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Energy, Production and Environmental Characteristics of a Conventional Weaned Piglet Farm in North West Spain

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Abstract: Postweaning is one of the most sensitive and energy-demanding phases of swine production. The objective of this research was to assess the energy, production and environmental characteristics of a conventional farm with temperature-based environmental control. The selected energy, environmental and production variables were measured on farm, in a high livestock density area of NW Spain, for seven production cycles. The quantification of variables was aimed at obtaining the maximum performance with the lowest possible use of resources, focusing on animal welfare and production efficiency. The Brown–Forsythe, Welch and Games-Howell tests revealed significant differences in terms of temperature, relative humidity and CO₂ concentrations among production cycles, and among the critical, postcritical and final periods. Improved humidity management resulted in a 17% reduction of climate control energy, which involved energy savings in the range of 33% to 47% per kg produced at the end of the postweaning cycle. Accordingly, adding humidity as a control variable could result in higher ventilation rates, thereby improving animal welfare, reducing heating energy use and increasing weight gain per unit climate control energy. In addition, the strong correlations found between heating energy and relative humidity ($R^2 = 0.73$) and ventilation energy and CO₂ ($R^2 = 0.99$) suggest that these variables could be readily estimated without additional sensor costs.

Keywords: postweaning; carbon dioxide; relative humidity; heating energy consumption; ventilation energy consumption

1. Introduction

Postweaning is a sensitive phase for piglets [1], particularly for newly weaned piglets, insofar as it results in simultaneous stresses [2,3] that can affect the growth performance and intestinal health of piglets [4]. During this six-week phase, piglets triple their weight and their climatic requirements undergo important changes. Consequently, environmental control must be adapted to the growth needs

of the piglets, and the environmental variables must be maintained at optimum levels that will change according to the changes in requirements [5]. Moreover, in an oceanic climate, environmental control systems must provide supplemental heat and sufficient ventilation, which is strongly conditioned by the high air humidity levels.

In postweaning, the heating energy demand is high [6] because of the high temperatures required for animal growth, which poses a risk of heat stress caused by high indoor temperatures in warm periods [7]. Some authors [2] analysed temperature requirements in three periods: The critical period (the first two weeks), the postcritical period (the following two weeks) and the final period. During the critical period, the lower-critical temperature must be in the range 26–28 °C [2], which can be reduced to 24 °C in the following two weeks [8]. During the final period, the indoor temperature can be rapidly reduced by 2–3 °C per week until the temperature in the finishing house is reached.

The effects of humidity on animal growth rate are much smaller than those of temperature [9]. In fact, air humidity is not expected to have much influence on the performance of weaned piglets maintained within thermoneutrality [10,11]. However, recent research has found positive correlations between relative humidity and microbial diversity or the relative abundance of fungal allergen genera in pig farms [12,13]. Actually, wet surfaces resulting from the condensation formed on the animals or on the facilities have been identified as one of the main problems in the middle latitudes inside livestock buildings [14]. Accordingly, humidity is a critical environmental variable because of its effects on the energy dynamics of the climate inside the building.

On intensive livestock farms, animals are directly exposed to air pollutants, which indirectly favours the emergence of illnesses [15,16]. Also, the regulation of climatic parameters influences the health, performance, welfare and behaviour of pigs, and causes indirect effects on the level of emissions [17,18]. Air quality is associated with carbon dioxide concentration [19,20], with a maximum recommended level of 1540 ppm [21]. Therefore, CO₂ levels greater than 3000 ppm negatively affect growth performance [22].

Controlling the facilities to maintain indoor air quality and thermal environment at the right levels [23] involves many problems. Particularly, postweaning facilities consist of many rooms, which requires installing a large amount of measurement and control devices on a single farm. Yet, environmental control has commonly been based on the use of data from a single temperature probe [24,25], whereas other variables such as humidity [26] or CO₂ [27,28] are of increasing interest because of their impact on swine production [29] and must be included in automation. A good control strategy can prevent some delayed control effects caused by time lags of devices and provide an expected in-time indoor thermal environment control [30].

The objective of this study was to define new low-cost strategies that could be easily implemented on conventional farms in areas with an oceanic climate. Such strategies should contribute to the achievement of maximum performance with the lowest possible use of resources while focusing on animal welfare and production efficiency. To this end, a conventional farm with temperature-based environmental control located in a high livestock density area was characterized in terms of production, energy performance and environment. The characterization of the farm revealed the relationships between easily measurable environmental variables and their adaptation to piglet growth over the cycle, as well as the main problems related to control strategies.

2. Materials and Methods

The study was conducted in a postweaning room for piglets from 6 kg to 20 kg live weight on a swine farm with a capacity for 4985 sows. The farm is located in Northwest Spain (ED50: 43°10'15'' N 8° 19' 24'' W), a high livestock density region with an oceanic climate.

The inside dimensions of the room were 11.82 m in length by 5.86 m in width and 2.50 m to 2.25 m in height. The room contained six pens on each side of a central aisle and housed a maximum of 300 piglets (Figure 1). The ventilation system was composed of a 500-mm helical extractor fan with the following specifications: 230 VAC, 50 Hz, 1330 rpm and 480 W power. Fresh air entered the room

through two windows, with air deflectors in the wall opposite to the fan on each side of the entrance door to the room. The radiant floor heating system was composed of two 1.20×0.40 -m polyester spreader plates for water, with a capacity of 2.90 L, placed at the centre of each pen.

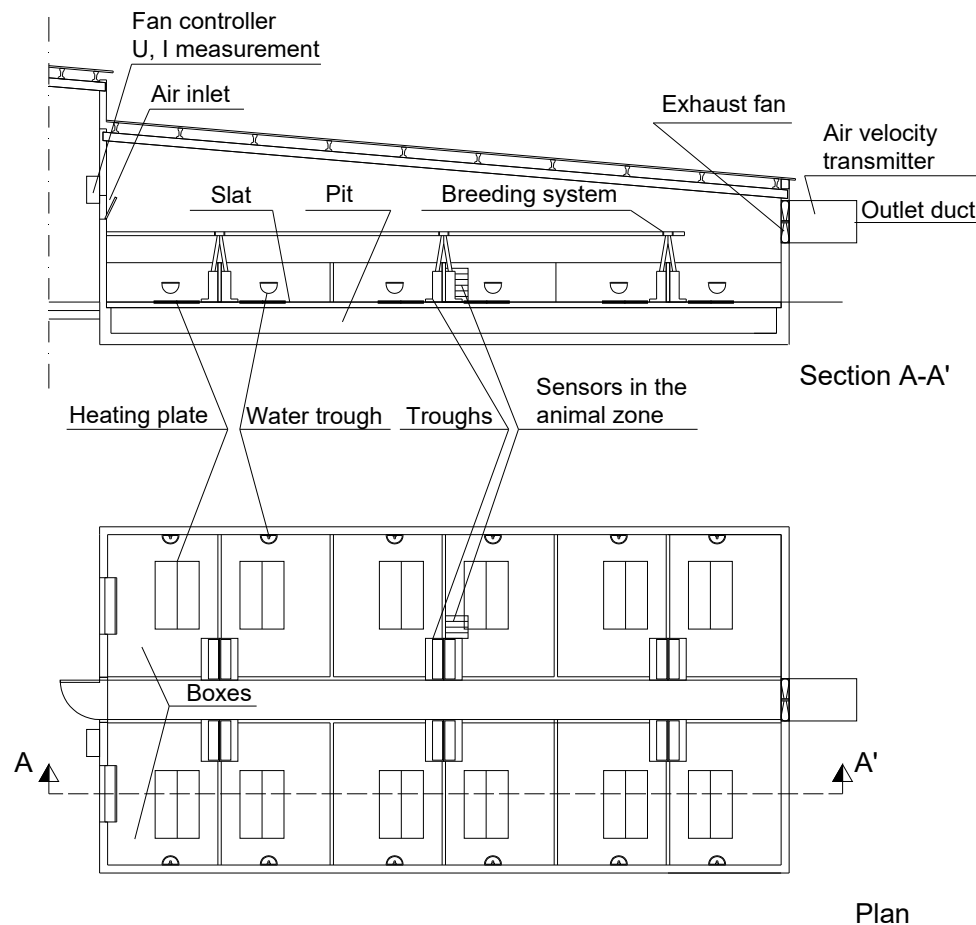


Figure 1. Postweaning room and location of sensors.

2.1. Measurement and Determination of Variables

Environmental variables affecting animal welfare and production that could be easily measured and implemented on conventional farms were selected. The sensors should be inexpensive, robust, reliable and capable of providing long-term measurements with minimal maintenance, such that they could be readily incorporated into environmental controls. Accordingly, the most important variable was indoor temperature [7,9,10,19], which is the basis of the environmental control system. Relative humidity was used because of its effects on animal welfare and energy balance [7,9,10,18]. In addition, air velocity in the animal zone was measured because animals are very sensitive to air currents during postweaning [11]. Finally, CO₂ concentration was measured [18–20] because, contrary to other gases, CO₂ meets the criteria defined for the selection of variables. Therefore, the variables measured inside the room were temperature, humidity, CO₂ concentration and air velocity (Figure 1). The sensors used for measuring indoor environmental comfort variables were positioned in a central pen in the animal zone, at a height of 0.40 m. A description of the sensors used for measuring each environmental variable follows:

- Humidity (HR) and temperature (T) in the animal zone were measured using S-THB-008 sensors (Onset Computer Corporation), with measurement ranges of 0% to 100% and -40 °C to 75 °C.

- CO₂ concentration in the animal zone (C_{CO2}) was measured using Delta Ohm HD37BTV.1 transmitters with double-wave infrared technology (NDIR) and a measurement range of 0–5000 ppm.
- Air velocity in the animal zone (v) was measured using a Delta Ohm HD103T.0 omnidirectional hotwire probe, with measurement range of 0.08–5 m s⁻¹.

In addition, outdoor temperature (T_{out}), humidity (HR_{out}), atmospheric pressure, wind speed and direction were measured using an Onset Computer Corporation EIC Control U-30 weather station.

A number of authors measured energy variables [7,14]. To determine heating and ventilation energy and ventilation rates, the following parameters were measured using the described sensors:

- Flow of the heating system (Q_{hs}): Siemens SITRANS F US Clamp-on FST020 IP65 NEMA 4X ultrasonic flowmeter.
- Temperature at the inlet (T_i) and outlet (T_o) of the heating system: Campbell Scientific Ltd. model 108, with a measurement range of -5°–+95 °C, >±0.5 °C.
- Fan operating voltage (U): Magnelab AC Potential Transformer (PT) T-MAG-SPT-600 (Onset Computer Corporation), which, connected to an Onset Computer Corporation TRSM module, provided effective value.
- Fan operating current (I): Magnelab AC Current Transformer SCT-0750-050 (Onset Computer Corporation), which, connected to an Onset Computer Corporation TRSM module, provided effective value.
- Velocity of the air extracted through the ventilation system (v_m): Delta Ohm HD2903TTC310 active air velocity transmitter installed at the fan outlet according to the method described by the authors of [31] and adapted to the hotwire probe.

The temperatures measured with temperature probe 108 (T_i and T_o) were stored in a Campbell Scientific Ltd. CR-10X datalogger. The rest of indoor measurements were stored in an Onset Computer Corporation HOBO H-22 datalogger.

In addition to the above indoor variables, some outdoor variables were measured because of their effects on building energy balance, namely temperature (T_{out}) [14] and humidity (HR_{out}) [7]. In addition, atmospheric pressure, wind speed and direction were measured. Outdoor variables were collected using an Onset Computer Corporation EIC Control U-30 weather station.

All the variables were sampled at 1-s intervals and stored every 10 min. Data was collected between 6 October 2011, and 31 August 2012, which comprised seven weaning cycles, with a total of 319,762 records (Table 1). In addition, piglets were weighed at entry into and exit from the postweaning room. Finally, data of piglet death rates were collected for each cycle. Death rates were estimated from daily observations performed on the room for each production cycle.

Table 1. Start and end dates for each cycle.

Date	Cycles						
	I	II	III	IV	V	VI	VII
Start	06 October 2011	21 November 2011	09 January 2012	26 February 2012	12 April 2012	31 May 2012	19 July 2012
End	16 November 2011	03 January 2012	20 February 2012	04 April 2012	21 May 2012	11 July 2012	31 August 2012

The heating system energy requirements for each cycle, W_{hs} in kJ, were determined from the following expression:

$$W_{hs} = \sum_1^n Q_{hs} \rho c (T_i - T_o) \Delta t \quad (1)$$

where n is the number of intervals measured per cycle; Q_{hs} is the average flow of the heating system measured by the flowmeter at 1-s intervals and stored at 10-min intervals, in m³ s⁻¹; ρ is water density, 9933.7 kg m⁻³; c is the volume-specific heat capacity of water at 30 °C, 4.178 kJ kg⁻¹ °C⁻¹; T_i and T_o are the temperatures of the water flowing inside and outside the heating system, respectively, in °C; and Δt is the time for each measurement interval, 600 s.

The electric energy requirements for the forced ventilation system, W_{vs} in kJ, were calculated using the following expression:

$$W_{vs} = \sum_1^n UI \cos \varphi \Delta t \quad (2)$$

where n is the number of intervals measured per cycle; U is the fan operating voltage, in V; I is the fan operating current, in A; $\cos \varphi$ is the power factor for the fan, and Δt is the time for each measurement interval, 600 s.

The flow of air extracted through the fan, Q in $\text{m}^3 \text{s}^{-1}$, was determined using the following expression:

$$Q = 1.401 v_m S \quad (3)$$

where 1.401 is the ratio between average velocity and experimentally measured velocity, v_m is the measured velocity in m s^{-1} and S is the duct section, 0.302 m^2 .

2.2. Statistical Methods

A comprehensive descriptive analysis of the environmental variables measured in the animal zone was conducted for the entire dataset, for each cycle and for the critical, postcritical and final periods. To determine whether to use a parametric or a non-parametric test, the Kolmogorov–Smirnov test was used for testing normality. The analysis of the data for each cycle revealed a non-normal distribution of the study variables. Yet, these statistics are too sensitive to small deviations from normality when large samples are used [32]. Random samples of 300 observations were collected for each variable and cycle such that normality tests could be used without loss of reliability. Thus, all the variables were normal either directly (temperature during cycle I, relative humidity during cycles I and VII, and CO_2 concentration during cycle I), or using the Johnson's System of Distributions. Accordingly, a parametric analysis was performed.

As the data did not satisfy the assumption of homoscedasticity according to the Levene's test, ANOVA could not be used. The Brown–Forsythe [33] and Welch [34] statistics, used by the authors of [35], provide a robust alternative to the ANOVA F statistic when the assumption of homoscedasticity is not satisfied. The Games–Howell post-hoc test is appropriate when the assumption of homogeneity of variances is not satisfied [32,36]. Therefore, the Brown–Forsythe, Welch and Games–Howell tests were used to determine how the evolution of climate affected the production cycles and how the periods of each cycle affected the environmental variables in the animal zone. The significance level was 0.05.

The statistical software used was R, version R-3.3.2.

3. Results

The results for the most significant production and environmental variables in the seven analysed cycles are summarized in Figures 2 and 3. The average duration of a cycle was 41 days. The average weight of each piglet was 5.60 kg (Standard Deviation, SD = 0.62) at the beginning of the cycle and 18.03 kg (SD = 1.48) at the end of the cycle, which involved an average daily weight gain of 0.295 kg (SD = 0.03). The average mortality rate was 3.06%. The 10-min values between temperature in the animal zone and outdoor temperature showed an overall value of 0.10. In fully saturated cycles, finding the correlation between outside relative humidity and relative humidity in the animal zone was not appropriate, but during cycles I and VII, the R^2 values were 0.49 and 0.56, respectively.

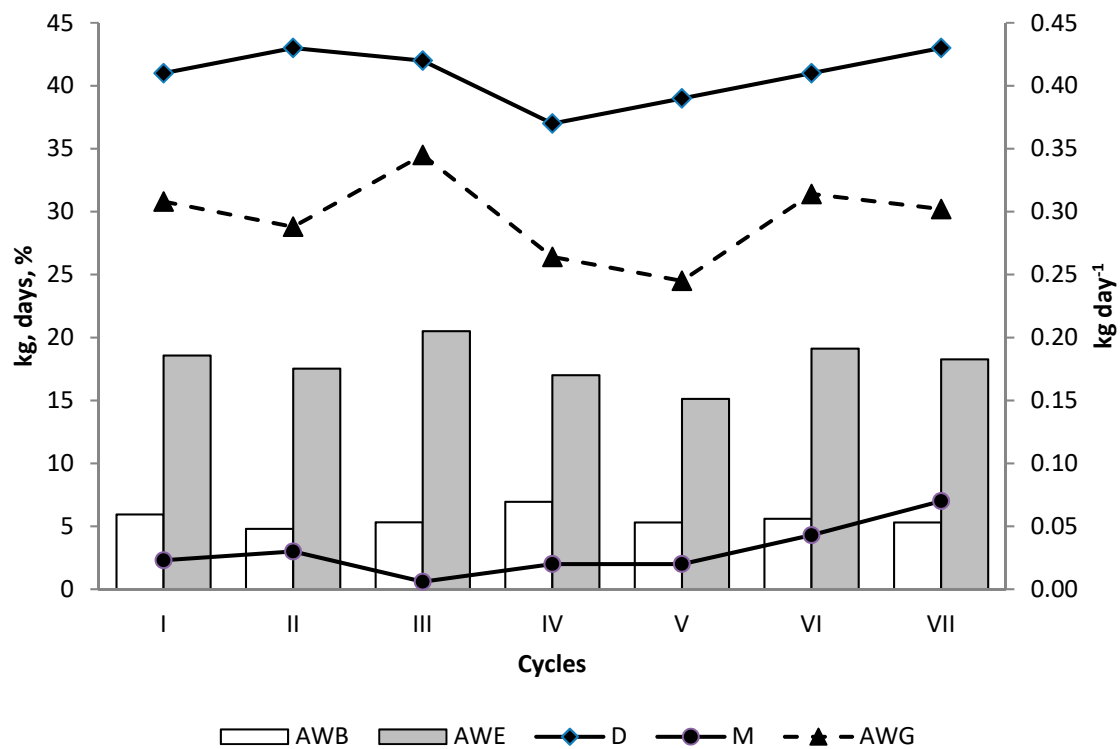


Figure 2. Production variables for each cycle. AWB: Average weight at the beginning of the cycle (kg), AWE: Average weight at the end of the cycle (kg), D: Duration (days), M: Mortality (%), AWG: Daily average weight (kg day⁻¹).

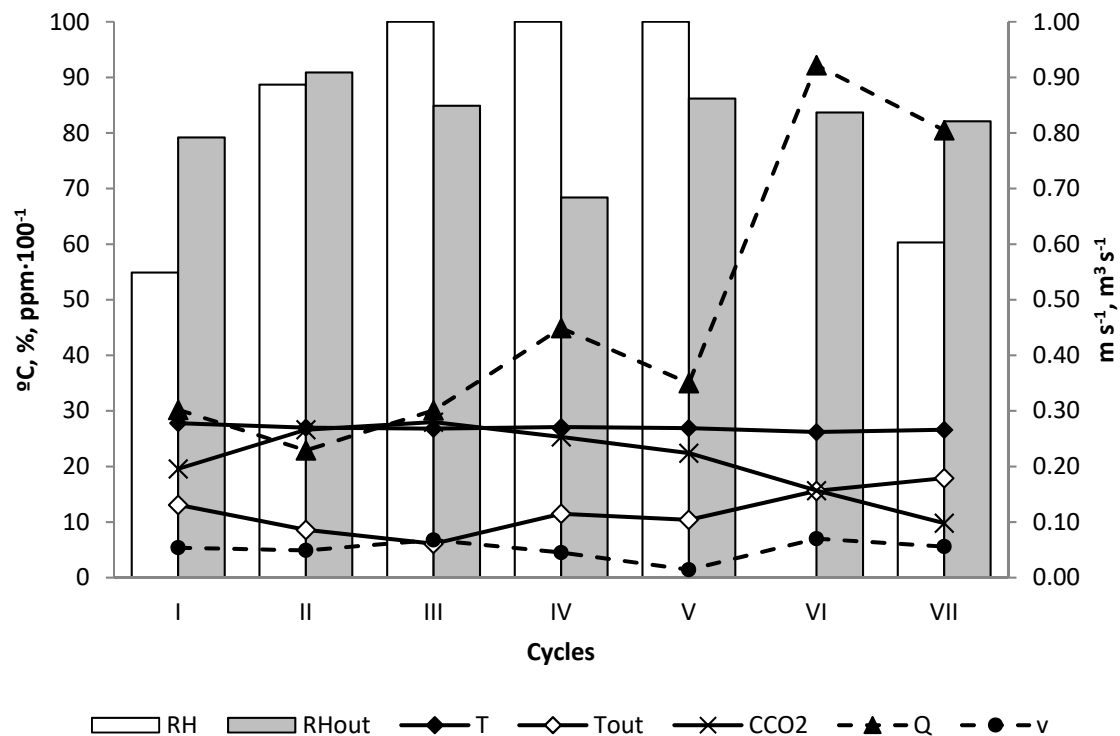


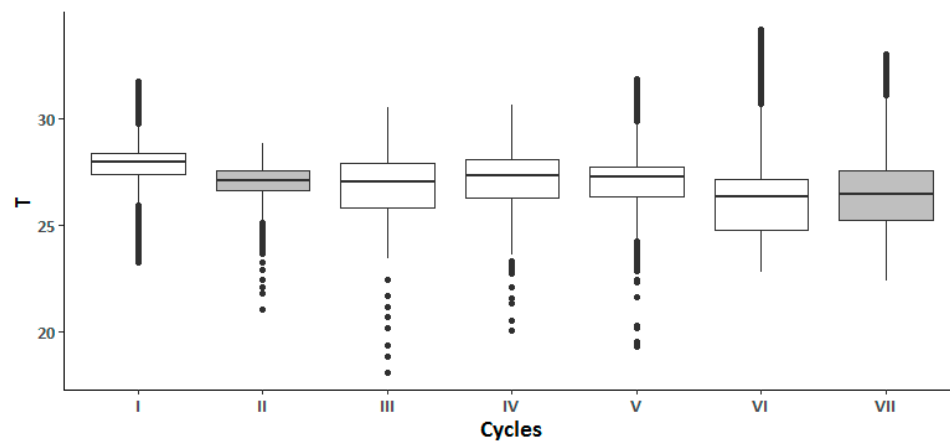
Figure 3. Environmental variables for each cycle. RH: Average relative humidity in the animal zone (%), RH_{out}: Average outdoor relative humidity (%), T: Average temperature in the animal zone (°C), T_{out}: Average outdoor temperature (°C), C_{CO2}: Average CO₂ concentrations in the animal zone (ppm·100⁻¹), Q: Average flow extracted with the fan (m³ s⁻¹), v: Average air velocity in the animal zone (m s⁻¹).

Table 2 shows the mean values of the environmental variables for each cycle and period. The Brown–Forsythe, Welch and Games-Howell tests were applied to temperature, relative humidity and CO₂ concentration in the animal zone. Temperature showed slight variations between cycles (Figure 4a) and marked differences among periods (Figure 4b). Significant differences were found for average relative humidity in every cycle and among periods during non-saturated cycles (RH < 100%, I, II and VII). The average CO₂ concentrations per cycle were statistically different for every cycle (Figure 5). The average CO₂ concentrations for the three periods of cycles II–V were different in every case (Table 2). Three equal values of CO₂ concentrations were found in successive periods.

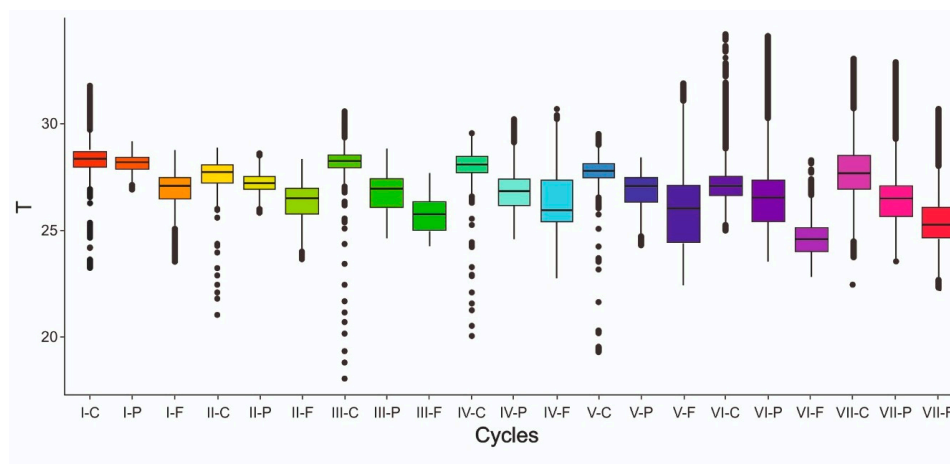
Table 2. Mean and standard deviation (SD) values for environmental variables in the animal zone during the critical, postcritical and final periods.

Cycle	T (°C)			RH (%)			C _{CO2} (ppm)		
	C (SD)	P (SD)	F (SD)	C (SD)	P (SD)	F (SD)	C (SD)	P (SD)	F (SD)
I	28.5 (0.9)	28.1 (0.4)	26.9 (0.8)	51.9 (9.2)	54.2 (4.9)	59.0 (5.0)	1602.9 (340.8)	2137.3 (305.9)	2146.9 (346.8)
II	27.6 (0.6)	27.2 (0.5)	26.3 (0.8)	75.9 (10.8)	89.2 (17.5)	100.0 (0.0)	3021.9 (977.3)	2369.7 (776.3)	2598.4 (931.8)
III	28.1 (0.7)	26.7 (0.8)	25.7 (0.7)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	3323.8 (1100.1)	2477.9 (394.2)	2594.7 (330.9)
IV	28.0 (0.7)	26.8 (0.9)	26.4 (1.5)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	3115.4 (890.4)	2376.9 (504.2)	1865.1 (491.5)
V	27.8 (0.7)	26.8 (0.8)	26.0 (1.9)	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	3017.2 (1148.4)	1973.5 (296.4)	1587.6 (318.9)
VI	27.2 (1.2)	26.7 (2.0)	24.6 (0.9)				1469.8 (266.2)	1469.6 (253.4)	1775.0 (672.2)
VII	27.8 (1.7)	26.6 (1.6)	25.4 (1.3)	57.5 (6.2)	58.4 (6.2)	64.7 (6.4)	949.4 (300.5)	996.0 (264.6)	995.3 (345.3)

T: Temperature. RH: Relative humidity. C_{CO2}: Carbon dioxide concentrations. C: Critical period, first 14 days. P: Postcritical period, following 14 days. F: Final period. Humidity and CO₂ averages were all different and highly significant ($p < 0.01$), both per cycle and per period. For temperature, differences were found for cycles II and VII, and for every period.



(a)



(b)

Figure 4. Average temperatures in the animal zone (T) for (a) each cycle and (b) each of the critical (C), postcritical (P) and final (F) periods. The same colour suggests equal averages.

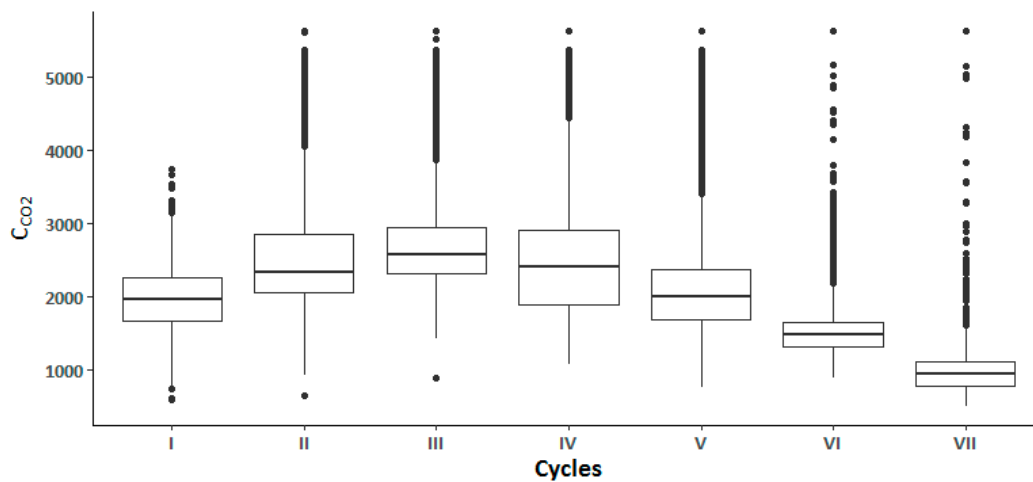


Figure 5. Average CO₂ concentrations in the animal zone (C_{CO2}) for each cycle.

The highest heating energy requirements were found in cycles III, IV and V (Figure 6), whereas the highest ventilation energy requirements were found in cycles I, VI and VII. The incorporation of the production component to energy performance analysis (Figure 7) revealed that cycles I and VI showed the minimum energy requirements per piglet weight gain, whereas cycles IV and V showed the maximum energy requirements.

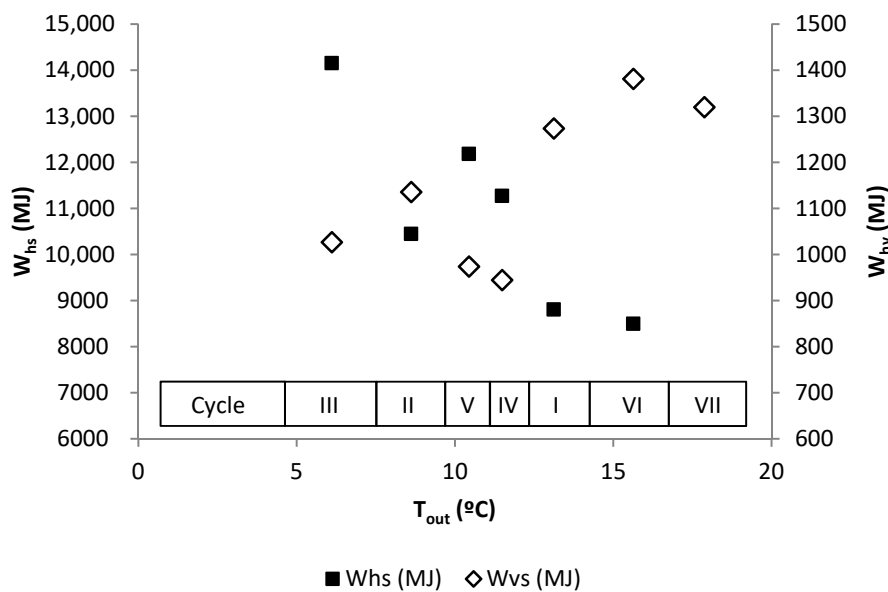


Figure 6. Energy requirements for heating (W_{hs}) and ventilation (W_{vs}) systems according to outdoor temperature (T_{out}) for each cycle.

Table 3 shows the Pearson coefficients (R^2) between environmental and energy variables, with outstanding values of 0.91 between T_{out} and C_{CO2} , and RH and W_{vs} .

Table 3. Pearson coefficient (R^2) between environmental and energy variables.

	T_{out}	RH	C_{CO2}	W_{vs}	W_{hs}
T_{out}	1.00	0.55	0.91	0.54	0.75
RH		1.00	0.59	0.91	0.66
C_{CO2}			1.00	0.61	0.63
W_{vs}				1.00	0.66
W_{hs}					1.00

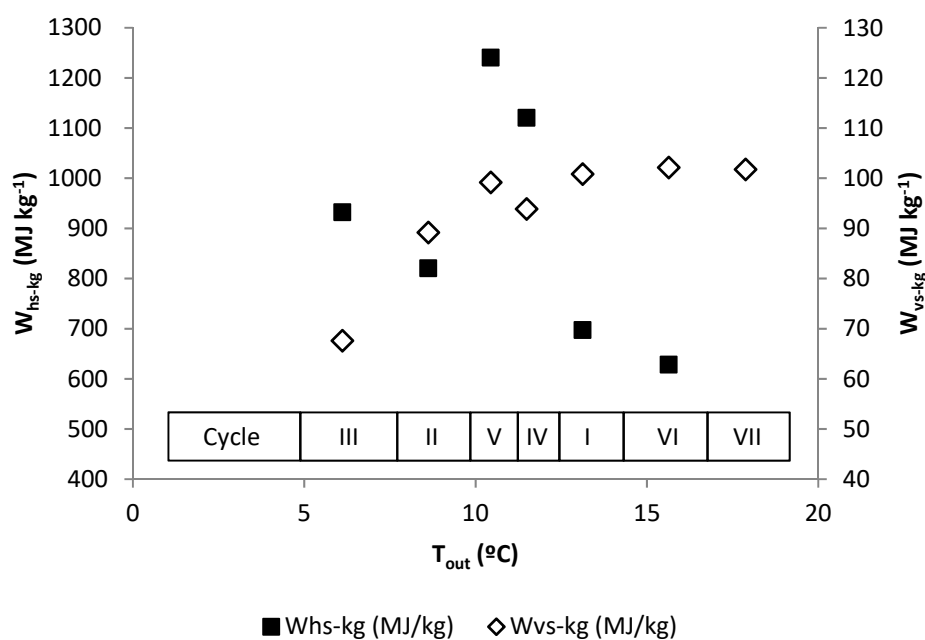


Figure 7. Energy requirements per piglet weight gain for heating (W_{hs-kg}) and ventilation (W_{vs-kg}) systems according to outdoor temperature (T_{out}) for each cycle.

4. Discussion

The best results for production variables were obtained during cycle III, with the lowest indoor and outdoor temperatures (Figures 2 and 3).

The supplemental heat provided by the temperature-based control system contributed to keeping the animal zone at a substantially constant temperature, showing a weak dependence on outside temperature. However, two cycles (II and VII, Figure 4a) were significantly different from the rest of cycles, evidenced in grey. The low correlation coefficients of the 10-min values between temperature in the animal zone and outdoor temperature ($R^2 = 0.10$) contrast with the strong and positive correlation ($R^2 = 0.67$) found in Australian weaner buildings [37] with no supplemental heat.

The decrease in setpoint temperature observed over each cycle caused an effective decrease in temperature in the animal zone (Figure 4b). Also, the statistics revealed differences in temperature for every period, which evidenced the effects of growth period. During the critical period, the average temperature was usually below the recommended 30–32 °C [38] and occasionally below 26 °C [2]. During the postcritical and final periods, the average temperature was above the 24 °C recommendation [8].

Under temperature-based environmental control, relative humidity performed well only during cycles I and VII, with values between 50% and 75% [11] for 79.4% and 91.3% of the time, respectively (Figure 3). Actually, three of the cycles were permanently at saturation (III–V), partly because of the high humidity values found in oceanic climate areas. Similar results were found in Korea for finishing pigs between 85 kg and 110 kg, with an average internal relative humidity of 87.3%, where the ventilation control system did not meet the recommended humidity because the ventilation controller was operated while considering only the air temperature [29].

In non-saturated cycles, average relative humidity increased as the cycle progressed. During cycles I and VII, which showed significant differences, the R^2 values between outside relative humidity and relative humidity in the animal zone were 0.49 and 0.56, respectively, which is in agreement with other reported values [37]. Relative humidity behaved differently from temperature, with very low correlations between indoor and outdoor values, which suggests that it is easier to control air temperature than relative humidity levels [23]. The lowest and highest average daily weight gains

were obtained during the saturated cycles (Figure 3), which suggests a poor influence of humidity on the piglets maintained within thermoneutrality [10].

The average CO₂ concentrations per cycle followed a sinusoidal evolution along the year (Figure 5) and showed a strong negative linear correlation with outdoor temperature ($R^2 = 0.91$, Table 3). The highest values corresponded to cold seasons, which was related to the restricted operation of the ventilation system. These results are in agreement with the results reported by other authors [27,39].

The mean CO₂ concentrations in the animal zone were below the recommended 3000 ppm [22] and cycle VII was the only cycle that did not exceed 1540 ppm [21], which is in agreement with the values found in swine gestation confined animals [19]. In cycles at or near saturation (II–V)—with low ventilation flows—CO₂ concentrations (Figure 3) were directly proportional to the final weight of the animals (Figure 2). In contrast, in cycles I and VII—when CO₂ was effectively extracted—CO₂ concentrations tended to increase as the cycle progressed. According to these results, CO₂ concentrations are related to relative humidity, ventilation system and animal weight and age.

As shown in Figure 6, a 9.52-°C increase in outdoor temperature reduced heating energy consumption by 39.96%. These results are in agreement with modelled results for swine farrowing facilities, where total operational costs increased about 4% when the mean outdoor temperature decreased by 1 °C [40]. Similarly, a 30% reduction in heating fuel use was observed with a reduction of 6 °C in the room temperature setting at night [41]. The highest heating energy consumptions corresponded to cycles at saturation (III, IV and V) because heating the air with high humidity levels requires more energy. Particularly, during cycle V—with an average outdoor temperature of 10.4 °C—the heating system energy requirements were 17% higher than during cycle II, with an average outdoor temperature of 8.6 °C.

Therefore, restrictions in the ventilation system can lead to an increase in heating energy consumption. Accordingly, incorporating humidity as a control variable could contribute to improving the environmental controls in these buildings [26] by reducing the high humidity levels that result in condensation and are detrimental to heating efficiency [14,23].

The daily average values measured for ventilation energy consumption and heating energy consumption showed a negative linear correlation, with $R^2 = 0.66$ (Table 3). The restrictions in the ventilation system were justified by the low outdoor temperatures measured during cycle III, but not during cycle V or VI, during which such restrictions caused air saturation and an increase in heating energy costs. The energy savings caused by the decrease in ventilation rates (20% for cycles II and IV) did not compensate for the heating energy requirements, insofar as heating requirements were, on average, 10-times higher. In finishing pigs, a simulated ventilation energy saving of 43% was obtained by incorporating an energy balance equation model to the control system [30].

Outdoor temperature values per cycle showed a negative correlation with heating energy consumption ($R^2 = 0.75$), but a strong positive correlation with ventilation energy consumption ($R^2 = 0.54$, Table 3). The increase in ventilation energy consumption involved a decrease in relative humidity and CO₂ concentrations ($R^2 = 0.91$ and $R^2 = 0.61$, respectively, Table 3). Likewise, linear correlations were found between heating energy consumption and relative humidity and CO₂ concentrations (R^2 of 0.66 and 0.63, respectively, Table 3).

An increase in outdoor temperature (cycles I and VI) involved a decrease in energy requirements per piglet weight gain. However, the highest energy requirements were not observed during the coldest cycles but during cycles IV and V, certainly because of air saturation (Figure 7). Therefore, relative humidity showed the most important variable in energy consumption, well ahead of temperature, which resulted from neglecting relative humidity in the operation of the ventilation system. Cycles IV and V required between 33% and 47% more energy per kg of pig produced than cycle II, with a lower outdoor temperature (8.6 °C as compared to 11.5 °C and 10.4 °C, respectively).

The results of the Brown–Forsythe and Welch, and Games–Howell tests suggest that, generally, temperature, relative humidity and CO₂ concentrations inside the building showed significant differences both among cycles and among the critical, postcritical and final periods that result from

the changes in the environmental and growth conditions. CO₂ concentrations showed more marked seasonal variations, with annual sinusoidal seasonality, conversely to variations in outdoor temperature.

At similar outdoor temperatures, the comparison of saturated and non-saturated cycles revealed that improved humidity management led to a saving of 17% in climate control energy during one cycle, which involved savings between 33% and 47% in energy consumption per kg of pig produced. Recent research points to the incorporation of advanced estimation techniques into complex control systems to achieve energy savings [24,29,30,42,43], or to the use of a large number of sensors in advanced technologies in order to consider animal welfare [44]. Yet, farms currently use control systems based on a single temperature probe. Incorporating humidity as a control variable would involve higher ventilation rates, with positive consequences for animal welfare, a reduction in heating energy consumption and an improvement in productivity in terms of weight gain per unit of climate control energy used.

The high R² values per cycle obtained for the relationships between heating system energy and outdoor temperature (0.75), between ventilation system energy and relative humidity (0.91) and between outdoor temperature and CO₂ concentration (0.91) suggest that these variables could be readily estimated by the control system without additional sensor costs.

Author Contributions: Conception and design of experiments: M.D.F., E.L. and M.R.R. Performance of experiments: M.D.F., J.A.O., R.B. and M.R.R. Data analysis: J.A.O., T.A., S.L. and M.B. Contribution of analysis tools: E.L., M.J.G.-V. Writing of the manuscript: M.R.R., M.D.F. and T.A. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors have declared that no competing interests exist.

References

1. Massari, J.M.; Moura, D.J.D.; Curi, T.M.D.C.; Vercellino, R.D.A.; Medeiros, B.B. Zoning of environmental conditions inside a wean-to-finish pig facility. *Eng. Agríc.* **2016**, *36*, 739–748. [[CrossRef](#)]
2. Le Dividich, J.; Herpin, P. Effects of climatic conditions on the performance, metabolism and health-status of weaned piglets: A review. *Livest. Prod. Sci.* **1994**, *38*, 79–90. [[CrossRef](#)]
3. Gilbert, H.; Ruesche, J.; Muller, N.; Billon, Y.; Begos, V.; Montagne, L. Responses to weaning in two pig lines divergently selected for residual feed intake depending on diet. *J. Anim. Sci.* **2019**, *97*, 43–54. [[CrossRef](#)] [[PubMed](#)]
4. Lu, X.; Zhang, M.; Zhao, L.; Ge, K.; Wang, Z.; Jun, L.; Ren, F. Growth performance and post-weaning diarrhea in piglets fed a diet supplemented with probiotic complexes. *J. Microbiol. Biotechnol.* **2018**, *28*, 1791–1799. [[CrossRef](#)] [[PubMed](#)]
5. Saha, C.K.; Zhang, G.; Kai, P.; Bjerg, B. Effects of a partial pit ventilation system on indoor air quality and ammonia emission from a fattening pig room. *Biosyst. Eng.* **2010**, *105*, 279–287. [[CrossRef](#)]
6. Pedersen, S.; Jørgensen, H.; Theil, P.K. Influence of diurnal variation in animal activity and digestion on animal heat production. *Agric. Eng. Int. CIGR J.* **2015**, 18–29, Special issue: 18th World Congress of CIGR.
7. Dolz, N.; Babot, D.; Álvarez-Rodríguez, J.; Forcada, F. Improving the environment for weaned piglets using polypropylene fabrics above the animals in cold periods. *Int. J. Biometeorol.* **2015**, *59*, 1839–1847. [[CrossRef](#)]
8. Close, W.H.; Stanier, M.W. Effects of plane of nutrition and environmental temperature on the growth and development of the early-weaned piglet. 2. Energy metabolism. *Anim. Prod.* **1984**, *38*, 221–231. [[CrossRef](#)]
9. Huynh, T.T.T.; Aarnink, A.J.A.; Gerrits, W.J.J.; Heetkamp, M.J.H.; Canh, T.T.; Spoolder, H.A.M.; Kemp, B.; Verstegen, M.W.A. Thermal behaviour of growing pigs in response to high temperature and humidity. *Appl. Anim. Behav. Sci.* **2005**, *91*, 1–16. [[CrossRef](#)]
10. Guo, H.; Lemay, S.P.; Barber, E.M.; Crowe, T.G.; Chénard, L. Humidity control for swine buildings in cold climate. Part II: Development and evaluation of a humidity controller. *Can. Biosyst. Eng.* **2001**, *43*, 37–46.
11. Forcada, F.; Babot, D.; Vidal, A.; Buxadé, C. *Ganado Porcino. Diseño de Alojamientos e Instalaciones*, 1st ed.; Servet: Zaragoza, Spain, 2009; pp. 38–70.

12. Kumari, P.; Woo, C.; Yamamoto, N.; Choi, H.L. Variations in abundance, diversity and community composition of airborne fungi in swine houses across seasons. *Sci. Rep.* **2016**, *6*, 37929. [[CrossRef](#)] [[PubMed](#)]
13. Tang, Q.; Huang, K.; Liu, J.; Shen, D.; Dai, P.; Li, Y.; Li, C. Seasonal variations of microbial assemblage in fine particulate matter from a nursery pig house. *Sci. Total Environ.* **2020**, *708*, 134921. [[CrossRef](#)] [[PubMed](#)]
14. Schaubberger, G.; Piringer, M.; Petz, E. Steady-state balance model to calculate the indoor climate of livestock buildings, demonstrated for finishing pigs. *Int. J. Biometeorol.* **2000**, *43*, 154–162. [[CrossRef](#)] [[PubMed](#)]
15. Kim, K.Y.; Ko, H.J.; Lee, K.J.; Park, J.B.; Kim, C.N. Temporal and spatial distributions of aerial contaminants in an enclosed pig building in winter. *Environ. Res.* **2005**, *99*, 150–157. [[CrossRef](#)]
16. Ni, J.Q.; Heber, A.J.; Darr, M.J.; Lim, T.T.; Diehl, C.A.; Bogan, B.W. Air quality monitoring and on-site computer system for livestock and poultry environment studies. *Trans. ASABE* **2009**, *52*, 937–947.
17. Philippe, F.X.; Nicks, B. Review on greenhouse gas emissions from pig houses: Production of carbon dioxide, methane and nitrous oxide by animals and manure. *Agric. Ecosyst. Environ.* **2015**, *199*, 10–25. [[CrossRef](#)]
18. Chen, C.; Liu, X. An intelligent monitoring system for a pig breeding environment based on a wireless sensor network. *Int. J. Sens. Netw.* **2019**, *29*, 275–283. [[CrossRef](#)]
19. Peters, T.M.; Anthony, T.R.; Taylor, C.; Altmaier, R.; Anderson, K.; O’shaughnessy, P.T. Distribution of particle and gas concentrations in swine gestation confined animal feeding operations. *Ann. Occup. Hyg.* **2012**, *56*, 1080–1090.
20. Besteiro, R.; Arango, T.; Ortega, J.A.; Rodríguez, M.R.; Fernández, M.D.; Velo, R. Prediction of carbon dioxide concentration in weaned piglet buildings by wavelet neural network models. *Comput. Electron. Agric.* **2017**, *143*, 201–207. [[CrossRef](#)]
21. Donham, K.J. Association of environmental air contaminants with disease and productivity in swine. *Am. J. Vet. Res.* **1991**, *52*, 1723–1730.
22. Lee, C.; Giles, L.R.; Bryden, W.L.; Downing, J.L.; Owens, P.C.; Kirby, A.C.; Wynn, P.C. Performance and endocrine responses of group-housed weaner pigs exposed to the air quality of a commercial environment. *Livest. Prod. Sci.* **2005**, *93*, 255–262. [[CrossRef](#)]
23. Van Wagenberg, A.V.; Metz, J.H.M.; den Hartog, L.A. Methods for evaluation of the thermal environment in the animal-occupied zone for weaned piglets. *Trans. ASAE* **2005**, *48*, 2323–2332. [[CrossRef](#)]
24. Detsch, D.T.; Conti, D.; Diniz-Ehrhardt, M.A.; Martínez, J.M. On the controlling of temperature: A proposal for a real-time controller in broiler houses. *Sci. Agric.* **2018**, *75*, 445–451. [[CrossRef](#)]
25. Fournel, S.; Rousseau, A.N.; Laberge, B. Rethinking environment control strategy of confined animal housing systems through precision livestock farming. *Biosyst. Eng.* **2017**, *155*, 96–123. [[CrossRef](#)]
26. Lorencena, M.C.; Southier, L.F.P.; Casanova, D.; Ribeiro, R.; Teixeira, M. A framework for modelling, control and supervision of poultry farming. *Int. J. Prod. Res.* **2020**, *58*, 3164–3179. [[CrossRef](#)]
27. Banhazi, T.M.; Stott, P.; Rutley, D.; Blanes-Vidal, V.; Pitchford, W. Air exchanges and indoor carbon dioxide concentration in Australian pig buildings: Effect of housing and management factors. *Biosyst. Eng.* **2011**, *110*, 272–279. [[CrossRef](#)]
28. Zhang, G.; Bjerg, B.; Strom, J.S.; Morsing, S.; Kai, P.; Tong, G.; Ravn, P. Emission effects of three different ventilation control strategies—A scale model study. *Biosyst. Eng.* **2008**, *100*, 96–104. [[CrossRef](#)]
29. Yeo, U.H.; Lee, I.B.; Kim, R.W.; Lee, S.Y.; Kim, J.G. Computational fluid dynamics evaluation of pig house ventilation systems for improving the internal rearing environment. *Biosyst. Eng.* **2019**, *186*, 259–278. [[CrossRef](#)]
30. Xie, Q.; Ni, J.Q.; Bao, J.; Su, Z. A thermal environmental model for indoor air temperature prediction and energy consumption in pig building. *Build. Environ.* **2019**, *161*, 106238. [[CrossRef](#)]
31. Hinz, T.; Linke, S.A. Comprehensive experimental study of aerial pollutants in and emissions from livestock buildings. Part 1: Methods. *J. Agric. Eng. Res.* **1998**, *70*, 111–118. [[CrossRef](#)]
32. Pardo-Merino, A.; Ruiz, M.A. *Análisis de Datos con SPSS 13 Base*; Mc Graw-Hill: Madrid, Spain, 2005; pp. 272–367.
33. Brown, M.B.; Forsythe, A.B. Robust tests for the equality of variances. *J. Am. Stat. Assoc.* **1974**, *69*, 364–367. [[CrossRef](#)]
34. Welch, B.L. The generalization of Student’s problem when several different population variances are involved. *Biometrika* **1947**, *34*, 28–35. [[CrossRef](#)] [[PubMed](#)]

35. Di Pasquale, J.; Nannoni, E.; Sardi, L.; Rubini, G.; Salvatore, R.; Bartoli, L.; Adinolfi, F.; Martelli, G. Towards the Abandonment of Surgical Castration in Pigs: How is Immunocastration Perceived by Italian Consumers? *Animals* **2019**, *9*, 198. [[CrossRef](#)] [[PubMed](#)]
36. Li, N.; Zhu, C.; Liu, C.; Zhang, X.; Ding, J.; Zandi, P.; Li, H. The persistence of antimicrobial resistance and related environmental factors in abandoned and working swine feedlots. *Environ. Pollut.* **2019**, *255*, 113116. [[CrossRef](#)]
37. Banhazi, T.M.; Seedorf, J.; Rutley, D.L.; Pitchford, W.S. Identification of risk factors for sub-optimal housing conditions in Australian piggeries: Part 3. Environmental parameters. *J. Agric. Saf. Health* **2008**, *14*, 41–52. [[CrossRef](#)]
38. Muirhead, M.R.; Alexander, T.J.L. *Managing Pig Health and the Treatment of Disease: A Reference for the Farm*; Chapter 3; 5M Enterprises Ltd.: Sheffield, UK, 1997.
39. Park, J.H.; Peters, T.M.; Altmaier, R.; Sawvel, R.A.; Anthony, T.R. Simulation of air quality and cost to ventilate swine farrowing facilities in winter. *Comput. Electron. Agric.* **2013**, *98*, 136–145. [[CrossRef](#)] [[PubMed](#)]
40. Alberdi, O.; Arriaga, H.; Calvet, S.; Estellés, F.; Merino, P. Ammonia and greenhouse gas emissions from an enriched cage laying hen facility. *Biosyst. Eng.* **2016**, *144*, 1–12. [[CrossRef](#)]
41. Johnston, L.J.; Brumm, M.C.; Moeller, S.J.; Pohl, S.; Shannon, M.C.; Thaler, R.C. Effects of reduced nocturnal temperature on pig performance and energy consumption in swine nursery rooms. *J. Anim. Sci.* **2013**, *91*, 3429–3435. [[CrossRef](#)]
42. Besteiro, R.; Ortega, J.A.; Arango, T.; Rodriguez, M.R.; Fernandez, M.D. ARIMA modelling of animal-zone temperature in weaned piglet buildings: Design of the model. *Trans. ASABE* **2017**, *60*, 1–9. [[CrossRef](#)]
43. Ortega, J.A.; Losada, E.; Besteiro, R.; Arango, T.; Ginzo-Villamayor, M.J.; Velo, R.; Fernandez, M.D.; Rodríguez, M.R. Validation of an AutoRegressive Integrated Moving Average model for the prediction of animal zone temperature in a weaned piglet building. *Biosyst. Eng.* **2018**, *174*, 231–238. [[CrossRef](#)]
44. Chen, C.S.; Chen, W.C. Research and development of automatic monitoring system for livestock farms. *Appl. Sci.* **2019**, *9*, 1132. [[CrossRef](#)]



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