance airflow under warmer-than-anticipated conditions.

The experimental phase ran from 18 April 2023 to 5 December 2023 and consisted of three fattening periods (table 1) of 70 days (10 weeks) during which 14 castrated male pigs (approximately 45-120 kg) were raised per room. At the beginning of each period, pigs were assigned to rooms to ensure similar average starting weights across treatments. However, pigs arrived heavier in Period 3 due to external factors. To monitor growth, pigs were weighed eight times: at the start, before and after each heatwave (days 14, 22, 35, 43, 56, and 64), and at the end. At the sixth weighing, two pigs per room were removed to maintain the recommended stocking density, typically the heaviest ones, except for one sick pig in Period 3. Another pig during this period showed lameness and died suddenly on day 14.

Daily feed consumption was monitored by weighing individual feed bags before manually filling the feeders in each room (giving a feed measurement resolution of approximately 25 kg per bag, each one or two days), or $\sim 2 \text{ kg d}^{-1} \text{ pig}^{-1}$. Water consumption was measured using 1-L per contact water meters installed in each room (VPD Meter, Carlon Meter, Grand Haven, Mich.). However, the effective resolution of the water consumption data was 10 L per contact, since the Maximus controller recorded values only after every 10 contacts in the daily data reports. Manure in rooms 1 and 3 was stored in an underfloor pit beneath the slatted floor and emptied after each experimental phase. Room 2 featured a V-shaped scraper for liquid-solid manure separation beneath the slatted floor, which was activated daily. Gas emissions (CO_2 , CH_4 , NH_3 , N_2O) were measured to verify that the manure management method did not influence the outcome. The analysis revealed that they increased with the pigs' growth and were not affected by the room. Consequently, emission data are not presented herein.

The ambient conditions in the conditioning room were set at 22°C and artificial heatwaves episodes on three occasions (week 3 = days 15 to 21; week 6 = days 36 to 42; and week 9 = days 57 to 63) were activated by gradually increasing the air temperature in the conditioning room before lowering it back to baseline (day 1 = 26°C ; day 2 = 28°C ; days 3 to 6 = 30°C ; day 7 = 26°C). At night (starting at 18:00 h), the temperature setpoints decreased by 4°C over 2 h before gradually increasing in the morning (starting at 06:00 h).

COMFORT STRATEGY TREATMENTS

Operation of the Comfort Strategy

The comfort strategy utilizes the HS2I to enable the controller to assess pigs' thermal comfort by integrating multiple environmental and physiological factors, such as temperature (T_{db} ; 16°C to 33°C), relative humidity (RH; 10% to 90%), air speed (u_{air} ; 0.1 m s^{-1} to 3 m s^{-1}), bodyweight

Table 1. Details of the experimental phases of the study (year = 2023).

	Period 1 (Spring)	Period 2 (Summer)	Period 3 (Fall)
Start date	18 April	4 July	26 Sept.
Heatwave 1	2-8 May	18-24 July	10-16 Oct.
Heatwave 2	23-29 May	8-14 Aug.	31 Oct.- 6 Nov.
Heatwave 3	13-19 June	29 Aug.- 4 Sept.	21-27 Nov.
End date	27 June	12 Sept.	5 Dec.

(BW; 50 to 120 kg) and wetted skin status (sprinkling system S_{on} ; 0 or 1), into a single metric scored from 0 (no heat stress) to 10 (severe heat stress) (Ramirez et al., 2018). By analyzing fractional feed intake and critical temperature models from Renaudeau et al. (2011), Ramirez et al. (2018) determined that heat stress begins at an HS2I value above 3 (moderate heat stress), a threshold further validated through comparison with the WDTI. HS2I equations and coefficients are detailed in Ramirez et al. (2018).

The core principle of the strategy is to maintain a stable targeted HS2I value (or setpoint) at the pigs' level, ensuring consistent thermal conditions regardless of environmental variations. To achieve this, the airspeed at animal level and the sprinkler system activation are dynamically adjusted. Specifically, when pigs' skin is wet ($S_{on} = 1$), air speed is reduced to account for the chilling effect of airflow on damp skin.

The control logic (fig. 3) starts with actual variables in the room (BW = mean body weight of the pigs, T_{db} and RH = dry-bulb temperature and relative humidity at inlet and outlet, S_{on} = dry or wet skin). The heat and moisture balance model used the actual room variables to estimate the required airflow, which was then applied to adjust exhaust fan speed. Simultaneously, the targeted HS2I (depending on the treatment) and the measured variables were used to iteratively compute the air speed required (u_{air}) necessary to achieve the targeted HS2I. If this required u_{air} was less than 2 m/s, the recirculation fan speed was adjusted in combination with the exhaust fan speed (section Airflow Rates and Air Speed at Animal Level). Conversely, when the required u_{air} exceeded 2 m/s, a decision rule was applied: if $S_{on} = 0$, sprinkling was activated because the cooling potential of air speed was insufficient. Sprinkling volume was determined according to treatment (section Determination of the low-pressure water sprinkling volumes) and applied until the calculated volume was delivered, after which sprinkling was stopped, and S_{on} was set to 1 for the subsequent 15 minutes. With $S_{on}=1$, u_{air} was recalculated. If the recalculated u_{air} was lower than 2 m/s, the control cycle resumed as previously described; if u_{air} remained higher than 2 m/s, recirculation fan speed was adjusted to achieve a u_{air} of 2 m/s at animal level, as pigs' skin was already wet.

For example, with a targeted HS2I of 2.5, under conditions of 26°C, 65% RH, and 100 kg pigs with $S_{on}=0$, the required u_{air} is ~2.35 m/s. Since the value u_{air} exceeds 2 m/s, sprinkling is triggered ($S_{on} = 1$). After sprinkling, the recalculated u_{air} decreases to ~0.66 m/s, which then guides the u_{air} following the exhaust fan speed determined by heat and moisture balance (fig. 3).

Figure 4 illustrates the control logic when RH is 70% and BW is 90 kg, showing a decrease in air speed at approximately 26°C due to sprinkler activation to maintain a setpoint of 2.5. To avoid the HS2I from dropping below the setpoint and prevent activation errors and cold stress, a buffer of 0.125 HS2I must be exceeded before the sprinkling system is activated (not included in fig. 3). This explains why air speed stabilizes at 2 m s⁻¹ and the HS2I value increases by 0.125 upon activation (fig. 4).

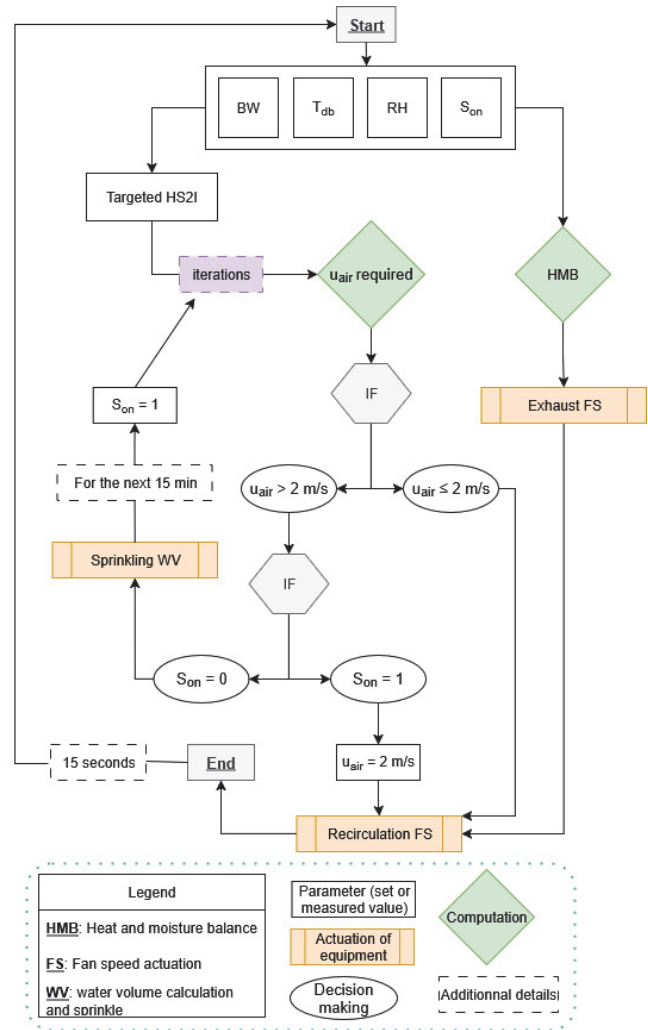


Figure 3. Ventilation and cooling strategy control logic.

The operation of the comfort strategy can be summarized in the following steps (with steps 4 and 5 occurring independently of steps 2 and 3):

1. Acquisition of environmental and animal data (temperature, humidity, and estimated pigs' BW);
2. Iterative calculation of HS2I to determine the required air speed;

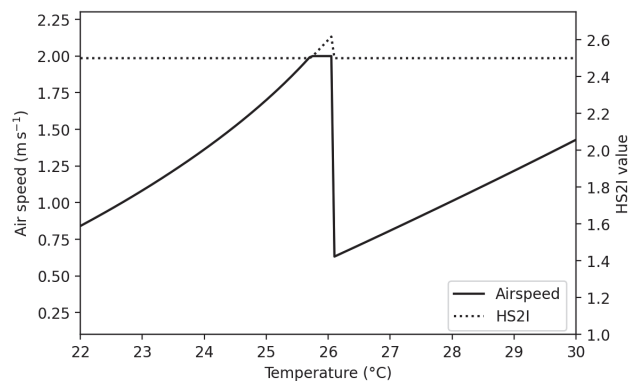


Figure 4. Example of air speed controlled by a targeted HS2I of 2.5 relative to ambient T_{db} (RH = 70% and BW = 90 kg). HS2I axis shows constant conditions for the pigs except at the 0.125 HS2I buffer.

3. Application of decision logic to assess the need for sprinkling;
4. Heat and moisture balance;
5. Exhaust fan control;
6. Recirculation fan control.

Estimated Body Weight

HS2I calculation requires the mean BW of pigs in the room as an input parameter (fig. 3). However, the facility used in this study was not equipped with a real-time weighing system. Despite this limitation, accurately estimating average pig BW remains essential for determining both HS2I values and the water volumes used for sprinkling. Godbout et al. (2023) addressed this issue by estimating BW using the ADG model of Renaudeau et al. (2011), which incorporates ambient temperature, days of rearing, and initial BW. However, this methodology did not consider the BW measured during the experiments. For this project, a recalibrated approach was implemented to precisely assess the pigs' updated BW. This method estimated ADG using daily feed intake data and periodic pig weights, based on a Gompertz growth model. Specifically, ADG was calculated as the time derivative of the Gompertz growth function described by Wellock et al. (2004):

$$ADG = B * BW(t) * \ln\left(\frac{A}{BW(t)}\right) \quad (1)$$

In this approach, the theoretical adult body weight (A) is assumed to be 250 kg. The body weight at time t , denoted as $BW(t)$, corresponds to the most recent weight measurement entered in the system. The growth rate parameter, B , characterizes the rate at which the animal approaches its mature weight; its value may vary, but is generally not lower than 0.0125. To estimate B , two methods may be used: (1) based on the most recent and initial BW measurements, or (2) using feed consumption data in combination with estimated feed efficiency and the initial BW. Method 2 is used for each day between weigh-ins. This flexibility allows for dynamic recalibration of the growth model, particularly when real-time weighing data are unavailable.

Determination of the HS2I Setpoints

The comfort strategy is dependent on HS2I calculations for air speed requirements at any given time and sprinkling activation (fig. 3). The accuracy of HS2I calculations depends on measurement precision and associated uncertainties. By estimating absolute measurements uncertainties of 0.5°C for T_{db} , 3% for RH, 0.2 m s⁻¹ for u_{air} , and 3 kg for BW; error propagation calculation, based on standard uncertainty equations of ISO/IEC (2008), determined a mean absolute error of ±0.285 for HS2I values between 1 and 4, with an observed error value of ±0.56 in a “worst case scenario” at an HS2I value of 3. In the earlier work of Godbout et al. (2023), different HS2I values were tested. At 1.75, on-site workers observed that pigs were on the verge of cold stress, despite the imposed hot conditions.

Based on the findings of Godbout et al. (2023), this study focused on HS2I setpoints of 2.0, 2.5, and 3.0, the latter representing the theoretical upper limit of HS2I for the onset of heat stress. It was hypothesized that using an HS2I of 3.0 as

a setpoint could reduce the frequency of sprinkling events, thus overall water usage. A 2.5 setpoint was chosen to account for potential calculation errors, ensuring that conditions remained below the heat stress threshold (the setpoint used in Godbout et al. (2023)). Meanwhile, a 2.0 setpoint was considered the lower limit before risking cold stress, though it is associated with increased water use because air speed reaches its cap at “lower” conditions.

Determination of the Low-Pressure Water Sprinkling Volumes

The sprinkling system (fig. 3) was designed to calculate the theoretical water volume required to achieve adequate cooling (eq. 2) based on the heat balance model developed by Fialho et al. (2004). In this model, total heat loss includes, among others, evaporative heat loss (Q_{evap} , the amount of heat required to evaporate water on the skin). The animal controls it by varying the wetted fraction of its skin (r_w). This parameter depends on perspiration (r_{wp}) and wallowing (r_{ww}). The former is relatively constant within the survival zone. The latter is expected to be 0 in the thermoneutral zone (r_{ww0}), but pigs are thought to be able to wet their skin up to 0.15 (r_{ww1}) on a slatted floor with water and urine (Black et al., 1986; Fialho et al., 2004). Ramirez et al. (2018) used a value of $r_{ww1} = 0.30$ to represent the wetted skin area after sprinkling. The heat balance model was used to determine Q_{evap} , following each model assumption on r_w , which was then converted into the required water volume for each model using:

$$V_{Sprinkling} = \frac{Q_{evap}}{(h_{evap} - h_{water})} N_{pigs} F_p * 900 \text{ s} \quad (2)$$

where

900 s = the water volume corresponds to the subsequent 15-min interval

N_{pigs} = number of pigs in the room

h_{water} = enthalpy of liquid water (kJ kg⁻¹)

h_{evap} = enthalpy of evaporation of water at skin temperature (kJ kg⁻¹)

F_p = weighting factor

Q_{evap} = heat loss by evaporation of water (kW pig⁻¹), which is obtained through iterations of the heat balance model and correspond to the third term of equation 15 in Fialho et al. (2004).

$V_{Sprinkling}$ = sprinkling water volume (kg → L).

The 900 s is the minimal interval between two sprinkling events. This time is constant: it estimates that the water used to wet pigs' skin is evaporating in 15 minutes. In Godbout et al. (2023), this interval was 10 minutes to achieve readable water volumes by the water meters, as some calculated volumes could have been too small with two treatments. This equation incorporates a weighting factor (F_p) to account for water spilling directly on the floor instead of on the pigs' skin. It considers the pigs' body surface area, the number of pigs, and the total floor area:

$$F_p = \frac{(N_{pigs} A_B + A_F)}{N_{pigs} A_B} \quad (3)$$

where

A_B = body surface area (m^2), $A_B = k_A BW^{2/3}$
(k_A = coefficient of body surface, $0.09 m^2/kg^{2/3}$
(Bruce and Clark, 1979)

A_F = area of the floor (m^2)

Additionally, the enthalpy of evaporation at skin temperature (h_{evap}) and the enthalpy of liquid water (assuming an average water temperature of $\sim 15^\circ C$) were used to estimate the volume of water required for effective skin wetting, with 1 kg of water assumed to be equivalent to 1 L. Using the heat balance model, datasets of required water volumes were generated for a range of body weights, temperature, humidity levels and HS2I values. These datasets were modelled using polynomial regression equations, expressing $V_{sprinkling}$ as a function of temperature, humidity, body weight and HS2I values for each model (as detailed in the next section). Equation 3 represents the polynomial used in this modeling, where coefficients A through M were determined by model fitting using the curve fit function from the SciPy library in Python (Fortune and Webster, 2021).

$$V_{modelled} = A + Bw + Cw^2 + Dw^3 + ET + FT^2 + GT^3 + Hh + Ih^2 + Jh^3 + Ki + Li^2 + Mi^3 \quad (4)$$

where

$V_{modelled}$ = volume of sprinkling water calculated by the custom program to determine rapidly the amount needed

w = estimated mean bodyweight of the pigs in the room (kg) (instead of BW for conciseness)

T instead of T_{db} (for conciseness)

h instead of RH (for conciseness)

i = HS2I value in real-time.

Sprinkling Models

In the study by Godbout et al. (2023), equation 2 was used to construct the sprinkling model. The underlying hypothesis was that a sprinkling event wets 30% of a pig's skin surface ($r_w = 0.3$), while in the absence of sprinkling, the skin remains dry ($r_w = 0$). This assumes that pigs do not wet themselves except through wallowing. The model, reused in the present study, is referred to as the complete model (CM), as it targets the full 30% wetting ratio. The root-mean-squared error (RMSE) of the fitting was 0.015 L.

However, pigs can wet themselves, in part, through wallowing. So, to refine the approach, two additional sprinkling models were developed in the present study. The partial model (PM) assumes that by the time sprinkling is required, pigs have already partially wetted themselves through wallowing ($r_{ww1}=0.15$). This number was estimated by Black et al. (1986) for pigs on slatted floors. Therefore, the required water volume is reduced, corresponding to the amount necessary to wet 30% of the skin, minus the volume already achieved through wallowing (fitting RMSE of 0.004 L). In the gradual model (GM), r_{ww1} varies dynamically between 0 and 0.15 based on the pigs' mean body temperature (T_b), as determined by the heat balance model. The lower critical temperature (T_l) was set at $38.5^\circ C$ (body temperature), and the evaporative critical temperature (T_e) at $39.5^\circ C$ (body temperature). At T_l ($38.5^\circ C$), r_{ww0} remains at 0, while at T_e

($39.5^\circ C$), r_{ww1} reaches 0.15 (fitting RMSE of 0.008 L). This gradual adjustment ensures that water volumes increase progressively as body temperature theoretically rises, as described by Fialho et al. (2004).

Sprinkling Cycle and Volume Calculation

The volume of water obtained from the sprinkling model was calculated for a 15-min cycle, as the minimum frequency of sprinkling is 15 min (fig. 3). This interval estimates that water fully evaporates before the next application, preventing excessive floor wetting and minimizing dripping into the manure pit. Following a sprinkling event, the S_{on} value is set to 1 in the HS2I calculation for the next 900 seconds, during which no additional sprinkling can occur (fig. 3).

Treatments

A factorial-type design was employed to evaluate nine comfort strategy treatments: three HS2I setpoints (2.0, 2.5, and 3.0) and three sprinkling models (partial, gradual, and complete). Theoretically, these nine comfort strategy treatments are functional and adapted to maintain thermal comfort. Given the availability of only nine rooms (three rooms per period), full replication was not feasible due to constraints on space, time, and budget. Table 2 summarizes the random allocation of treatments across the rooms for the three trials.

ENVIRONMENTAL MEASUREMENTS AND CONTROLS

Heat and Moisture Balance

To assess the required ventilation rate (fig. 3), heat and moisture balances for each room were conducted, following the ASABE Standards (2022) guidelines for ventilation design. Pigs' metabolic heat production influences heat balance, heat exchange with the building envelope, and ventilation rates. Similarly, moisture balance depends on moisture generated by pigs, emissions from the room (e.g., manure, wastewater from drinkers), and removal via ventilation. Heat and moisture contributions from pigs were calculated using the equations developed by Brown-Brandl et al. (2014), which estimate total heat production (THP) and latent heat production (LHP) for barrows. These equations use ambient temperature and BW as independent variables. Circadian variations in heat production were incorporated using a "plot digitizer" tool to extract diurnal patterns from graphs published in Brown-Brandl et al. (2014). While the HS2I model was used as the basis for environmental control, relying solely on ambient temperature and BW to estimate animal energy production was considered insufficient for comfort management strategies. To better reflect actual heat production and support growth performance under comfort-targeting conditions, the equations from Brown-Brandl et al. (2014) were applied using a reference ambient temperature

Table 2. Distribution among rooms and experimental periods for the nine treatments combining targeted HS2I values (2.0, 2.5, or 3.0) and sprinkling models.^[a]

	Room 1	Room 2	Room 3
Period 1	2.0 PM	3.0 CM	2.5 GM
Period 2	2.5 CM	2.0 GM	3.0 PM
Period 3	3.0 GM	2.5 PM	2.0 CM

^[a] Partial (PM), gradual (GM), or complete (CM).

equal to the lower critical temperature plus 3°C (LCT + 3), as recommended by the National Research Council (2012).

Airflow Rates and Air Speed at Animal Level

Airflows rates from each exhaust fan were assessed according to ASHRAE Standard (1992; ASHRAE 41.2-1987, RA92). These assessments were used to develop predictive models, where airflow rate ($\text{m}^3 \text{h}^{-1}$) was expressed as a function of both static pressure (Pa) and fan blade angular speed (RPM). Static pressure and RPM were continuously logged during the experiments using a Campbell Scientific data logger (Model CR1000, Campbell Scientific Inc., Edmonton, AB, Canada) for airflow determination. During the experiments, the comfort strategy program utilized a polynomial model to determine airflow in each room, based on the exhaust fans' operating speed levels and static pressure. The model was then rearranged to estimate (by iterations) the fan operating level (eq. 5) needed to achieve the airflow required by the heat and moisture balance models.

$$Q = \alpha + \beta E + \gamma E^2 + \delta E^3 + \varepsilon E^4 \quad (5)$$

where

Q = volumetric airflow rate (L s^{-1})

$\alpha, \beta, \gamma, \delta$ and ε are modelling coefficients

E = exhaust fan operating level (%). This is only feasible with the engine curve configuration of the automated system controller (Maximus) for "small fan."

For air-speed evaluation at the pig level, real-time anemometer probes were not used during the experiments for HS2I calculations. Instead, spatial variability in air speed was mapped before the trials using an omnidirectional hot-wire anemometer (SOM 900, KIMO Instruments, Sauer- mann Industries, France). Measurements were taken at approximately 50 cm above the slatted floor (approximately animal height) at nine evenly distributed points in the rearing area (center, four corners, and four mid-wall points). Air speed in the rooms was primarily influenced by two independent ventilation systems: the recirculation fan and the exhaust fan, both operating at varying levels. To capture the dynamic interactions between these systems, 20 combinations of operational levels were tested: exhaust fan at 25%, 50%, 75%, and 100%, and recirculation fan at 0%, 25%, 50%, 75%, and 100%. These percentages referred to predefined performance curves in the automated control system. For each fan setting combination, air speed was recorded continuously for 5 min at all nine measurement points. The resulting data were used to compute the mean, standard deviation, minimum, and maximum air speeds.

The average air speed across the nine measurement points for each combination was used to construct a room-specific air speed model, referred to as the "9-point model," expressed as a multivariable polynomial function of the exhaust and recirculation fan levels. Model fitting was performed using the curve fit function from the SciPy API in Python (Fortune and Webster, 2021). This model enabled real-time estimation of average air speed at 50 cm above the floor for any given fan configuration. The root-mean-squared error (RMSE) of this fitting was 0.06 m s^{-1} . However, for HS2I-based environmental control, a more targeted model, referred to as the "4 max-point model" (eq. 6), was

developed (RMSE = 0.07 m s^{-1}). This model used the mean of the four highest air-speed measurements among the nine recorded points for each fan combination, regardless of their physical locations. The rationale behind this approach is that, when exposed to hot conditions, pigs are likely to seek out higher airspeed zones within the pen. Consequently, we assumed this model, used for the experiments (fig. 3), provides a more realistic representation of the effective air speed experienced by pigs under thermal stress.

$$u_{4\text{-point}} = a + bE + cE^2 + dE^3 + fR + gR^2 + hR^3 \quad (6)$$

where

$U_{4\text{-point}}$ = estimated air speed at 50 cm in the pen obtained with the 4 max-point model

a to h are modeling coefficients

R = recirculation fan operating level (%). This is only feasible with the engine curve configuration of the automated system controller (Maximus) for "small fan."

Pig Skin Temperature

Previous work also demonstrated the potential of infrared thermography (IRT) for early disease detection in piglets (Gagnon et al., 2018), following Cook et al. (2015). These studies utilized thermographic images captured by an infrared camera to determine the maximum skin temperature of pigs. The objective was to compare measured, interpreted, mean skin temperature with "estimated skin temperature" ($T_{\text{est-skin}}$) using the heat balance model [which estimates the mean body temperature (T_b) and skin temperature (among others) based on observed energy balance; Fialho et al., 2004]. This was done to assess the model's reliability in predicting skin temperature, as it also served as the foundation for the development of the HS2I index (Ramirez et al., 2018). Previous work by Godbout et al. (2023) found a Pearson correlation of 0.701 between "mean, interpreted, pig skin temperature measured with infrared camera" ($T_{\text{skin-IR}}$) and $T_{\text{est-skin}}$ according to the model (using T_b of 38.5°C - 39.5°C). The current project used IRT with the same objective and the same custom program to analyze IR images.

Pig skin temperature in Rooms 2 and 3 was monitored using two ceiling-mounted infrared cameras (TIM40, Micro-Epsilon, distributed by Hoskin Scientific, QC, Canada). The infrared camera software was programmed to save a snapshot of its field of view every 15 s. During Period 2, a house fly infestation in room 2 resulted in a dirty IR camera lens, which also skewed some of the data.

Analysis of every snapshot was done using a custom program developed by Godbout et al. (2023). This program analyzes each image by distinguishing environmental and animal-related temperatures using an intermediate threshold. This threshold is determined dynamically for each image using a density probability plot of temperatures, which provides two peaks (modes): environmental temperatures and skin temperatures. The threshold is the local minimum between the two peaks. All temperatures above this threshold were used to establish the "mean, interpreted, pig skin temperature" ($T_{\text{skin-IR}}$). Every $T_{\text{skin-IR}}$ was then averaged over 15 min every hour.

As previously mentioned, use of the heat balance model requires knowledge of pigs' THP along with various environmental parameters (T_a , RH, BW, u_{air} , T_{mr} , number of pigs, S_{on}). THP can be estimated either from Brown-Brandl et al. (2014) bioenergetic model or according to the heat balance of the rearing room. Data analysis using the heat balance model was performed with 15-min-averaged environmental data to obtain $T_{est-skin}$ and then compared with $T_{skin-IR}$ using Pearson correlation analysis, combining data from every room (regardless of comfort strategy treatment).

DISTINCTIONS WITH PREVIOUS WORK

Since the present study builds upon and optimizes the work of Godbout et al. (2023), it is necessary to emphasize the key distinctions between the two. These differences concern the methodology used to estimate pigs' BW during the experiment, the air speed modeling approach, the HS2I treatments, the sprinkling strategies, and the heat balance calculations (table 3).

CALCULATION AND STATISTICAL ANALYSIS

Data came from three sources: the experimental custom program data collection (text file of environmental data measurements every 15 s), the infrared camera (a CSV file every 15 s), and the individual and mean weights of the pigs and daily feed consumption (manually filled spreadsheets). Thus, data aggregation was necessary to build an hourly database for every treatment and parameter. Water consumption and sprinkling water utilization were added to obtain the hourly usage.

Hourly HS2I values had to be redetermined with the corrected bodyweight of the pigs, because during the experiment, only the estimated bodyweight was known. Moreover, additional corrections were necessary. First, the initial bodyweight was not updated in the experimental program of Period 2 and Period 3, which led to a systematic error on BW (period 2; +2 kg and period 3; +9 kg). Second, in Period 3, a hardware failure prevented water sprinkling during the first

month, leading to inaccuracies in all calculations that assumed sprinkling was active.

Zootechnical performances were established with average daily feed intake (i.e., consumption) (ADFI; with the established ± 25 kg resolution in the room), daily pigs' BW using estimated ADG and FCR (ratio between ADFI and ADG). Statistical analyses were performed using mean and standard deviation values over the 70-day periods to compare performance and water usage between the nine treatments of a ventilation and cooling strategy. The Pearson correlation coefficient was also used to compare $T_{skin-IR}$ and $T_{est-skin}$. Lastly, a time series is presented to illustrate variations in heatwaves across environmental parameters.

Because the experiment lacked replication, statistical comparisons between treatments were not performed. Instead, descriptive comparisons and observed trends are presented. Although these results help highlight potential patterns, the conclusions should be interpreted with caution.

RESULTS

THERMAL COMFORT METRICS

Table 4 reports the corrected mode of the HS2I (correction for the actual BW of pigs and for sprinkling in Period 3, see last section in Materials and methods) for each treatment over the entire rearing period. The mode was chosen to identify the most frequently occurring HS2I value during the experiment. For treatments in Period 1 and Period 2, the correction revealed only a minor deviation of ± 0.05 from the target indices, indicating that, in general, each treatment could achieve its targeted setpoint. However, the correction revealed an RMSE of about 0.18 for treatments in Period 3. Treatments during Heatwaves 1 and 2 (weeks 3 and 6) of Period 3 (fig. 5) were the most inefficient because of the complications related to BW estimation and sprinkling activation. Figure 5 thus shows that during Heatwave 3, each treatment maintained its setpoint for HS2I.

Table 4. Corrected index mode for the nine treatments combining targeted HS2I values (2.0, 2.5, or 3.0) and sprinkling models: partial (PM), gradual (GM), or complete (CM).

Treatment (Period)	2.0 PM	2.0 GM	2.0 CM	2.5 PM	2.5 GM	2.5 CM	3.0 PM	3.0 GM	3.0 CM
	1	2	3	3	1	2	2	3	1
Corrected index mode	1.97	1.98	2.18	2.69	2.48	2.53	2.99	3.17	3.00

Table 3. Summary of distinctions between previous study by Godbout et al. (2023) and current study.

Optimization	(Godbout et al., 2023)	Current Study
Body weight estimation	Following Renaudeau et al. (2011) model, function of ambient temperature, age, and initial body weight.	Uses the Gompertz model, as described by Wellock et al. (2004).
Air speed modeling	Modeling used the average of four points measurement in the pen	Measurements were made with nine points in the pen, where the mean of the four maximum air speed of each combination was used for modeling.
HS2I treatments	Compared a comfort strategy targeting a constant 2.5 HS2I to a conventional temperature-based strategy.	Compared the comfort strategy targeting HS2I's of 2.0, 2.5, and 3.0.
Sprinkling models	Uses equation 2 for the modeling of complete sprinkling (30% of the skin)	Partial and gradual sprinkling model account for estimated wallowing of the pigs (reducing sprinkling volumes for sprinkling treatments)
Sprinkling treatments	Compared a conventional sprinkling strategy to the comfort strategy for sprinkling (equivalent to the current complete model treatment)	Compared three treatments of sprinkling volumes calculation: complete model, gradual model and partial model.
Heat balance	Heat production calculation from Brown-Brandl et al. (2014) heat production for barrows, function of ambient temperatures and body weight.	Uses Brown-Brandl et al. (2014), where ambient temperature in the equation is replaced with National Research Council (2012)'s LCT+3 (least critical temperature +3°C).

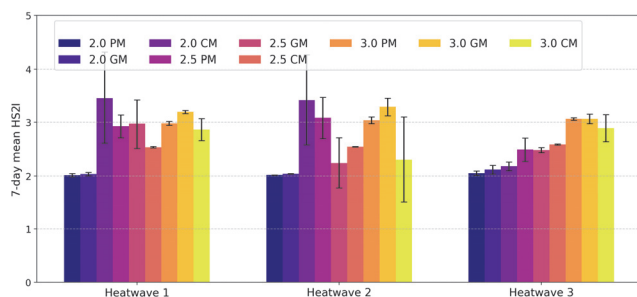


Figure 5. Average daily HS2I during the artificial heatwaves for the nine treatments combining targeted HS2I values (2.0, 2.5, or 3.0) and sprinkling models: partial (PM), gradual (GM), or complete (CM). Error bars are standard deviations of the average HS2I of the 7 days counted into each average.

WATER INTAKE AND SPRINKLING WATER VOLUMES ACROSS TREATMENTS

Sprinkling water use for Periods 1 and 2 was representative of sprinkling models: PM < GM < CM (table 5). Sprinkling volumes for Period 3 were representative only of conditions during Heatwave 3, because of the issues that prevented sprinkling during Heatwaves 1 and 2. In figure 6, the low volume of 3.0 GM is explained by the low outside temperatures (late autumn), which kept the room temperature cooler (see Room Environmental Conditions section), preventing the warm conditions needed to activate sprinkling at this higher HS2I setpoint.

Water consumption averaged 7.15 L d⁻¹ pig⁻¹ across all treatments. All treatments in period 2 exhibited higher water consumption than the average, as well as treatment 3.0 CM in period 1. As reported in the Room environmental conditions section, Period 2 was hotter than Periods 1 and 3, likely explaining the higher consumption of water. When combining both water consumption and sprinkling across all treatments, an average of 7.92 L d⁻¹ pig⁻¹ is obtained (table 5). The same treatments, such as those for water consumption, are above this average.

ZOOTECNICAL PERFORMANCE

The initial weight difference likely contributed to the variation in final live weights after the 70-day rearing period (table 6): pigs in Period 3 reached an average of 126 kg, compared to 118 kg in Period 1 and 122 kg in Period 2. Despite these differences, the ADG remained constant across treatments and periods, suggesting that the higher final weights in Period 3 were primarily a result of the pigs'

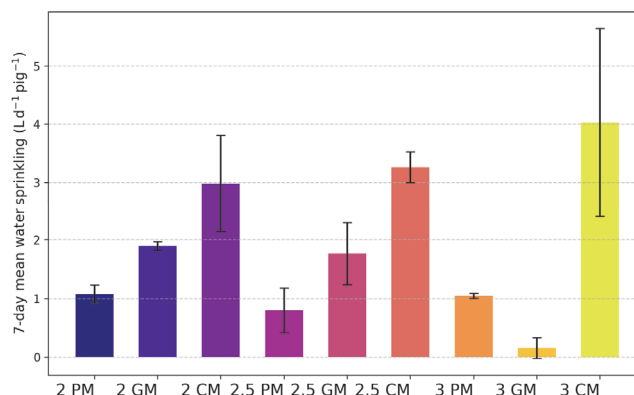


Figure 6. Average sprinkling volumes (L d⁻¹ pig⁻¹) during Heatwave 3 for the nine treatments, which combine targeted HS2I values (2.0, 2.5, or 3.0) with sprinkling models: partial (PM), gradual (GM), or complete (CM). Error bars are standard deviations of the average volumes of the 7 days counted into each average.

higher starting weights (table 6). Similar ADG across treatments would also suggest that none of the nine treatments brought any growth advantages or disadvantages for any group of pigs.

On average, pigs consumed 3.00 kg of feed per day across all treatments (table 7). Feed consumption was 3.04, 2.99, and 2.98 kg d⁻¹ pig⁻¹, respectively, for the HS2I treatments of 2.0, 2.5, and 3.0. FCR was 2.77, 2.75, and 2.75, respectively, for the HS2I treatments of 2.0, 2.5, and 3.0. Pigs in the 2.5 GM treatment had the lowest feed intake (2.76 kg d⁻¹) and the lowest final weight among the nine treatments. In table 7, standard deviations on ADFI and FCR showcase variation between daily means, not between pigs within the pens.

Figure 7 displays the weekly ADFI values during each heatwave for the nine treatments. Feed intake in this graph is over 2.5 kg d⁻¹ pig⁻¹ during Heatwave 1, and mostly over 3.0 kg d⁻¹ pig⁻¹ during Heatwaves 2 and 3. These feed intakes, relative to BW and conditions, are greater than theoretical feed consumption that can be determined from literature (Quiniou et al., 2000; Renaudeau et al., 2011; National Research Council, 2012). Pigs weighed approximately 60 to 75 kg during Heatwave 1, 80 to 95 kg during Heatwave 2, and 100 to 120 kg during Heatwave 3, which explains why ADFI increased at Heatwaves 2 and 3.

BODY WEIGHT ESTIMATION TOOL

Table 8 presents the RMSE of the Gompertz growth model used to compare measured and estimated BWs. For

Table 5. Water intake and sprinkling water use for the nine treatments, which combine targeted HS2I values (2.0, 2.5, or 3.0) with sprinkling models: partial (PM), gradual (GM), or complete (CM).

HS2I Treatment	Sprinkling Treatment	Sprinkling (L d ⁻¹ pig ⁻¹)	Water Consumption (L d ⁻¹ pig ⁻¹)	Total (L d ⁻¹ pig ⁻¹)	Mean (L d ⁻¹ pig ⁻¹)
2.0	PM (Period 1)	0.42	6.61	7.04	7.88
	GM (Period 2)	1.27	7.53	8.8	
	CM (Period 3)	0.77	7.03	7.8	
2.5	PM (Period 3)	0.21	6.56	6.76	7.85
	GM (Period 1)	0.61	6.98	7.58	
	CM (Period 2)	1.88	7.34	9.22	
3.0	PM (Period 2)	0.41	8.86	9.27	8.01
	GM (Period 3)	0.13	6.25	6.68	
	CM (Period 1)	1.2	7.19	8.38	
Mean		0.77	7.15	7.92	-

Table 6. Growth performance of pigs by treatment (standard deviation) for the nine treatments, which combine targeted HS2I values (2.0, 2.5, or 3.0) with sprinkling models: partial (PM), gradual (GM), or complete (CM).

Period	Treatment	Initial Average Live Weight (kg)	Final Average Live Weight (kg)	ADG ^[a] Over the 70 Days (kg d ⁻¹)	Theoretical ADG ^[b] Over the 70 Days (kg d ⁻¹)
1	2.0 PM	40.07 (2.46)	121.75 (6.41)	1.18 (0.09)	0.81 (0.05)
	3.0 CM	40.21 (2.01)	119.00 (11.41)	1.13 (0.17)	0.82 (0.05)
	2.5 GM	40.07 (2.30)	114.42 (5.16)	1.07 (0.08)	0.80 (0.07)
	Average (Period 1)	40.12	118.39	1.13	0.81
2	2.5 CM	42.36 (2.21)	123.50 (6.27)	1.16 (0.08)	0.79 (0.05)
	2.0 GM	41.79 (2.61)	119.50 (5.95)	1.12 (0.08)	0.79 (0.06)
	3.0 PM	41.86 (2.48)	124.42 (6.56)	1.18 (0.08)	0.80 (0.06)
	Average (Period 2)	42.00	122.47	1.15	0.79
3	3.0 GM	49.07 (4.97)	122.50 (8.68)	1.06 (0.12)	0.86 (0.06)
	2.5 PM	49.36 (2.37)	129.00 (8.63)	1.14 (0.11)	0.79 (0.06)
	2.0 CM	48.69 (4.33)	126.83 (6.16)	1.12 (0.09)	0.88 (0.08)
	Average (Period 3)	49.04	126.11	1.11	0.84
General average		43.75 (4.11)	122.32 (7.25)	1.13 (0.04)	0.81

[a] Average daily gain.

[b] Theoretical average daily gain calculated using the model of Renaudeau et al. (2011) based on body weight and ambient temperature.

Table 7. Pig feed consumption performances (standard deviation) for the nine treatments, which combine targeted HS2I values (2.0, 2.5, or 3.0) with sprinkling models: partial (PM), gradual (GM), or complete (CM).

HS2I	Sprinkling Treatment	ADFI ^[a] (kg d ⁻¹ pig ⁻¹)	Mean FCR ^[b]	Theoretical ADFI ^[c] Over the 70 Days (kg d ⁻¹)
2.0	PM (Period 1)	3.03 (0.91)	2.66 (0.99)	2.54 (0.37)
	GM (Period 2)	3.04 (0.96)	2.78 (0.97)	2.47 (0.43)
	CM (Period 3)	3.05 (0.99)	2.87 (1.21)	2.82 (0.48)
	Average	3.04	2.77	2.61
2.5	PM (Period 3)	3.16 (0.99)	2.88 (1.08)	2.88 (0.47)
	GM (Period 1)	2.76 (0.97)	2.71 (1.22)	2.47 (0.41)
	CM (Period 2)	3.06 (0.94)	2.67 (0.86)	2.51 (0.44)
	Average	2.99	2.75	2.62
3.0	PM (Period 2)	2.96 (1.02)	2.57 (0.95)	2.52 (0.46)
	GM (Period 3)	3.02 (0.99)	2.98 (1.15)	2.77 (0.43)
	CM (Period 1)	2.97 (0.92)	2.71 (0.98)	2.56 (0.39)
	Average	2.98	2.75	2.62
General average		3.00	2.76	2.62

[a] Average daily feed intake.

[b] Feed conversion ratio.

[c] Theoretical average daily feed intake calculated using the model of Renaudeau et al. (2011) based on body weight and ambient temperature.

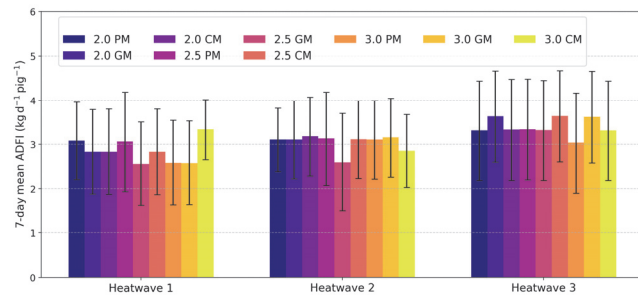


Figure 7. Average ADFI during each heatwave for the nine treatments, which combine targeted HS2I values (2.0, 2.5, or 3.0) with sprinkling models: partial (PM), gradual (GM), or complete (CM). Error bars are standard deviations of the average ADFI of the 7 days counted into each average.

Periods 1 and 2, the low RMSE values indicate that the estimations were reasonable, with only minor deviations, despite the issue encountered in Period 2. The tool functioned

adequately, except during Period 3, when the initial 9-kg body weight (BW) estimation error introduced an offset in the estimated BW, leading to larger deviations among treatments. This, in turn, affected the calculated HS2I values in the rooms. Table 4 presents the corrected HS2I values obtained using the true BWs.

ANIMAL MODEL

Data analysis, as previously detailed, underscores a significant positive correlation (fig. 8) between $T_{\text{skin-IR}}$ and estimated skin temperature using the heat balance model (Pearson analysis, $r = 0.725$). Here, the estimated skin temperature is calculated using the THP method from Brown-Brandl et al. (2014). This result suggests that the model closely tracks the variations observed through IRT, although some discrepancies remain. The linear relationship indicates a coefficient of variation of 0.7 and an intercept of 8.1°C. Further investigation is needed to elucidate the quasi-

Table 8. Root-mean-squared error (RMSE) in kg of the estimated body weight tool for the nine treatments, which combine targeted HS2I values (2.0, 2.5, or 3.0) with sprinkling models: partial (PM), gradual (GM), or complete (CM).

Treatment	2.0 PM	2.0 GM	2.0 CM	2.5 PM	2.5 GM	2.5 CM	3.0 PM	3.0 GM	3.0 CM
Period	1	2	3	3	1	2	2	3	1
RMSE	1.82	2.50	12.89	10.72	1.65	3.12	2.80	12.19	1.73

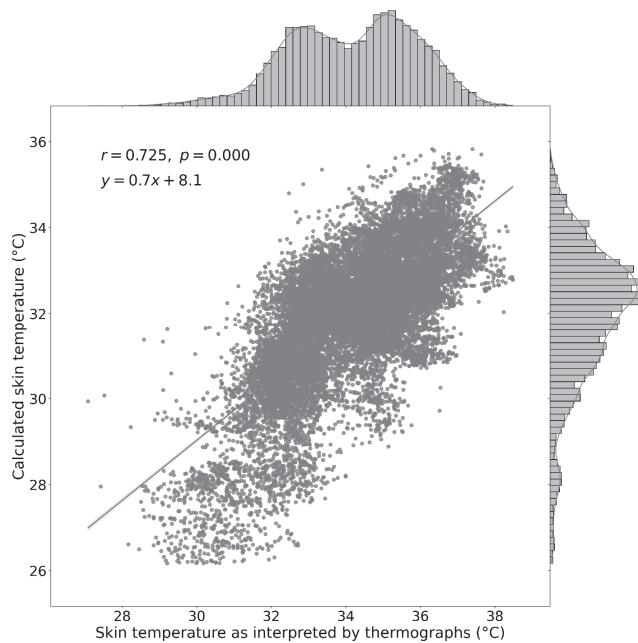


Figure 8. Pearson correlation between skin temperature as interpreted by IRT and estimated skin temperature using the heat balance model by Fialho et al. (2004), regardless of comfort strategy treatments.

systematic underestimation of calculated skin temperature observed in the lower left region of the graph (fig. 8).

ROOM ENVIRONMENTAL CONDITIONS

Room environmental conditions varied both across days and between experimental periods. While temperatures were managed according to established protocols, outdoor weather conditions had an impact on indoor conditions during specific periods (tables 1 and 9). At the beginning of Period 1 (early spring) and at the end of Period 3 (late autumn), cooler outdoor temperatures resulted in milder conditions between heatwaves (fig. 9). During Period 1, RH fluctuated around 50% during the first half, then gradually increased to approximately 70% toward the end of the rearing period as summer approached. This trend aligns with rising external humidity levels, likely influenced by increased photosynthetic activity. During Period 2, RH remained relatively stable around 70%, whereas Period 3 showed a gradual decline in relative humidity over time. Analysis of average WDTI values indicates that Period 2 experienced higher heat stress than Period 1, resulting in a higher heat stress level than during Period 3.

Figure 9 shows the daily WDTI trends over 70-day periods, averaged across the three rooms, regardless of treatment, highlighting the day-to-day variability in indoor conditions. Heat exchange between the experimental facility and the external environment, primarily through the walls and ceiling, contributed to warmer indoor conditions at the

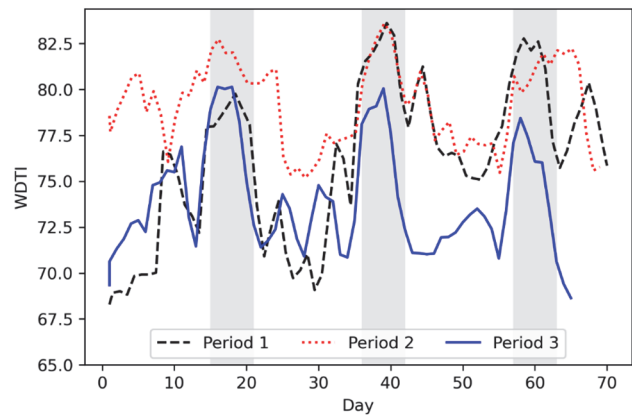


Figure 9. Average daily Wet-and-Dry-Bulb Temperature Index (WDTI) during the three periods (24 h average of the three rooms regardless of treatments). The grey shaded areas depict the artificial heatwaves.

end of Period 1, throughout Period 2, and at the beginning of Period 3 (summer). The grey-shaded areas, depicting artificial heatwaves, indicate higher heat-stress conditions according to the WDTI. In contrast, Period 3 (autumn) experienced milder heat stress during these events. During most heatwaves, the average daily room conditions exceeded a WDTI value of 78, except during Heatwave 3 during Period 3, when colder outdoor temperatures of November prevented indoor temperatures from rising, highlighting insulation limitations. All values presented are 24-h averages, meaning cooler nighttime temperatures influenced the daily means shown in figure 9.

REDUCED-FLOW VENTILATION

The ventilation system operated at reduced flow rates, capped at approximately $30 \text{ L s}^{-1} \text{ pig}^{-1}$ ($\sim 64 \text{ ft}^3 \text{ min}^{-1} \text{ pig}^{-1}$). Table 10 highlights the most common extraction rates for each treatment, showing that even under warm conditions, ventilation remained relatively low. Room 3, which hosted treatments 2.0 CM, 2.5 GM, and 3.0 PM, exhibited higher airflows, likely due to its ventilation duct design (fig. 1). Specifically, 50% of the duct supplied Room 3 directly, while the remaining 50% first opened for Room 2 before reaching Room 1.

DISCUSSION

PROPER FUNCTIONING OF THE STRATEGY

The comfort strategy first depends on its setpoint for HS2I. A lower HS2I (i.e., 2.0) resulted, on average, in a higher airspeed and more frequent sprinkling because, for the same ambient conditions and BW, more cooling is required to achieve the target value. For example, in figure 4, at 70% RH with a BW of 90 kg, the maximum airspeed is reached at approximately 24.6°C and 26.0°C for an HS2I setpoint of 2.0 and 2.5, respectively. This means that if these conditions are encountered, sprinkling could occur every 15 min as long as the temperature is above 24.6°C , thus achieving more frequent sprinkling linked with a lower HS2I setpoint. This was usually accomplished during the experiment, except for the 2.0 CM treatment (Heatwaves 1 and 2,

Table 9. Average temperature, relative humidity, and Wet-and-Dry-Bulb Temperature Index (WDTI) per experimental period (standard deviation).

	Period 1	Period 2	Period 3
Average temperature ($^\circ\text{C}$)	26.21 (0.33)	27.23 (0.12)	24.73 (0.36)
Relative humidity (%)	52.95 (1.20)	70.39 (2.46)	54.06 (1.59)
WDTI (using $^\circ\text{F}$)	76.17 (0.57)	79.16 (0.36)	73.67 (0.69)

Table 10. Fraction of time (%) that the ventilation rate exceeds different thresholds for the nine treatments, which combine targeted HS2I values (2.0, 2.5, or 3.0) with sprinkling models: partial (PM), gradual (GM), or complete (CM).

Ventilate Rate ^[a]	Treatment								
	2.0 PM (Period 1)	2.0 GM (Period 2)	2.0 CM (Period 3)	2.5 PM (Period 3)	2.5 GM (Period 1)	2.5 CM (Period 2)	3.0 PM (Period 2)	3.0 GM (Period 3)	3.0 CM (Period 1)
13.2 L s ⁻¹ pig ⁻¹	84.1	96.8	98.8	69.4	92.2	99.3	98.6	94.8	62.2
14.1 L s ⁻¹ pig ⁻¹	75.7	94.8	98.2	64.7	86.3	98.6	98.6	89.4	58.6
15.1 L s ⁻¹ pig ⁻¹	68.1	88.0	94.7	59.5	79.5	97.7	98.6	87.5	52.1
16.5 L s ⁻¹ pig ⁻¹	62.2	87.4	85.4	50.2	75.1	96.0	98.5	78.9	49.2
17.7 L s ⁻¹ pig ⁻¹	57.4	75.8	78.1	47.0	71.1	92.2	98.0	69.9	45.6
18.9 L s ⁻¹ pig ⁻¹	47.8	43.0	71.6	43.6	66.5	75.8	97.3	48.9	30.9
20.0 L s ⁻¹ pig ⁻¹	27.6	27.2	65.4	28.8	62.9	60.6	96.1	25.4	19.1
21.2 L s ⁻¹ pig ⁻¹	16.4	21.0	59.5	12.4	59.0	43.4	94.7	12.2	9.4
22.7 L s ⁻¹ pig ⁻¹	5.2	13.6	57.0	3.5	55.2	25.8	94.0	7.2	2.9
23.6 L s ⁻¹ pig ⁻¹	2.0	8.9	53.9	0.9	52.8	19.9	93.5	2.2	1.3
30.0 L s ⁻¹ pig ⁻¹	0.3	5.5	24.6	0.1	13.6	0.3	69.1	0.0	0.4

^[a] 1 L s⁻¹ = ~2.12 cfm.

Period 3) where the HS2I value reached 3.5 (fig. 5) due to a hardware malfunction. False sprinklings were recorded during Period 3: while sprinklings were supposed to occur, and were occurring according to the program, they did not. Therefore, the program accounted for wetted skin and reduced airspeed most of the time for the 2.0 setpoint and required minimal sprinkling for the 3.0 setpoint under the same conditions. This issue could also have been avoided by validating sprinkler volumes using water meter data in the control program.

Then, HS2I-based control strategies naturally depend on their variable inputs. While temperature and humidity are easily measured with reliable sensors and sprinkling is an on/off function, average BW and airspeed are more complex inputs to determine. In this study, BW was estimated using the Gompertz model (Wellock et al., 2004). Although the BW estimation tool proved to be reliable, with errors mainly related to the manipulation of the programming code, future experimental or commercial works could benefit from an automated scaling system for growing pigs (e.g., automated sorting scales) or newer iterations of weighing systems for pigs (Decarie et al., 2025). An airspeed assessment was conducted before the experiments to estimate a representative airspeed value at the animal level. The airspeed models for each room enabled real-time HS2I calculation based on the operation levels of the recirculation and exhaust fans. Computational fluid dynamics simulations mapping the distribution of air temperature, humidity, and velocity could have been a helpful tool, as demonstrated by Bjerg et al. (2018). Given the hypothesis of homogenized environmental parameters in the rearing room, a representative airspeed value was deemed sufficient for HS2I-based control, rather than developing the ability to determine the distribution of HS2I values within the rearing room. Finally, Gao et al. (2016) demonstrated the feasibility of multi-point airspeed measurements (in real-time) in livestock facilities, using a newly designed omnidirectional anemometer.

The relevance of the HS2I and the HS2I-based strategy was further supported by a correlation coefficient of 0.725 between measured and estimated skin temperatures, obtained using the heat balance model that developed the HS2I. As previously noted, Godbout et al. (2023) reported a correlation of 0.701 for a similar data analysis. Given the number of data points, this correlation (0.725) appears noteworthy, as it validates that the animal model used to design the HS2I

(Fialho et al., 2004) can also estimate skin temperature by assessing heat transfer between the pig and the thermal environment.

HEAT STRESS INDICATORS AND REDUCED VENTILATION RATES

The analysis of average WDTI values indicates that Period 2 experienced significantly higher heat stress than Period 1, which, in turn, had higher heat stress than Period 3. According to Hahn et al. (2009) and Ramirez et al. (2018), WDTI threshold values would classify the mean environmental conditions of Periods 1 to 3 in the “Alert,” “Danger,” and “Normal” categories, respectively. Similarly, as shown in figure 9, the third heatwave of Period 3 did not reach the “Danger” category (WDTI = 79), unlike most of the other heatwaves. This partly suggests that the artificial heatwaves did create heat-stress conditions sufficient to test the HS2I-based strategy.

The project also demonstrated the technical feasibility of controlling indoor climate during hot periods by using reduced mechanical ventilation airflow rates (<30 L s⁻¹ pig⁻¹) in combination with adapted cooling. Low airflows enable cost-effective equipment solutions that offer valuable benefits to the pork industry. Besides avoiding the high costs of oversizing, this approach is compatible with innovations such as centralized ventilation, air filtration, air inlet preconditioning, and exhaust air treatment (Vitt et al., 2017).

PIG PERFORMANCE

Tables 6 and 7 present theoretical values for ADG and ADFI based on models proposed by Renaudeau et al. (2011). These models, derived from a meta-analysis, are a function of BW and ambient temperature. The values were calculated with the current study’s conditions for comparison purposes only. The pigs outperformed the theoretical model Renaudeau et al. (2011) by 0.32 kg d⁻¹ for ADG and 0.38 kg d⁻¹ pig⁻¹ for ADFI (tables 6 and 7). This suggests that imposed heat stress conditions may have been mitigated by any of the nine treatments, as growth and feed intake did not appear to be negatively affected compared to theoretical expectations from 2011.

ADFI was higher in Period 3 compared to Periods 1 and 2, which aligns with expectations: pigs in Period 3 started at 49 kg, while pigs in Periods 1 and 2 began at 40 to 42 kg (table 6). Heavier pigs typically consume more feed daily

(Quiniou et al., 2000; Renaudeau et al., 2011). Finally, in table 7, the average ADFI for an HS2I of 2.0, 2.5, and 3.0 was 3.04, 2.99, and 2.98 kg d⁻¹ pig⁻¹, respectively. This decreasing trend toward 3.0 may be coincidental, or it may indicate that a setpoint of 2.0 encourages pigs to eat more due to heat-stress alleviation. Alternatively, HS2I setpoints of 2.5 and 3.0 may have allowed heat stress to persist, leading to a decrease in feed consumption compared to HS2I of 2.0.

CONSUMED AND SPRINKLED WATER

Water consumption is influenced by various factors, including feed composition and intake, boredom, external stress, drinker design, water quality, and the thermal environment (National Research Council, 2012; Patience, 2012). Assuming that all these factors remained constant during the three periods except the latter, water intake by the pigs can be used as an indicator of heat stress between the treatments. Because water requirements remain difficult to define, comparing treatments may be a more reliable approach. Thus, treatment 3.0 PM, shown in figure 10, resulted in the highest water consumption during heatwaves. It may be coincidental that the 3.0-PM pigs drank more, or they could have been under heat stress due to a lack of cooling, which was linked to the treatment and occurred during the summer period (fig. 9).

A report on water usage by pig houses in Québec presents that the growing-finishing phase consumes, on average, 6.3 L d⁻¹ pig⁻¹ over a typical year (Turcotte et al., 2023). Based on this report, a mean water consumption of approximately 10 L d⁻¹ pig⁻¹ during summer can be estimated using a published graph in Turcotte et al. (2023). In comparison, the water usage observed for the current experiment remained below this average consumption (table 5). In figure 10, only treatments considering an HS2I of 3.0 approached the 10 L d⁻¹ pig⁻¹ threshold, particularly for Heatwaves 2 and 3. This suggests that heavier pigs (>100 kg

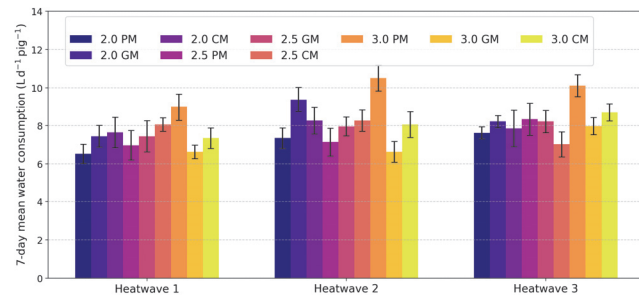


Figure 10. Average water intake during the artificial heatwaves for the nine treatments, which combine targeted HS2I values (2.0, 2.5, or 3.0) with sprinkling models: partial (PM), gradual (GM), or complete (CM). Error bars are the standard deviations of the average consumption of the 7 days counted into each average.

during Heatwave 3) may not benefit from a 3.0 HS2I setpoint and a reduced sprinkling model (PM), as they drank more water than pigs in other treatments during Heatwave 3. However, the treatment 3.0 PM was applied during the hottest period (#2). Higher water consumption could have also been underlined if 3.0 GM or 3.0 CM was applied during the same period. Additionally, this observation is consistent with the fact that heavier pigs are more susceptible to heat stress due to their higher energy intake (and thus heat production), lower body surface area-to-body weight ratio, and greater subcutaneous adipose tissue (Renaudeau et al., 2012).

The analysis of sprinkling water volumes revealed variability across the treatments (table 5 and fig. 6). In general, the PM treatment used less water, while the CM treatment used the most. Some overlap occurred among the three treatments due to external factors and issues encountered during the experimental phase, including BW estimation and sprinkler activation issues. Despite these challenges, we can conclude that the minimum sprinkling model (PM) generally provides an adequate volume of water for sprinkling pigs, because the feed consumption and growth data (tables 6 and 7) suggest that increasing the amount of sprinkling water beyond this level does not result in any additional benefits for the strategy.

A synthesis of results indicated that all treatments were functional under hot conditions, despite some issues encountered (particularly with HS2I compliance). For instance, in Periods 1 and 2, when WDTI exceeded 76 (alert level), ADG and ADFI were comparable to those observed in Period 3. A similar trend was observed for average water consumption across the 70-day periods. Finally, although average sprinkling volumes varied among treatments, pig performance remained similar: higher or lower sprinkling volumes did not appear to confer any additional advantage (table 11).

COMMERCIAL IMPLICATIONS

Overall, besides some technological missteps, the comfort strategy treatments were valid and functional. The three HS2I setpoints seem to be functional for lighter pigs, but HS2I setpoints between 2.0 and 2.5 are likely to be better for heavier pigs. Due to higher water consumption for larger pigs during the hottest conditions of Period 2, a 3.0 setpoint may have to be discarded in a future study, because when experimental or calculation errors happen, the perceived conditions by the pigs are higher than an HS2I of 3.0, which means the beginning of heat stress. As a complementary recommendation, the HS2I setpoint could be linearly adjusted from 3.0 to 2.0 as pigs grow. This adjustment would yield a comfort strategy that applies more intensive cooling to heavier pigs, while being less stringent for smaller pigs that can

Table 11. Synthesis of results on HS2I mode, environmental conditions and pigs' performances.

Treatment	2.0 PM	2.0 GM	2.0 CM	2.5 PM	2.5 GM	2.5 CM	3.0 PM	3.0 GM	3.0 CM
Period	1	2	3	3	1	2	2	3	1
Corrected HS2I mode	1.97	1.98	2.18	2.69	2.48	2.53	2.99	3.17	3.00
Average wet-dry bulb index	76.17	79.16	73.67	73.67	76.17	79.16	79.16	73.67	76.17
Water consumption (L d ⁻¹ pig ⁻¹)	6.61	7.53	7.03	6.56	6.98	7.34	8.86	6.25	7.19
Sprinkling (L d ⁻¹ pig ⁻¹)	0.42	1.27	0.77	0.21	0.61	1.88	0.41	0.13	1.2
Average daily gain (kg d ⁻¹)	1.18	1.12	1.12	1.14	1.07	1.16	1.18	1.06	1.13
Average daily feed intake (kg d ⁻¹)	3.03	3.04	3.05	3.16	2.76	3.06	2.96	3.02	2.97

tolerate higher temperatures. The implementation of this strategy currently relies on existing HS2I coefficients, which will need to be updated in the medium to long term to account for genetic progress. Moreover, the proposed ventilation and cooling strategy should be applied only during heat stress, since temperature-based ventilation is already suitable for cooler conditions. The introduction of the comfort strategy in an actual commercial farm would primarily rely on manufacturers of automated ventilation controllers. If a farm is already equipped with air-speed cooling equipment, a sprinkling system, or other cooling systems, most of the investment would focus on updating the controller to include HS2I calculation and summer-period logic control. This assumes that temperature, RH, and BW are measured on the farm. If a given commercial farm does not include cooling equipment (i.e., only high ventilation airflow), air speed can still be assessed, and airflows can then be partially adjusted following HS2I targets. On this farm, the comfort strategy may lead the business to invest in cooling equipment, as thermal comfort would not necessarily be optimal based on HS2I data, for example.

The primary technical challenge would be assessing air-speed, though the experimental solution employed in this study appeared functional. In this context, details on air speed measurement and calibration methodologies for commercial barns are essential for a complete and applicable commercialization. Further investigation is required to accurately assess airspeeds within the pens. For instance, the methodology used in these experiments did not include calibrating the air-speed models with pigs present. Consequently, additional experiments should be conducted to evaluate the effect of animal presence on air speed, compared with measurements taken in their absence.

CONCLUSION

A ventilation and cooling strategy based on the HS2I index for growing-finishing pigs was optimized during this study. Experimental trials tested nine functional treatments of the strategy by combining three HS2I setpoints (2.0, 2.5, or 3.0) with three sprinkling water models (partial, gradual, or complete) based on theoretical evaporative cooling requirements, as determined by a heat balance model. Among these models, the one using the least amount of sprinkling water (PM) proved to be the most advantageous, as increasing sprinkling water volumes did not improve pig growth performance. The comfort strategy demonstrated promising potential to improve production amid increasing risks of heat stress associated with climate change. Future studies could further refine HS2I setpoints by using an evolutive HS2I setpoint based on pig weight, thereby maximizing thermal comfort and production efficiency and better coping with heat-stress conditions.

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NOMENCLATURE

- A = adult body weight of a pig (kg)
 ACIs = animal comfort indices
 ADFI = average daily feed intake (kg d⁻¹)
 ADG = average daily gain (kg d⁻¹)
 B = rate of growth coefficient in the Gompertz model
 BABE 2.0 = Laboratory 2.0 for Agri-Environmental Assessments of Livestock Buildings
 BW = bodyweight (kg)
 CIGR = International Commission of Agricultural Engineering
 CFM = cubic feet per minute (ft³/min)
 CM = complete model for sprinkling
 CTBS = conventional temperature-based strategy
 d = day
 FCR = feed conversion ratio
 FTIR = Fourier-transform infrared gas analyzer
 GM = gradual model for sprinkling
 HS2I = housed swine heat stress index
 IPCC = Intergovernmental Panel on Climate Change
 IRT = infrared thermography
 LCT+3 = lower critical temperature + 3°C
 LHP = latent heat production
 PM = partial model for sprinkling
 Q_{evap} = heat needed to evaporate water (kW pig⁻¹)
 RH = relative humidity (%)
 RMSE = root-mean-squared error

RPM	= fan blade angular speed	T_e	= evaporative critical temperature
r_w	= wetted fraction of pig skin	$T_{est-skin}$	= estimated skin temperature ($^{\circ}C$)
r_{wp}	= wetted fraction of pig skin because of perspiration	THP	= total heat production
r_{ww}	= wetted fraction of pig skin because of wallowing	T_l	= lower critical temperature
S_{on}	= wetted skin status (0 or 1)	$T_{skin-IR}$	= mean interpreted pig skin temperature measured with infrared camera ($^{\circ}C$)
T_b	= pig mean body temperature as defined by Fialho et al. (2004)	u_{air}	= air speed ($m\ s^{-1}$)
T_{db}	= ambient dry-bulb temperature ($^{\circ}C$)		