JOURNAL OF ANIMAL BEHAVIOUR AND BIOMETEOROLOGY

RESEARCH ARTICLE
Published Online: May 08, 2021
https://doi.org/10.31893/jabb.21031

Assessment of spatial variability of environmental conditions in different swine production typologies in tropical conditions

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Abstract Comfort index and environmental variables are indicators of thermal stress conditions inside a livestock facility. The environmental conditions of ten different constructive typologies of swine-production facilities with natural ventilation were characterized in a tropical country (Antioquia, Colombia). Temperature and humidity index (*THI*), enthalpy (*H*), animal surface temperature (*ST*), light intensity, and noise level were measured and computed for each typology, which were located at heights above sea levels between 8:00-23:00. Data was analyzed as a function of each typology, geographical altitude, and time of the day. It was employed descriptive statistics, analysis of variance, and contour maps to analyze the data. It was found that more than 80% of the typologies presented moderate or critical stress conditions associated with the construction typology, not suitable *THI* and light intensity values, especially in warm and mild-mild climates. Showing high special variability inside the facilities. New typological designs and bioclimatic conditioning for swine facilities need to be studied To be implemented in these climatic conditions.

Keywords animal welfare, comfort index, pig production, thermal stress

1. Introduction

In swine production, correctly planning a shelter's design and construction can guarantee the animals space according to their vital requirements, welfare and ensure efficient meat production. (Kiefer et al 2010; Machado et al 2016; Cecchin et al 2018; Cecchin et al 2019). Pigs are considered homoeothermic animals; this means that they withstand specific body temperature conditions, when that value exceeds the limit, the animal begins to have behavior and health problems (Barreto et al 2010; Barbari & Conti 2009).

The thermal environment directly influences the heat exchange between the pig and its surrounding environment. The main variables that positively or negatively affect the environment are temperature, air velocity, illumination, gases concentration, and relative humidity (Carvalho et al 2014; Machado et al 2016). For animal species, there is a thermal environment where maximum productivity occurs, characterized by these variables, that desirable condition is called the "thermal comfort-zone of the animal" (dos Santos et al 2018).

There is a predetermined thermal comfort-zone range suggested by several authors, if these conditions are suitable, it could guarantee that the production is efficient and that the normal physiological conditions of the animal are not altered (Barreto et al 2010 and Carvalho et al 2014). This comfort zone depends on filo, age, weight, sex, quantity, and feed quality, mainly. A pig under thermal stress can trigger physiological adjustments so that its body temperature remains constant (Ramos et al 2017; Roller and Goldmn 1969). These adjustments have implications for reducing food consumption and decreasing productivity (Vieira et al 2010).

Recently, other variables have been studied to complement those related to the thermal environment, such as sound pressure, light intensity and gas emissions, researches that have been carried out in different animal facilities (Schiassi et al 2012; Ferraz et al 2020; Castrillon et al 2020).

In tropical regions, the climate is the main determining factor that limits animals' maximum performance due to the stress that high temperatures can trigger (Toniolli et al 2014; Machado et al 2016). This is why housing plays a fundamental role; therefore, it is necessary to have a design that complies with the basic principles of bioclimatic architecture and considers a set of environmental variables that guarantee an appropriate space for the animal that does not depend on mechanical systems.

To characterize and identify the suitable thermal comfort zones for the swine species, thermal comfort indices are developed. It should be noted that, these conditions have also been studied in other species such as birds and cattle.

 Received: March 23, 2021 | Accepted: April 22, 2021

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The comfort index is represented by a dimensionless value, that characterize the animal's surrounding thermal environment, while providing information about the environment and the stress it is may be generating.

The construction typology in a pig farm can condition its thermal environment, as several studies have shown (Machado et al 2016; Cecchin et al 2017). The type of floor, the sewer conduction system, the lateral structure, and the ventilation on the roof (like others), can condition the thermal environment, which can be assessed through some indexes.

In Colombia, the subject has been little explored. There is no standard typological classification that allows knowing which typology is the most suitable for each specific animal production condition (Castrillon et al 2020). That is why this work aimed to evaluate the thermal environment distribution of pig farms with different construction typologies with natural ventilation, located in the state of Antioquia - Colombia, a region that concentrates around 40% of pig production nationwide (ICA 2019).

2. Materials and Methods

2.1. Location and characterization of the study area

The study area was located in the department of Antioquia in Colombia. This territory concentrates the largest production of pigs nationwide (Vélez et al 2018; ICA 2019). Ten fattening pig commercial farms were randomly selected. Facilities were located from 800 to 2300 meters above the sea level (MASL), which were classified in three thermal floors (Warm 0-1000 MASL; Mild 1001-2000 MASL; Cold 2001-3000 MASL) based on the weather model of Caldas lang and according to ICA 002640 of 2007 (Colombian regulations resolution). They are considered technician farms or that their production includes a set of guidelines such that quality production is guaranteed. The data associated with the farms, such as typology, date of visit, municipality, orientation, type of ventilation, construction materials, and height above sea level, are detailed in Table 1.

Table 1 Description of the different constructive typologies.

Typology	Orientation	MASL	Thermal floor	Roof Features	Ventilation ratio Area/Total Area
I	W-E	2174	Cold	Open Ridge ventilation and Clay Tiles.	0.14
II	N-S	1179	Mild	Without Open ridge Ventilation and Eternit Tiles.	0.44
III	N-S	1481	Mild	Open Ridge ventilation and Eternit Tiles.	0.39
IV	W-E	2202	Cold	Without Open Ridge and Concrete roof	0.16
V	N-S	1504	Mild	Without Open Ridge and Concrete roof	0.12
VI	N-S	816	Warm	Open Ridge Ventilation and Zinc Tiles	0.39
VII	N-S	1732	Mild	Open Ridge Ventilation and Zinc Tiles	0.33
VIII	W-E	2263	Cold	Open Ridge Ventilation and Eternit Tiles	0.13
IX	N-S	1408	Mild	Open Ridge Ventilation and Eternit Tiles	0.36
X	N-S	1000	warm	Open Ridge Ventilation and Zinc Tiles	0.28

2.2. Characteristics of the animals evaluated

The pigs of the farms under study were in the fattening productive stage with an average weight between 60-80 kg, separated male females, and the density of animals per square meter was similar in all facilities. Their primary food was the same commercial concentrate for all the farms evaluated, and they had all the necessary equipment. Feed and water ad libitum through feeders and drinking troughs, where feeders were recharged three times a day. The dry area was differentiated from the wet one, and aeration was regulated through natural ventilation.

2.3. Experimental development

Field visits were made between June and August of 2019, in a dry period with some isolated rainfalls, according to the climatic characteristics proposed by Poveda (2004).

For the data collection, the method of subdivision by points or systematic sampling was used. The area of the shed, with its dimensions (length x width) in meters, was divided into grids (3 - 4 spaces across the width and 5 - 7 spaces throughout in length, depending on the size of the module, where each space had a surface area of 2 meters), and in each one, a measuring point was located, to take representative samples throughout the installation area (Figure 1). In total, 18 points were established for each typology.

The time measurement range was established for 12 hours, from 6:00 am to 6:00 pm, with measurement intervals of three hours during the day at 6:00, 9:00, 12:00, 15:00 and 18:00 hours, with three repetitions. This is to have a sampling throughout the day, when the greatest thermal variability occurs, the most significant peaks of high and low temperatures.

Different typologies were classified by thermal floor, as shown in Table 2, where the most significant number of typologies farms are found in mild climates, according to the reality of Colombian pig farming.

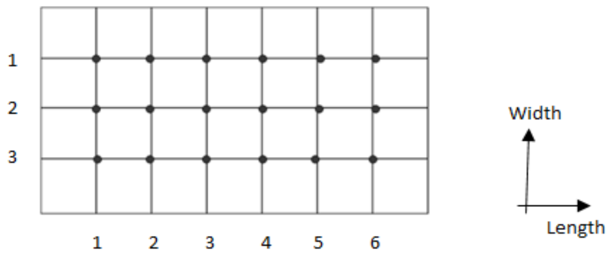


Figure 1 Typical scheme of distribution of sampling points in the facilities.

2.4. Variables and Thermal comfort index for pigs

The dry bulb temperature (T_{db}), relative humidity (*RH*) (HD32.2, Delta OHM), pig surface temperature ear based (ST) that was measurement with the thermal camera (Ti400, Fluke Corporation), light intensity (lx) (DT3809-, CEM), noise (db) (DT-815, CEM), enthalpy (*H* - $kJ.kg^{-1}$) and the Temperature Humidity Index (*THI*) were measurement and calculated in each point during the experiment in the different typologies.

The *THI* was calculated using equation 1, proposed by Thom et al (1958) (Bureau of Meteorology 2005; Zanetoni et al 2019).

$$THI = THI \; = T_{db} \; + \; 0.36 \, T_{dp} \; + \; 41.2 \qquad (1)$$

where T_{db} and T_{dp} – are the dry and wet bulb temperature (°C), respectively.

H was calculated using equation 2, according to Barbosa Filho et al (2009), to characterize the thermal environment inside the facilities.

$$H = 6.7 + 0.243 \, T_{db} + \left(\frac{RH}{100*10^{\frac{7.5 \, T_{db}}{237.3 T_{db}}}} \right) \qquad (2)$$

where *H* – is enthalpy (kcal/kg of dry air), T_{db} - dry bulb temperature (°C), *RH* - relative air humidity (%). These variables and the index allow to evaluate the thermal comfort inside the pig installations and characterize the environment to which the animals are subjected to analyze if these conditions of comfort are favorable or not for their productive performance.

The reference values adopted by various authors to determine the comfort or discomfort condition were used such us: Amaral et al (2020), Zanetoni et al (2019), Damasceno et al (2019), de Oliveira Júnior et al (2018), Zonderland et al (2008). Also, reference values for temperature and relative humidity, recommended to prevent the pig from being in a stress condition in its different physiological stages, are established (Tables 3 and 4).

Table 2 Classification of typologies according to the thermal floor.

Thermal Floor (MASL)	**Tipology**
Warm (0 - 1000)	VI, X
Mild(1000 – 2000)	II, III, V, VII, IX
Cold (2000 – 3000)	I, IV, VIII

2.5. Equipment used

Different equipments were required to measure the variables evaluated. The commercial names and the technical characteristics associated with the instruments are described in Table 5. The equipment was supplied by the Bioclimatic Laboratory of the Universidad Nacional de Colombia - Medellin Campus. Before collecting the information, the equipment was calibrated in the laboratory.

Table 3 Thermal comfort limits for pigs.

Noise (db)	
Comfort	Noise < 70
Discomfort	70 ≤ Noise ≥ 85
Stress	Noise > 85
THI	
Thermal comfort	THI ≤ 74
Alert	75 ≤ THI < 79
Dangerous	79 ≤ THI < 84
Emergency	THI ≥ 84
Light (Lux)	
Comfort	lx ≥40
Discomfort	lx < 40

Table 4 Optimal range to T_{db}, RH and H for fattening pigs.

Ideal T_{db} (°C) max-min	Ideal relative humidity RH (%)	Enthalpy H ($kJ.kg^{-1}$) (Moura 1999)
18 - 12	50 – 70	60.44 – 68.62

2.6. Statistical analysis

The information collected was subjected to an analysis of variance (ANOVA) to evaluate the values of the *THI, H, T_{db}, RH, Light* and *Noise* concentration and their differences in thermal floors relationship, identified for each construction typologies, using the statistical software R. The means were compared using the Tukey's test with a significance level of $P < 0.05$ for all cases.

The variables' spatial variability through the experiment was analyzed by semivariogram fitting and ordinary kriging interpolation (equation 3):

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h]^2 \qquad (3)$$

where N (h) is the number of experimental observation pairs, Z(xi) and Z (xi + h), separated by a distance, h.

The semivariogram was fitted using the restricted maximum likelihood (REML) method. The mathematical model used to fit the semivariogram was the spherical model.

3. Results and Discussion

Table 6 shows the average values for T_{db}, *RH, ST, Light, Noise, H* and *THI* indices for the construction typologies. The same letter in a columm means no significant differences in the variable for the typologies. The relative humidity were found between 57 to 76 % in different thermal floors and was above the optimal values for typologies I and II. The temperature was higher on the warm thermal floors, as is logical. The highest *THI* was found in the warm floor's typologies, followed by the II and IX in mild one. Therefore, was found that almost all the facilities had *THI* and *H* above the comfort limiting conditions according to Table 3, excepting the IV and VIII facilities in cold and III in the mild floor. There are not significant differences with the *ST*; however, the highest values are in the warm and mild floor. It was found that almost all typologies had a good light intensity except typologies I and IV, which have light intensity below 40 lx. The typologies VI and X in warm, thus II in the mild floor, were the facilities with noise levels over 70, resulting in discomfort conditions.

Although no correlation was found between the *THI* and the *ST*, it is observed that the higher *ST* are associated with the typologies with mayor *THI* for the warm and mild floor. The ST range for the warm and mild floor typologies was 34.08±1.58 to 35.77±2.54 °C, which agrees with what was found by Resquejo et al (2018), who carried out *ST* measurements in pigs subjected to alert thermal stress conditions, reporting a *ST* range of 32.82±2.29 to 35.89±1.50 °C. The results lead to infer that *ST* can indicate the thermal discomfort to which the pork is subjected. More extensive research in the matter need to be done to be conclusive.

Table 5 Equipment used.

Equipment		Accuracy and precision
Windsonic Ultrasonic Wind sensor (anemometer)	Wind speed and bi-directional wind direction	Wind Speed Range 0-60m/s Accuracy ±2% @ 12m/s Resolution 0.01m/s (0.02 knots) Response Time 0.25 seconds Threshold 0.01m/s
Thermo-hygrometer	Temperature Humidity Relative (°C, %)	Temperature Range -35-70 °C Accuracy ±2% Resolution 0.1°C Response time 0.25 sec Humidity relative Range 5-100% Accuracy ±2% Resolution 1% Response time 0.25 sec
Lux meter (Lux)	lx	Range 40, 400, 4000, 40000, 400000 Lux Accuracy ±3% Resolution 0.1 Lux Response Time 0.25 seconds
Thermography camera	Body temperature (°C)	Range -20 – 1200 °C Accuracy ± 2 °C or 2 % Detector resolution 320x240 (76,800 pixels) Resolution 0.1°C Response Time 0.25 seconds
Noise level (dB)	Noise (dB)	Range 0-130 dB Accuracy ±2.0 dB Resolution 0.1 dB Response Time 0.25 seconds

Figure 2, shows the distribution of *ST, Light, Noise, H* and *THI* for the different typologies and thermal floors at different hours during the day. The higher T_{db} were found in the typologies X (warm) and VII and IX (mild) between 12:00 and 15:00, coinciding with the highest *ST*. The highest *RH* was found in typology II (mild) and I and IV (Cold), and the lowest in typologies IX (mild) and X (warm). The most stable temperature *ST* during the 12 hours were found in the typologies III and V (Mild) and IV (cold).

The Light was below 40 lx in the typologies V and IX (mild) I and IV (cold) the most part of the day, indicating poor comfort conditions.. The noise levels were below 70db in all typologies except in the V one, in the first hours the day. *THI* in VI and X typologies in warm climate were all-time near to 80, meaning thermal discomfort. In mild climate, the *THI* was near to 80 only between 12:00 to 16:00, while in the other typologies, the *THI* was close to 70 most of the time. The *H* behavior was similar to the *THI* in all typologies; however, only in the typologies III (mild) and IV (cold) all-time, the *H* were lower than 70.

Table 6 Mean and standard deviation of T_{db}, *RH, ST, Light, Noise*, CH_4, *H* and *THI* for different construction typologies and thermal floor.

Thermal Floor (MASL)	Tipology	T_{db} (°C)	RH (%)	ST (°C)	Light (lx)	Noise (db)	H (Kj kg^{-1})	THI
Warm (0 - 1000)	VI	29.76±2.52^{a}	61±8^{cd}	35.37±1.82^{a}	98.2±4.82^{a}	70.26±6.10^{a}	72.98±4.04^{a}	79±2^{a}
	X	30.35±4.22^{a}	57±10^{a}	35.77±2.54^{a}	78.3±3.42^{ab}	66.65±6.44^{ab}	74.48±7.86^{a}	79±4^{a}
Mild (1000 – 2000)	II	26.57±2.35^{ab}	72±3^{ab}	34.08±1.58^{ab}	48.35±1.84^{cd}	66.69±7.38^{ab}	71.6±7.48^{ab}	77±3^{ab}
	III	24.58±1.52^{bc}	70±3^{abc}	34.42±1.19^{ab}	55.2±1.93^{bcd}	60.34±6.92^{b}	63.28±5.10	73±2^{bc}
	V	27.32±2.72^{ab}	61±3^{cd}	34.53±1.47^{ab}	45.3±1.61^{cd}	68.91±6.78^{ab}	68.09±8.82^{abc}	76±3^{ab}
	VII	27.07±4.57^{ab}	62±8^{bcd}	35.07±2.46^{a}	67.31±2.12^{abc}	67.03±6.42^{ab}	68.14±11.12^{abc}	75±6^{ab}
	IX	27.77±4.73^{ab}	62±10^{bcd}	35.37±2.31^{a}	48.3±1.35^{cd}	64.99±7.44^{abc}	68.84±9.60^{abc}	77±5^{ab}
Cold (2000 – 3000)	I	23.92±2.06^{bc}	76±8^{a}	34.13±1.69^{ab}	10.73±1.32^{c}	63.09±6.98^{bcd}	67.16±8.02^{abc}	72±3^{bc}
	IV	21.64±2.31^{c}	68±5^{abc}	33.74±1.22^{c}	25.23±1.75^{b}	65.09±4.72^{abc}	53.80±6.22^{b}	69±3^{c}
	VIII	24.45±2.44^{bc}	63±7^{bcd}	33.83±1.82^{c}	45.4±1.84^{cd}	66.71±7.30^{ab}	60.34±7.16^{bcd}	72 ± 3^{bc}

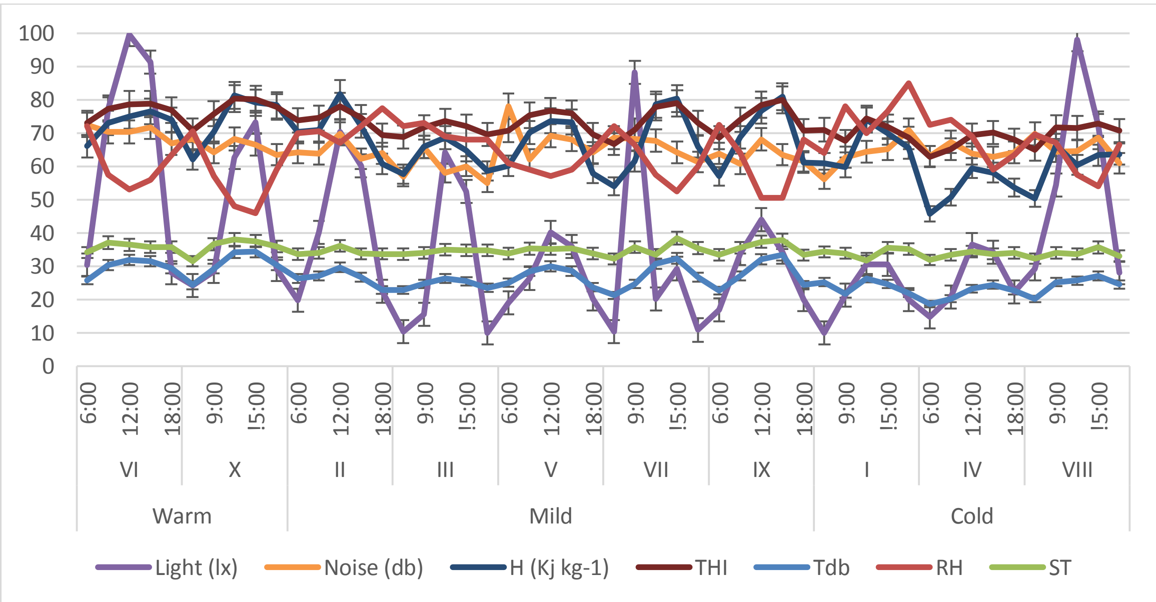


Figure 2 Distribution *Light, Noise, H, THI* and *ST* for different typologies at different hours during the day.

Table 7 shows the spatial distribution of *light*, *Noise*, and *THI* in the different typologies at 15:00 hours (when the typologies reach the highest values). Despite all typologies being refrigerated employing natural ventilation, most of the facilities presented *THI* above 70 in the day's hours with the highest temperatures, except for the typologies I, IV, and VIII that were in cold climates. Other Typologies, II, VI, and VII that were located in warm and mild climate have a good rate between ventilation area and total area, as shown in Table 1, which presents *THI* values over the thermal comfort limits. The I and IV in cold climate were the typologies that have the worse light intensity distribution.

Table 8 shows the overall comfort of each typology, in the function of parameters as Light Intensity, Noise, and *THI*, using a weighing matrix methodology, where the *THI* parameter has 50% of relative value, lx 30%, and Noise 20%, using a classification of zero (0) for discomfort and five (5) for comfort. It was found that the typologies III and VIII in mild and warm climate were the ones that showed the best thermal comfort conditions for pig production. The Typologies I and IV in warm climate have a middle thermal comfort, due to the lack to improve the light intensity conditions in each of them. The other typologies don't have good conditions for thermal comfort, mainly due to *THI* values above the limits.

Table 7 Typical Spatial Distribution (width and length in m) of *light* (lx), *Noise* (db) and *THI* in different typologies.

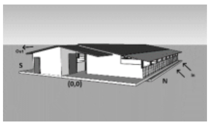
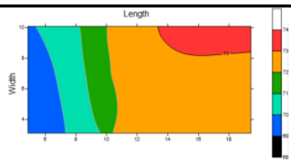
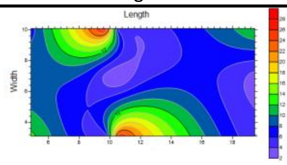
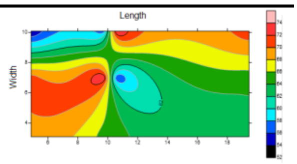
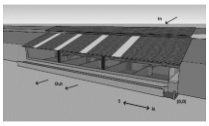
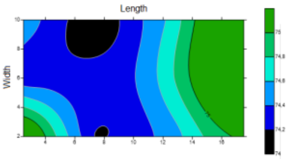
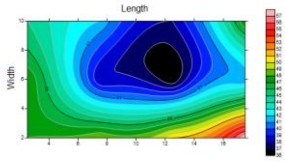
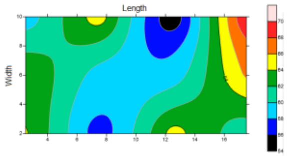
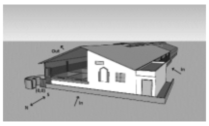
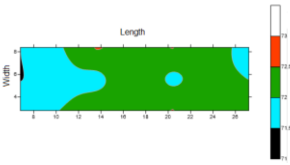
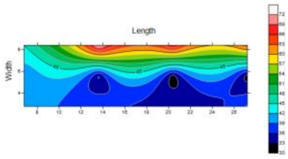
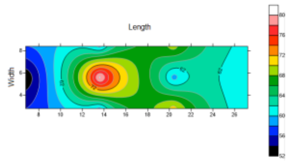
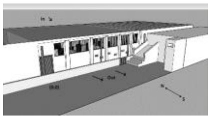
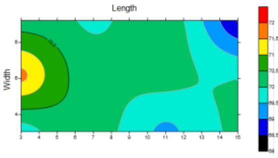
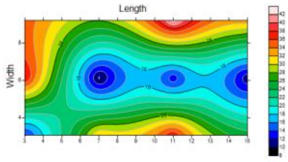
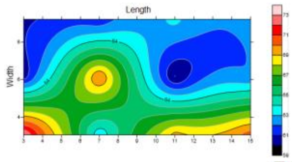
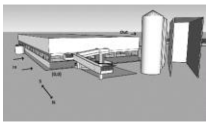
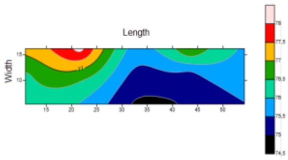
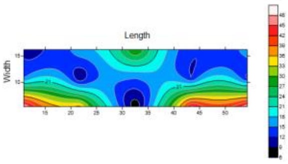
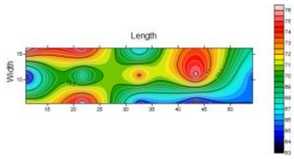
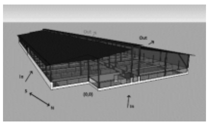
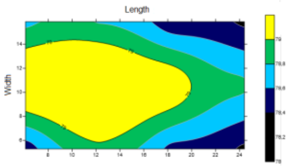
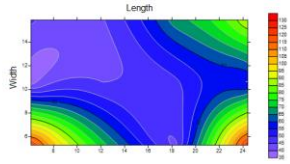
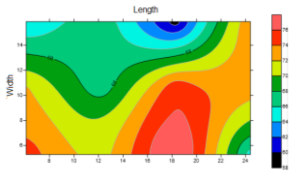
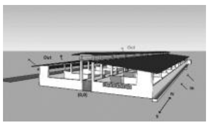
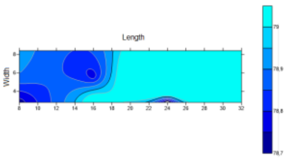
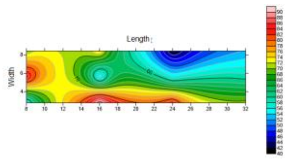
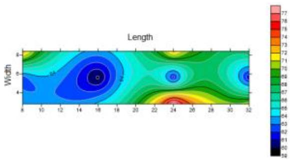
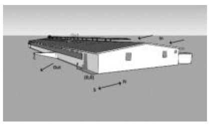
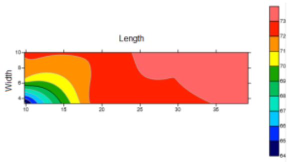
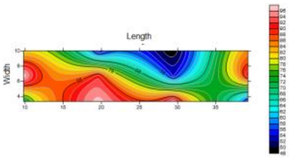
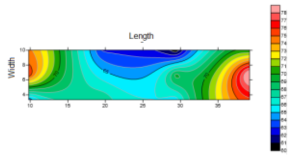
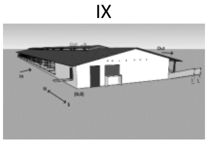
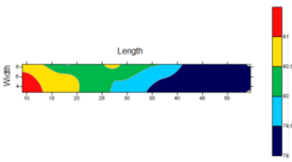
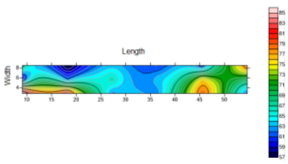
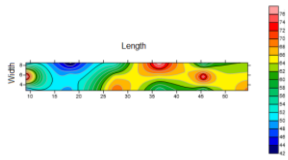
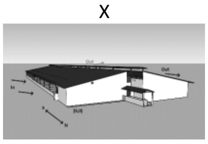
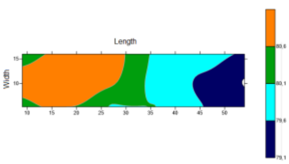
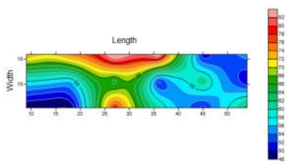
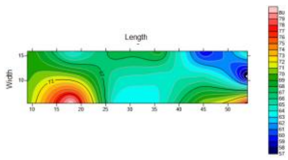
Tipology	THI	Light	Noise
I 			
II 			
III 			
IV 			
V 			
VI 			
VII 			
VIII 			
IX 			
X 			

Table 8 Determination of overall comfort for diferents typologies.

	Typology	Light	Noise	THI	Overall Comfort
Warm	VI	Comfort	Discomfort	Thermal Discomfort	1,5 – Low comfort
	X	Comfort	Comfort	Thermal Discomfort	2,5 - Low comfort
Mild	II	Comfort	Comfort	Thermal Discomfort	2,5 - Low comfort
	III	Comfort	Comfort	Thermal Comfort	5 – High comfort
	V	Comfort	Comfort	Thermal Discomfort	2,5 - Low comfort
	VII	Comfort	Comfort	Thermal Discomfort	2,5 - Low comfort
	IX	Comfort	Comfort	Thermal Discomfort	2,5 - Low comfort
Cold	I	Discomfort	Comfort	Thermal Comfort	3,5 - Middle comfort
	IV	Discomfort	Comfort	Thermal Comfort	3,5 - Middle comfort
	VIII	Comfort	Comfort	Thermal Comfort	5 - High comfort

4. Conclusions

In the state of Antioquia, the construction typologies assessment has shown that almost all typologies have been working on thermal discomfort, mainly because these facilities have *THI* above the allowed values. In these facilities, thermal control employing natural ventilation is not enough to achieve suitable *THI* values. The *THI* distribution, Noice, and light intensity are not homogeneus inside the facilities, having a mix of thermal comfort and discomfort zones. Typologies, especially in cold climates, have a good distribution of *THI* values, however, the light intensity distribution is not suitable for pork production. The results show that most of the current typologies are not suitable for pork production. To achieve a more efficient and friendly production, new typological designs and bioclimatic conditioning need to be studied.

Acknowledgements

Thanks to the Agroindustry Bioclimatic Lab of National University of Colombia – Medellin. To all the Antioquia's producers who participated in the research and allowed the collection of data in their commercial facilities.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This research did not receive any financial support.

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