UNIVERSIDADE FEDERAL DE LAVRAS

LÊNIO MARQUES DE MIRANDA

THERMAL ENVIRONMENT IN COMMERCIAL SWINE NURSERY HEATED WITH BIOGAS HEAT EXCHANGER

LAVRAS - MG
2020

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia Agrícola, área de concentração em Construções Rurais e Ambiência, para a obtenção do título de Doutor.

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Ficha catalográfica elaborada pelo Sistema de Geração de Ficha Catalográfica da Biblioteca Universitária da UFLA, com dados informados pelo(a) próprio(a) autor(a).

Miranda, Lênio Marques de.
Thermal environment in commercial swine nursery heated with biogas heat exchanger / Lênio Marques de Miranda. - 2019.
61 p. : il.

Orientador: Alessandro Torres Campos.
Coorientadores: Tadayuki Yanagi Junior; Allan Alves Fernandes
Tese (Doutorado) - Universidade Federal de Lavras, 2019.
Bibliografia.

1. Swine facilities. 2. Swine rearing in different sites. 3. Biogas heating system. I. Campos, Alessandro Torres. II. Yanagi Junior, Tadayuki. III. Título.

LÊNIO MARQUES DE MIRANDA

THERMAL ENVIRONMENT IN COMMERCIAL SWINE NURSERY HEATED WITH BIOGAS HEAT EXCHANGER

AMBIENTE TÉRMICO EM CRECHE COMERCIAL AQUECIDO COM TROCADOR DE CALOR POR BIOGÁS

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Engenharia Agrícola, área de concentração em Construções Rurais e Ambiência, para a obtenção do título de Doutor.

APROVADA em 16 de agosto de 2019.

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LAVRAS - MG
2020

Aos meus pais, Levi e Maria, pelo apoio imensurável, carinho acolhedor e motivação em todas as etapas de minha formação.
A minha esposa, Juliana, pelo seu carinho e por acreditar que meu sonho era possível.
Aos meus filhos, Júlia e Pedro Henrique, e em especial a Ana Helena que ainda pequenina superou minhas ausências, amores eternos e razões de meu viver.
Dedico

AGRADECIMENTOS

À Universidade Federal de Lavras, especialmente ao programa de pós-graduação em Construções Rurais e Ambiência do Departamento de Engenharia Agrícola, pela oportunidade.

Aos servidores de diferentes setores da Eng. Agrícola e em especial a secretária Helem Cristina, pela sua presteza e profissionalismo.

Ao professor Dr. Alessandro Torres Campos, pela orientação, paciência e disposição para ajudar.

A minha esposa, Juliana Ramires, que não mediu esforços para cuidar de nossa recém nascida, Ana Helena, para que eu pudesse realizar essa capacitação.

A minha mãe, D. Maria José e ao meu pai Sr. Levi Miranda, que ao retornar à cidade de Lavras para meu doutorado, me presentearam com os melhores momentos da minha vida como filho. A vocês meu respeito e amor eterno.

A toda minha família e amigos;

MUITO OBRIGADO!

RESUMO

O estudo de sistemas alternativos de aquecimento para os leitões em fase de creche, notadamente aqueles que demonstram sustentabilidade energética, são imperativos atulamente, viso que, nesta fase, os animais não atingiram autosuficiência para manutenção de sua homeotermia, e, dessa forma, o gasto energético para o aquecimento dos leitões é elevado. Diferentes sistemas de aquecimento estão disponíveis no mercado, entretanto, na literatura há carência de estudos relacionados com uso de trocadores de calor abastecidos com biogás, para os leitões. Nesta pesquisa objetivou-se analisar o ambiente térmico na fase creche de um sistema confinado comercial, em período de inverno e a resposta leitões por meio do ganho de peso. O sistema de troca de calor empregado tem, como fonte de energia, o biogás gerado por biodigestores. Parte do biogás produzido é convertido em energia térmica, conduzida aos galpões, que, por meio de trocadores de calor, aquecem as salas de creche. A sala de creche avaliada no presente trabalho, com área total de 183,14m², possui orientação da cumeeira na direção Leste-Oeste, com oito baias, e densidade média de 0,20m² por leitão. Para análise do conforto térmico, parâmetros que compõem o índice de temperatura do globo negro e umidade (BGHI), foram registrados diariamente a cada quinze minutos, nos 35 dias de permanência na creche. Para avaliar o peso dos leitões F1 (Large White x Landrace), foram monitorados 20 leitões machos, castrados quimicamente, e 20 leitões fêmeas, ambos escolhidos aleatoriamente. Separados os sexos em baias simetricamente opostas, os registros no primeiro dia e a cada 7 dias subsequentes de 5 leitões por baia, perfizeram um total de 240 observações. Observou-se a tendência esperada de ganhos de peso diferentes entre ambos os sexos com média 24,95kg para machos e média de 19,32kg para as fêmeas, favorável 28,87% aos machos. Dos registros de ganhos de peso, obteve-se os maiores valores ($p<0,05$) para os leitões machos, alojados nas baias localizadas na face Sul da sala. Dos valores obtidos de índice ITGU, foram encontrados intervalos de conforto térmico, com média ($p<0,005$) de 67,11 entre 5h e 8h e média de 73,97 entre 14h e 17h, horários com temperaturas ambiente mínimas e máximas do dia respectivamente. Os resultados submetidos à análise de variância, utilizando software estatístico Sisvar e nível de confiança de 95%, confirmaram que o sistema estudado, mesmo no período de inverno, manteve médias de ITGU aceitáveis, em intervalos encontrados na literatura para esta fase. O sistema de aquecimento a biogás se mostrou eficiente para a manutenção do conforto térmico para os leitões confinados, se caracterizando como alternativa intereressante na busca pela sustentabilidade energética na produção de suínos.

Palavras-chave: Instalações para suínos. Criação de suínos em sítios. Sistema de Aquecimento Alternativo. Conforto Térmico. Índices do ambiente térmico. Biodigestor. Biogás.

ABSTRACT

The study of alternative heating systems, notably those that demonstrate energy sustainability, are currently imperative for piglets in the nursery phase, since, at this stage, the animals cannot maintain homeothermy, resulting in a high energy cost. There are different heating systems on the market. However, the literature shows a lack of studies concerning the use of heat exchangers supplied with biogas for piglets. This research aimed to analyze the thermal environment in the nursery phase of a commercial confined system during the winter and the response of piglets through weight gain. Biogas generated by biodigesters is the energy source of the heat exchange system. Part of the biogas produced is converted into thermal energy, which is carried to the warehouses and heat the nursery rooms through heat exchangers. The nursery room evaluated in this study has a total area of 183.14 m^2, a ridge orientation in the East-West direction, eight pens, and an average density of 0.20 m^2 per piglet. The parameters of the black globe humidity index (BGHI) were recorded daily at every fifteen minutes during the 35 days spent in the nursery in order to analyze the thermal comfort. To evaluate the weight of F1 piglets (Large White vs Landrace), 20 chemically castrated male piglets and 20 female piglets, both randomly chosen, were monitored. After separating the sexes in symmetrically opposite pens, the records on the first day and at every seven subsequent days of 5 piglets per pen were recorded, totaling 240 observations. The expected tendency of different weight gains between both sexes presented an average of 24.95 kg for males and 19.32 kg for females, favoring 28.87% for males. The highest values ($p < 0.05$) were found for male piglets housed in pens located on the south side of the room from the weight gain records. The thermal comfort intervals from the values obtained from the BGHI presented a mean value ($p < 0.005$) of 67.11 between 5 am and 8 am and an average of 73.97 between 2 pm and 5 pm, for the periods with daily minimum and maximum ambient temperatures, respectively. The results submitted to analysis of variance, using the Sisvar statistical software and a 95% level of confidence, confirmed that even in the winter the studied system maintained acceptable BGHI averages, at intervals found in the literature for this phase. The biogas heating system proved to be efficient for managing the thermal comfort for confined piglets, being an interesting alternative in the search for energy sustainability in pig production.

Keywords: Pig facilities. Swine reared in sites. Alternative Heating System. Thermal comfort. Thermal environment indices. Biodigester. Biogas.

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1 INTRODUCTION

Pig farming facilities, modern and adapted to Brazil´s climatic variability, demand higher investments when aiming to expand production, having financial return and sustainability as objectives.

The thermal environment within the facilities directly influences animal performance and health. Consequently, better production costs and benefits will emerge when lower losses in the pig production process are obtained (GUIMARÃES et al., 2017).

More adequate specific structures for the thermal control of the production environment are essencial in the pig farming scenario. Variables such as relative humidity and air temperature and speed, as well as incident radiation on animals, directly impact their development. To achieve the desired efficiency in weight gain, environmental and nutritional variables, genetic profile, and social and behavioral relationships within the scope of animal welfare should always be considered (GALVÃO et al., 2019). According to the authors, specific demands, such as those that occur in the nursery stage, can modify the nutritional requirements of the animals. Thus, their performance in nutritional convergence will highly depend on the best conditions of thermal comfort.

Many thermal comfort indices have been developed to objectively assess the thermal environment in which the pigs are raised. The Globe Temperature and Humidity Index (BGHI) stands out among the indices that are mostly used in experiments regarding ambiance. This indicator combines the direct effects of temperature, relative humidity, and radiation variables, and the indirect effect of air movement. This index has been widely used to measure the thermal comfort of facilities by researchers in Brazil and worldwide.

Equipment projects that use alternative sources of energy or reuse pig waste have been intensifying recently. Shirzad et al. (2019) proved that the use of biodigesters as a source of energy from agricultural waste generated 82.83 MW in 2016 in a case study conducted in Iran. Pig farming has latent possibilities in the production of biogas and biofertilizer through biodigesters, which is an interesting form to feed the renewable energy generation system, enabling the producer to convert biogas into mechanical, electrical or thermal energy, among others.

In this context, the objective of this study was to evaluate a heating system in a pig nursery, consisting of a heat exchanger powered by biogas generated in biodigesters, in maintaining thermal comfort, and the ensuing response of the animals in terms of weight gain.

2 LITERATURE REVIEW

This literature review addresses topics concerning the ambiance in pig farming, the specific features of the facilities for the nursery, the use of thermal comfort indices in the environmental assessment of rural buildings, paying particular attention to the Globe Temperature and Humidity Index, using biodigesters as a form to convert waste into energy, and, finally, the heating systems to be used in the nursery phase in the pig farms.

2.1 Ambiance in pig farming

The latest report of the Brazilian Association of Animal Protein (BRAZILIAN ASSOCIATION OF ANIMAL PROTEIN - ABPA, 2018), confirmed the tendency of increasing Brazilian pig production in recent years, surpassing 3.75 million tons in 2017, with an internal consumption of 14.7 kg individual^{-1} in 2017, standing at the fourth place in export. The report confirms a favorable scenario for the field, but one that requires more investments.

In recent years, Brazilian pig farming has evolved substantially in the field of ambiance, noticeable by the significant number of produced academic and scientific papers (ABREU et al., 2019; BARROS; REZENDE; CAMPOS, 2019; CECCHIN et al., 2019; LOURENÇONI et al., 2019; VELOSO et al., 2020). One of the results of this evolution is the noticeable comsumption increase. The survey commissioned by the World Animal Protection (WAP) revealed that approximately 70% of Brazilians interviewed consider that products with a seal that proves animal welfare (AWF) are more expensive than those without the certification. However, 70% also stated that they would only purchase products with a welfare stamp if the price were the same as products without a stamp (WORLD ANIMAL PROTECTION - WAP, 2016).

Attentive to the foreign market, pig farming has recently noticed this shift in the paradigm of efficient production and animal welfare.

Campos et al. (2008) demonstrated the need to adapt the facilities to obtain the best performance and, consequently, increase productivity. When it comes to adjusting the facilities to the constant challenges of pig farming, the authors understand that the main issue is the variations in the thermal environment, which directly influence animal performance, both in reproduction and weight gain.

According to Sampaio et al. (2004), to obtain high pig productivity, which is desirable for all producers, the facilities must offer animals environmental conditions closer to the temperatures of thermal comfort.

The Globe Temperature and Humidity Index (BGHI) is considered a complete method to assess the piglet's thermal environment in its nursery phase. This index directly weighs the temperature and relative humidity of the ambient air and the radiation present in the environment, and, indirectly, the air movement. A challenge faced continuously by the worldwide pig industry is to plan the production cost cycle and continuously monitor the thermal environment in the warehouses that house these animals, aiming at better economic results (CECCHIN et al., 2017).

The difficulty in maintaining the ambiance in pig farming begins at the maternity hospital and extends to the nursery phase. Piglets have greater difficulty in maintaining body temperature, especially in the first two weeks of life. The literature has presented studies on heating through several techniques. Morello et al. (2018) state that, in the same environment, thermal variability differs even in controlled environments, which is, consequently, the most demanding challenge until the piglet can maintain homeothermy.

There are many challenges regarding the environment in pig farming since Brazil presents high air temperature variability, characteristics of the subtropical climate. As a continental country, there is a constant search to offer thermoneutrality for the breeding stock imposes on the producer constant search for facility and management improvements, with lower production cost (DIAS et al., 2018).

2.2 Nursery facilities and ambiance

In industrialized pig farms, the nursery phase, which begins at 21 days of age, is one of the most impacting stages for the animal. Separated from the sows and having weaning established, the piglets are gathered from different litters in high density in the stalls. New challenges are enforced on animals in terms of social interaction and competition for space and food. Fast adaptation to the handling is also required to impose itself hierarchically. Studies concluded that there is a previously established stress added to the status of incomplete endothermic generation at this stage, with consequent impairment in its development (HÖTZEL et al., 2011; SOBENSTIANSKI; BARCELLOS, 2012).

The constructive aspects of heating systems should, a priori, maintain ambient temperatures that favor the development of the piglets. For this purpose, the temperature in the nursery should be kept at an average of 24 °C, until the piglets reach 35 days of age. After this period, the temperature adjustments between 24 °C and 20 °C should be gradual. The systems should allow monitoring and control for 24 hours so that the maximum (31 °C) and minimum limits (8 °C) are not extrapolated (NÄÄS et al., 2014).

The variation in air temperature and the extrapolation of these limits trigger the inadequate conversion of the nutrients acquired in food, changing animal behavior (DIAS; SILVA; MANTEGA, 2015).

Performance indicators in the confined nursery phase, such as feed consumption, reflect on weight gain, in line with the thermal environment.

Thermal comfort favors the adequate conversion of ingested nutrients (BARROS et al., 2015; CAMPOS et al., 2008).

As for the typology used in the stall floors, Ferreira (2012) described that when the stalls are elevated the mesh floor partially favors the piglet's choice of time to seek greater ventilation or rest in an area with superior heat retention.

In the nursery phase, one of the primary positive responses to thermal comfort can be translated into the average weekly weight gain. According to Amaral et al. (2011) and Miller (2012), critical air temperature limits feed consumption and the consequent variation in weight. At this stage, the critical threshold of mortality is 2.5%, with an acceptable average of 1.5%.

Luz et al. (2015) argued that air temperature control should ensure the lowest variations to maintain the nursery’s environmental quality since it directly influences the well-being of the confined animals. Temperature variations can cause changes even in weight gain. The search for thermal system adjustments must always be guided by maintaining the environment inside the facility within the thermoneutrality zone.

Since piglets are homeothermic animals, at this stage the percentage of body fat is still in formation. Therefore, they have difficulty in maintaining their internal temperature. Thus, maintaining a temperature control close to a range of thermoneutrality impacts its development and, when left uncontrolled, it can compromise food convergence for weight gain and survival (BARROS et al., 2018).

The thermal comfort zone, which corresponds to the thermoneutral limits for each phase/age of the piglet, is a necessary measure to monitor and control the heating system during the nursery phase. The comfort-thermal indices become a reference for adequately adjusting the system temperature for each age during this phase, helping the animal to develop without losing energy to the environment and generating thermal stress (MARTÍNEZ-MIRÓ et al., 2016). It is understood that, in addition to the genetic profile of balanced nutrition, the thermal comfort zone completes the development tripod at this stage of the piglet's life.

2.3 Thermal comfort indices

Constructive characteristics of nursery warehouses collaborate substantially so that the thermal conditions of the facilities favor better responses to the thermal comfort indices (SAMPAIO et al., 2004).

In any environment in which there are homeothermic animals, their heat exchange relationship with the environment dictates its behavior concerning its development. When these conditions are favorable, the animal is considered to have found its balance, its thermoneutrality zone, or thermal comfort zone. Phenomena of heat transfers in search of body balance are identified by their particularities, such as exchange processes for conduction, radiation, evaporation, and radiation.

The main factor of the thermal environment is the ambient temperature, which, when reaching upper limits above 30 ºC in confined environments, causes evaporative processes to prevail as the primary form of heat exchange between animals and the environment. On the other hand, temperatures below the lower limit of 25 °C favor exchanges through non-evaporative processes. Therefore, thermoregulatory mechanisms will only be triggered by the pigs when the thermal sensation goes beyond these limits. Therefore, what is sought in confinements is a thermal environment that establishes a condition of thermoneutrality (FURTADO et al., 2012).

The first indicators of the thermal environment began with the objective of measuring comfort sensation and were developed for humans, varying the temperature and relative humidity with different wind speeds. The methodology was later applied to measure thermal comfort in animals. At the time, the authors published data related to the temperature-humidity index (THI) applied to cattle, in which observations were concluded in the intrinsic relationship between the decline in milk production when THI tended to inverse proportionality (CARGILL; STEWART, 1966; HAHN, 1985; JOHNSON et al., 1962; THOM, 1958, 1959).

Buffington et al. (1981) developed the Black Globe Temperature and Humidity Index (BGHI), which has since been considered by many researchers as one of the indices that adds more variables, such as thermal radiation with the temperature of the black globe (Tgn) and the effects of relative humidity and wind speed.

Another indicator that allows considering the exchange of radiant energy is the average radiant temperature, which is expressed in the envelope of the animal's contact surface with the environment, considering an infinitely large surface, known as thermal heat load (THL).

Castro et al. (2013) consider that the THI does not fully represent the thermal environment in which the animal is situated and that, in confinement situations, it would not be the indicated index since it does not allow measuring the thermal heat load from all directions. In THL and BGHI, the black globe would complement this information (CASTRO et al., 2013).

In studies developed in the piglet nursery phase, BGHI has satisfactorily expressed the relationships of the processes that are established between animal and environment, due to its practicality of collecting the parameters that feed the index, as well as result consistency (CAMPOS et al., 2008).

Values of BGHI above 80, internal temperatures above 30 °C, and RH above 70% are already considered heat stress indicators for piglets up to 35 days old (MANNO; OLIVEIRA; DONZELE, 2005; NUNES et al., 2008; OLIVEIRA et al., 1997; VAZ et al., 2005).

Oliveira et al. (1997) considered RH of 73.84% and BGHI 70.72 as conditions of thermoneutrality for pigs weighing from 15 to 30 kg.

Nunes et al. (2008) obtained a value of 74.5, characterizing thermoneutrality during the nursery phase. Manno, Oliveira & Donzele (2005) found a BGHI of 71.1 and RH of 71.2% under similar weight conditions, considering this value as an indicator of thermal comfort and RH values of 62.4% and BGHI of 84.9 as indicators of thermal stress.

Vaz et al. (2005) studied castrated male pigs in the weight range between 15 and 30 kg, finding thermal comfort conditions with RH of 67.5% and BGHI of 81.2. Nevertheless, Campos et al. (2008) analyzed two different types of nurseries and measured BGHI intervals between 78.4 and 78.5. In the same study, the authors recorded BGHI values between 68.9 and 70.7 as a minimum interval, also considering these intervals as indicators for thermal comfort.

Cecchin et al. (2017) found that the thermal environment for pig facilities is the core of a global thinking trend, with vital connections between production and environmental management. The interference of the environment on the individual and collective are variables that drive the economy in this market. The authors indicate that pig facilities non-compliant with the ambiance variables are considered a strong aggravating factor for the emergence of respiratory diseases and behavioral, as well as physiological changes.

2.4 Biodigesters as a form for converting waste into energy in pig farms

When planning to achieve environmental balance, farms must comply with current environmental legislation to minimize the environmental impacts generated by the pig farming activity. Among the existing definitions constantly debated by peers, the concept of environmental impact is found in art. 1 of the CONAMA Resolution 01 - NATIONAL ENVIRONMENT COUNCIL (CONAMA n. 001/86), namely:

> [...] Any change in the physical, chemical, and biological properties of the environment, caused by any form of matter or energy resulting from human activities that, directly or indirectly, affect: I. The health, safety, and well-being of the population; II. Social and economic activities; III. Biota; IV. The aesthetic and sanitary conditions of the environment; V. The quality of environmental resources (BRASIL, 1986, our translation).

In the early 19th century, Sir Humphry Davy, a British inventor and famous chemist, observed that organic wastes contained methane and carbon dioxide. In the mid-19th century, in Bambaim, India, the first anaerobic reactor was built to extract biogas, known as an Indian biodigester.

Biodigesters are gaining more and more recognition as they are one of the most interesting forms of mitigating the impacts of pig farming waste. They present constructive profiles that differ from each other and fit into different proposals regarding the flow of incoming waste, being classified as continuous or lot biodigesters. Veloso et al. (2018) corroborate that the self-mitigating power of biodigesters in pig farming can promote an 85% reduction in biochemical oxygen demand (BOD) and almost 82% in chemical oxygen demand (COD), which represent a significant stabilization of waste.

The waste originated from pig farming is considered to have high polluting potential because of the high organic content and, consequently, high biochemical oxygen demand (BOD). The biodigesters most commonly used in agricultural facilities, which differ by their construction characteristics, inlet flow, and not by the chemical principle of operation, are known as Indian, Chinese, and tubular, popularized as Canadian. When using the Canadian biodigester modified for pig farming, Wenzel et al. (2014) achieved efficiency in the reduction of COD in the order of 72.8%.

Two primary byproducts, biofertilizers and biomethane, are generated by the anaerobic digestion process in biodigesters and are also known as biogas. Biogas is composed mainly of carbon dioxide and methane gas, has a high calorific value, and is intended for generating thermal energy and electrical energy (RODRIGUES et al., 2019).

From the biodigester gasometer, biogas can be transformed into thermal energy using hot water boilers. The use of energy from biogas adds value to the activity. It can even make the nursery phase, considered one of the stages with the highest demand for heating, economically viable.

Campos et al. (2009) stated that the amount of waste produced per unit of time in industrial pig farming, where there is a higher density of animals, favors and justifies the use of continuous flow biodigesters, the category in which the Canadian tube or anaerobic reactor fits. The use of biodigesters have, in turn, relatively low cost, high performance, and ease of handling.

Biogas derived from the biodigestion of agricultural products and used in this system as the primary source of energy generally consists of fractions of methane (CH_4) (60%), carbon dioxide (CO_2) (35%), water vapor (H_2O), and other gases (5%). This portion includes nitrogen (N_2), ammonia (NH_3), carbon monoxide (CO), oxygen (O_2), hydrogen sulfide (H_2S), among others. Under normal conditions of temperature and pressure (CNTP), biogas can range between 40 and 80% of methane in its composition, depending on the organic matter of origin (FERNANDEZ-LOPEZ et al., 2015).

Castro et al. (2013) obtained an energy ratio of the order of 85 N m^3d^{-1} in 65.6% of biomethane when using a tubular biodigester.

When processing pig waste as byproducts in biodigestion, the biogas generated can constitute a source for both electricity and thermal energy, substantially contributing to production costs and adding value to the activity (CALZA et al., 2015).

Ravina et al. (2019) stated that the configurations of methane extraction solutions and applications should increase exponentially in the coming years, as the world craves solutions from renewable energy sources with low-cost generation in addition to the necessary environmental mitigations. The authors presented a tool model as a support for decision making in which the previous evaluation of the systems allows correlating variables such as energy potential, mass flow, and probable impacts that can generate different project configurations. The model denominated $MCBioCH_4$ meets the growing demand in Europe and will allow more significant support for decision-making for developing projects in biodigestion.

2.5 Heating system

The heating processes in pig farming during the nursery phase might occur from various sources of energy. There is no standard recommendation for heating equipment but a configuration according to the economic and specific demand for each project. Many factors will influence the most appropriate choice for the purposes outlined.

Sarubbi et al. (2010) studied the heating in nurseries using the convection principle, with heated floor systems and aerial resistances, as well as an electrical energy source. The authors applied a geostatistical method and evaluated thermal comfort using the THI. They concluded that floor heating had a better return in terms of energy consumption. Regarding the thermal comfort of the piglets, heat by aerial electrical resistances presented the best results.

Adelt, Wolf & Vogel (2011) warn about the sustainable tendency of replacing natural gas with renewable methane. The authors indicated a reduction of approximately 82% of greenhouse gases (GHG), with an expenditure of only 12% of specific energy, with 44.6g CO_2eq kWh^{-1}, having used fermented waste from environmentally friendly plants.

Nowadays, boilers have played an essential role as an alternative form of converting biogas into thermal energy. In his studies on the impact of polluting gases in natural gas or oil-fired boilers, Moreira (2012) stated that the demand for clean and renewable energy generation is growing, requiring a guarantee that these also meet the challenging needs of humanity regarding environmental conservation.

Boilers are currently adapted to generate energy by actuation from different energy sources. The most common sources are natural gas, liquefied petroleum gas (LPG), and diesel oil, among others. There has been a recent increase in the adaptation of boilers to use methane since anaerobic biodigestion processes have grown substantially.

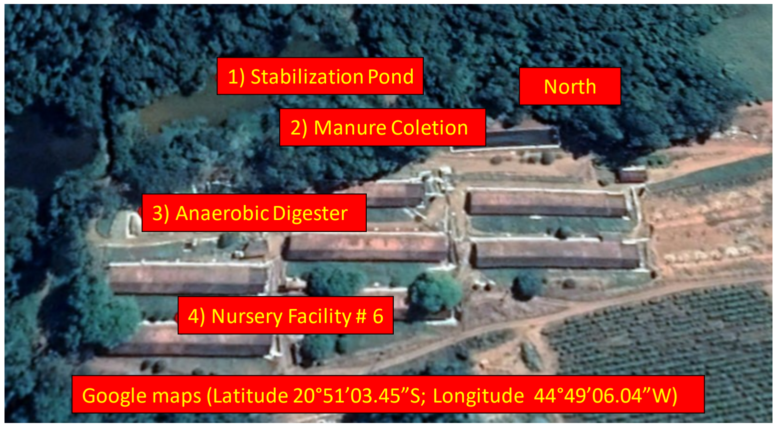
In comparative studies of specific volumetric flow rates of combustion air for various fuels, including biogas, Balanescu and Homutescu (2019) concluded that the most expensive component of the equipment is the blower, which is a fixed part of the system and requires no resources with exchanges. However, it is necessary to correctly select the type of nozzle or adjust the fuel supply system. The authors also concluded that, of the seven fuels tested in their work, biogas reached the highest flow rate of the water vapor content (up to 3.53%).

3 MATERIAL AND METHODS

The experiment was conducted in the winter, which began on July 13th and ended on August 17th, 2017. We collected the data in the municipality of Oliveira, MG, at the São Paulo Farm, km 634 of BR 381 - Fernão Dias Highway, which develops pig confinement in production sites. The pig nursery warehouses (Figure 1) evaluated in the present study are located at Latitude 20°51’03.45” S and Longitude 44°49’06.04” W, with an east-west orientation. The nursery site is situated at an altitude of 997 m, with a warm and temperate climate, denominated Cwa (MARTINS et al., 2018), according to the Köppen classification for the region of Oliveira, MG.

The São Paulo Farm includes six areas, namely beef cattle, forestry, coffee, sheep, grain storage, and pig farming. Once divided into sites, the pig farm could achieve greater control of management and operational costs, as well as impose sectoral sanitary isolation mainly in areas that require greater oversight. With a breeding stock of 5,000 sows, the company currently ranks among the top five pig farming companies with independent production in the state of Minas Gerais.

Figure 1 - Aerial View of the Nursery - São Paulo Farm.



Source: The Author (2020).

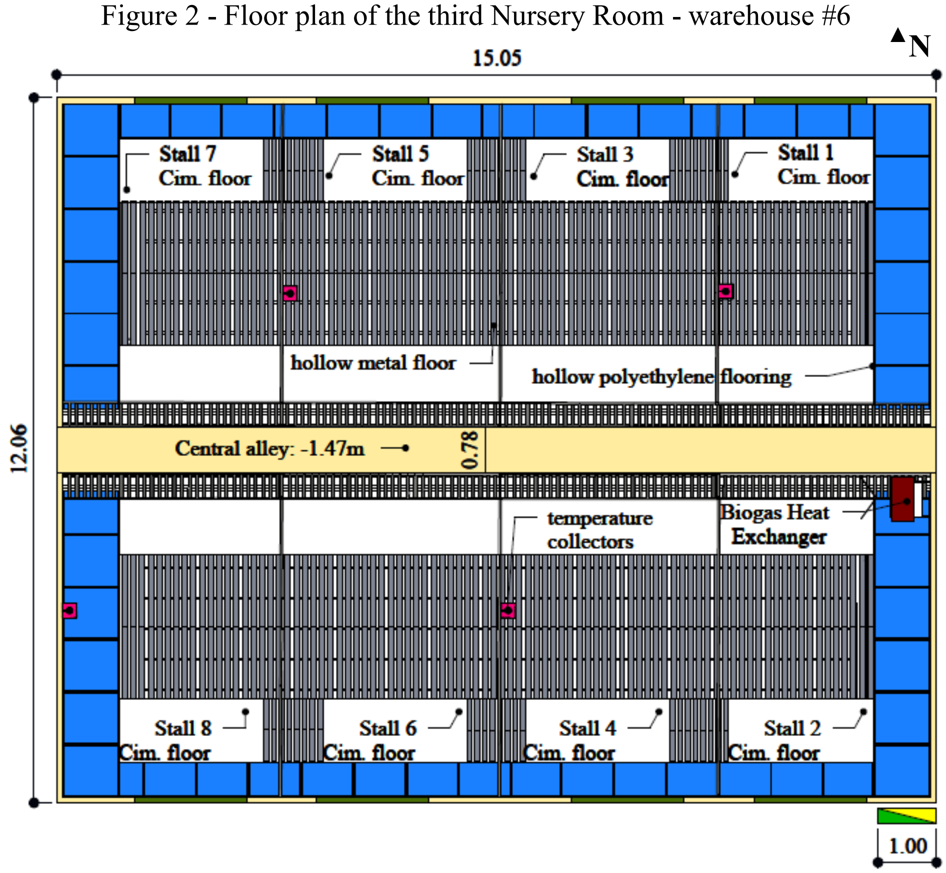
3.1 Studied environment

The experiment was conducted at the pig breeding site, which consists of seven masonry warehouses of the same construction pattern.

The studied warehouse, oriented in the true east-west direction, has a central corridor 0.78 m wide, masonry walls of concrete blocks, a total width of 12.0 m, and a full length of 68.0 m. The rooms are divided by masonry walls of concrete blocks, with transparent plastic curtains in front of the central corridors.

Figure 2 shows the position of the installed sensors, distribution of the stalls in relation to the central corridor, layout of the floors, and position of the heat exchanger in the room.

Figure 2 - Floor plan of the third Nursery Room - warehouse #6

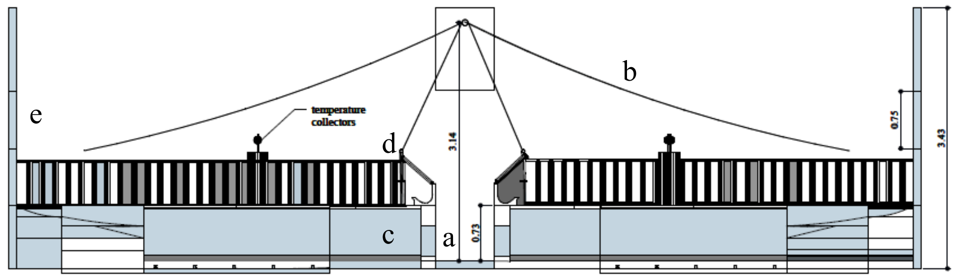


Source: The Author (2020).

The warehouse houses eight stalls, four on each side of the central corridor. Male piglets are housed in the stalls located on the south side of the corridor, while the females are in the stalls on the north side.

In the left cross-section of the nursery room (Figure 3), the heights of the partitions and elevation of the stalls are observed in relation to the floor of the central corridor.

Figure 3 - Transversal cut of the Nursery Facility (a: corridor; b: yellow canvas; c: separating walls; d: metal dividers; e: windows).

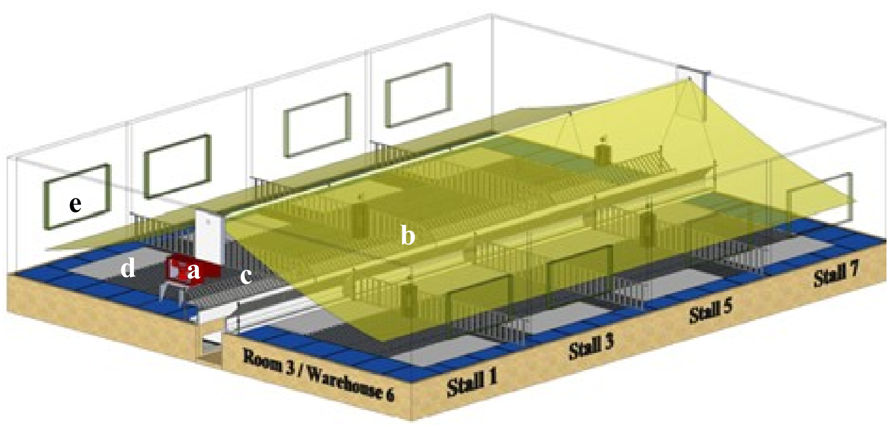


Source: The Author (2020).

The central corridor has dividing walls made of masonry with a height of 1.0 m and a width of 0.10 m.

Figure 4 shows the 3D view of the facility from the perspective of the division between stalls and the elevated yellow canvas extended in the facility.

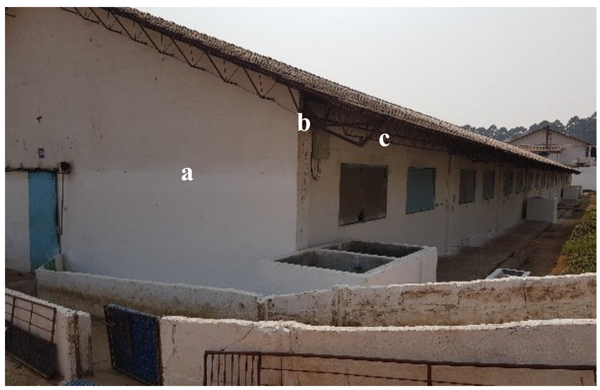
Figure 4 - 3D view of the Nursery room (a: heat exchanger, b: yellow canvas; c: metal dividers; d: stall; e: window).



Source: The Author (2020).

Figure 5 demonstrates the relevant external characteristics. The ceiling height is 4 m, with a roof made up of 6 mm thick asbestos cement tiles, supported by a latticed metallic structure and with a 30º inclination. Figure 4 also shows the lateral external corridors in masonry for handling the entry and exit of animals.

Figure 5 - External view of the East-West oriented nursery facility (a: cement block walls; b) metal truss; c) 6 mm fiber cement tiles).



Source: The Author (2020).

The nursery room used in the experiment has an elevated floor of 0.87 m. The stalls have 90% of mesh floor for collecting waste through the galleries. The central part of each stall has a mesh metal floor, and on the sides, the floor is cast in high-density polyethylene (HDPE) slabs. An inclined grid was installed on the corridor wall up to a height of 1.35 m (FIGURE 6).

Figure 6 - A and B - Nursery stall floor: a) metal mesh floor in the central area, b) polyethylene mesh material around the stall, and c) concrete floor in two specific areas to support the feeders. d) Heat exchanger, near the corridor door; e) yellow canvas, covering the stalls to maximize the heating; f) walls at the corridor, dividing the room in two areas; g) door.

Source: The Author (2020).

3.2 Piglet handling in the farm

The density of piglets per stall is listed in Table 1. The piglets were confined in a density between 0.20 m^2 and 0.38 m^2 per animal, according to the recommendations given by Teixeira (1997).

Table 1 - Dimensions per stall, dimensions of the windows; number of piglets per stall, and area per piglet in each stall.

Facility 8 stalls	**Stall dimensions (cm)**	**Metallic windows (cm)**	**Number of piglets per stall**		**Area per piglet in the stall (m^2 $piglet^{-1}$)**	
			(SOUTH) side of the facility (Males)	**(NORTH) side of the facility (Females)**	**(SOUTH) side of the facility (Males)**	**(NORTH) side of the facility (Females)**
Stalls 1 and 2	362 x 554	103 x 192	B2 (95)	B1 (95)	B2 (0.20)	B1 (0.20)
Stalls 3 and 4	374 x 554	103 x 192	B4 (95)	B3 (95)	B4 (0.20)	B3 (0.20)
Stalls 5 and 6	374 x 554	103 x 192	B6 (95)	B5 (95)	B6 (0.20)	B5 (0.20)
Stalls 7 and 8	375 x 554	103 x 192	B8 (90)	B7 (90)	B8 (0.21)	B7 (0.21)

Source: The Author (2020).

The studied experimental lot, with chemically castrated males, occupied the nursery room from the 21st day of life, all F1 piglets, obtained from the cross between Large White vs Landrace.

The animals were housed in the stalls following the farm routine in which the male piglets were placed in even stalls 2, 4, 6, and 8 on the south side of the facility and the females on the north side, in odd stalls 1, 3, 5, and 7. The experiment was completed when the animals reached 56 days of life, accounting for 35 (D_{35}) days of monitoring.

The feed offered to the animals was from the 337 Agroceres PIC line, with distribution and availability of 24 hours daily.

3.3 Monitoring of the lot regarding weight gain

Each animal was considered one replicate for a total of five replicates for each treatment. The treatments were composed of the combinations DAY (0, 7, 14, 21, 28, and 35), STALL (four male and four female stalls with five animals in each stall), totalizing 240 observations.

The data on piglet growth was collected by the company's monitoring system, therefore, measured *in loco*. The input weights were measured on day zero (D_0) for comparison purposes with the weight taken on the 35th day (D_{35}). The monitoring was done without sample replacement, with cyclic weighing regularity of seven days, totalizing six weighing cycles.

The samples were composed at random in each stall, totalizing 40 animals identified by earrings. The body masses were recorded, always beginning at 2:00 pm and maintaining the same sequence of stalls in all weekly replicates. The experiment was conducted without interfering on the nursery routine, standardizing the notes in a spreadsheet, and verifying the tare of the platform scale used by the company in each reading cycle.

3.4 Heating system

The energy generation process at the nursery site begins with the effluent treatment system of the company's pig farming sites where biogas is produced in tubular biodigesters (also known as Canadian biodigesters, FIGURE 7).

Figure 7 - Tubular anaerobic digester of the Nursery Site.

Source: The Author (2020).

Each biodigester has a cell of 3,300 m^3, with concrete floors and walls and covered with a waterproof PVC tarpaulin. The cover is made of high-density polyethylene canvas and fixed in channels with stainless screws.

Part of the biogas produced by the biodigesters is converted into electrical energy and supplies the entire farm, providing a monthly savings of approximately 35% in electricity consumption.

Another part of the biogas that is converted into thermal energy is destined to the heating process, of which process begins in the boilers (FIGURE 8), using technology adapted for burning the biogas and heating the hot water flow.

Figure 8 - Tubular biogas boiler.

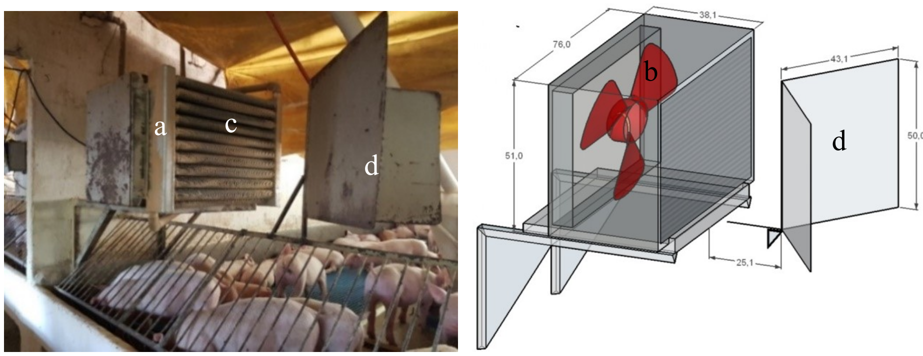
Source: The Author (2020).

The boiler heats the water in a fog tube burner of the ATA brand. The heated water is transformed into water vapor, which is distributed by convection in a closed circuit to the heat exchangers located in each nursery room. The system temperature is controlled by thermostats arranged along the pipes.

The heat exchangers installed in all rooms of the warehouses are arranged in a single distribution point of each room of the nursery, on the wall bordering another room, next to the door to the corridor (Figure 9).

Figure 9 shows the set of details of the heat exchanger used in each nursery room.

Figure 9 - Details - a: heat exchanger; b: propellers; c: radiator d: baffles.



Source: The Author (2020).

Two metallic baffles of 43.1 x 50 cm at 25.1 cm were installed from the front of the heat exchanger, forming an approximate angle of 133° to each other ("d" - Figure 9). Each set of heat exchangers has an attached and adjustable thermostat.

The heat exchange control done by the system is automated and of start/stop type, with a temperature indicator powered by a thermocouple sensor located in the center of each room on the central corridor, located approximately 30 cm below the ridge of the canvas.

Canvas was placed high above the stalls to reduce the loss of heat (Figure 4; Figure 6-B). The arrangement of the canvas allows partial or total openings over the days of the piglets' stay in the nursery. In the early days of the nursery period, the demand is characterized by maintaining the temperature between 24 °C and 26 °C. This apparatus allows reducing the volume of air to be heated by the biogas heat exchanger.

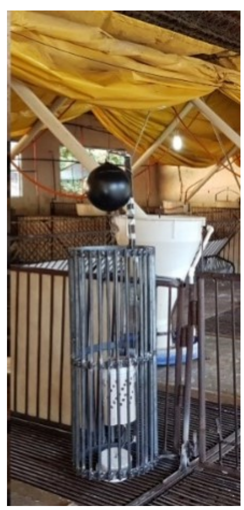
3.5 Assessment of the thermal environment

The data from the thermal environment of the experiment were collected and stored using sensors connected to the datalogger, U12-013 (Temp/RH/2

External Channel Datalogger), with an accuracy of ± 0.05 °C and measurement range between -40 to 100 °C. The sensors were calibrated against a TGD-400 thermal stress meter. The dataloggers were programmed to collect and store the parameters of temperature (T, ºC) and relative humidity (RH%) at every 15 minutes, according to the methodology proposed by Tinôco et al. (2007).

The sensors were symmetrically arranged to collect the data of the thermal variables between the stalls in four collection points. The dataloggers (Hobos U12-013) were placed with thermocouples to collect the air temperature, housed in PVC tubes diametrically perforated with enough density to ensure the passage of ambient air. The equipment was placed in a shelter with metal profiles for protection. The thermocouples were positioned 40 cm from the floor of the stall to collect temperature and relative humidity at the height of the animals' heads (Figure 10).

Figure 10 - Installation of black globes and hobo dataloggers in the stalls.



Source: The Author (2020).

The black globe temperature readings (Gn) were performed according to the recommendations of Damasceno et al. (2019). A height of 80 cm was adopted to read the black globe temperatures in the nursery room.

Readings were performed in the external environment using hobo thermocouples U12-013 (FIGURE 11) to monitor the thermal variations of the environment.

Figure 11 - Positioning of the external sensors.

Source: The Author (2020).

3.6 Environmental thermal parameters

The BGHI, developed by Buffington et al. (1981), is dimensionless and considers interactions between variables representative of ambient thermal comfort in a single value.

These relationships are expressed by Equation 1.

$$BGHI = t_{gn} + 0.36.t_{po} + 41.5 \quad (1)$$

in which,

t_{po} = temperature of the dew point (K), and

t_{gn} = temperature of the black globe thermometer (K).

Graphs were generated in an electronic spreadsheet showing the amplitudes of thermal comfort in 24 hours in intervals of 3 hours, using the generated BGHIs.

The BGHI results were subjected to analysis of variance. The SISVAR statistical software was used to analyze the statistical propositions related to BGHI and weight gain, applying the Scott-Knott test with 95% confidence.

Eight periods were formed for analysis of variance (Table 2), with three-hour intervals. These periods were chosen to include the maximum and minimum peaks, in function of the critical temperature spikes that occurred during the day.

Table 2 - BGHI periods in blocks of 3hours.

1	**23h to 2h**
2	**2h to 5h**
3	**5h to 8h**
4	**8h to 11h**
5	**11h to 14h**
6	**14h to 17h**
7	**17h to 20h**
8	**20h to 23h**

Source: The Author (2020).

This division was necessary to analyze the correspondence of the heating system to the meteorological variability during the day.

Concerning the BGHI values, each of the 35 days was considered as a block. Moreover, the effect of sex and period, as well as the interaction SEX*PERIOD was tested.

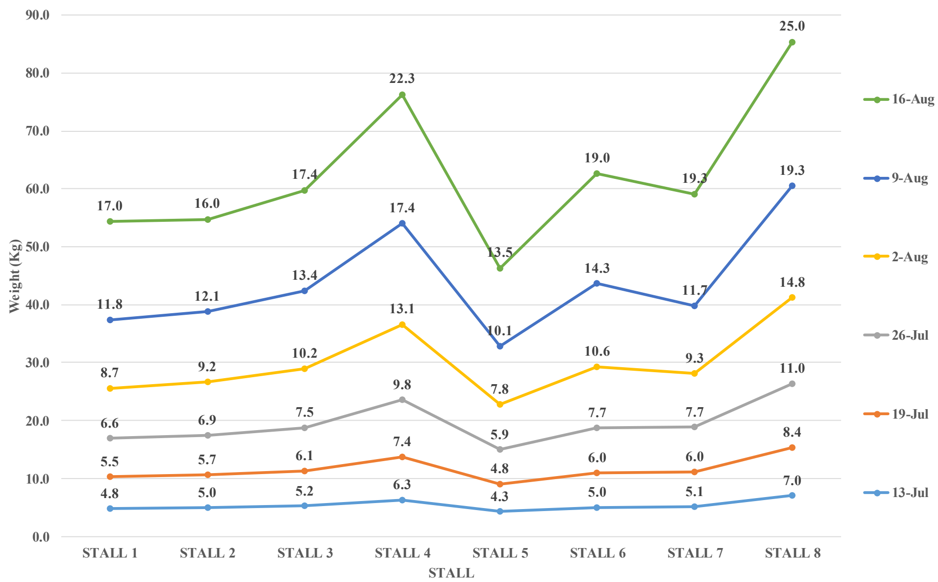
The effect "sex" corresponds to the average BGHI values of the sensor sets (2 and 4) located on the SOUTH side, and the average of the sensors (1 and 3), NORTH side, corresponds to the effects on males and females, respectively.

4 RESULTS AND DISCUSSION

4.1 Piglet performance

Figure 12 shows the values of the weight gains during the experimental period.

Figure 12 - Weight gain per stall in 5 weeks of monitoring.



Source: The Author (2020).

The results presented in Figure 12 show the most significant evolution in the weight gain of the animals in the stalls where the males were housed. These results are consistent with the expectations considering the chemical castration of the males and the F1 genetics (Large White and Landrace) and projected an average weight gain of 2.9 kg in five weeks. The females showed more homogeneous weight gain during the experimental period, resulting in an average of 2.4 kg in the nursery period. At the end of the nursery cycle, the general average weight gain of the monitored lot in room #3 was 2.67 kg, a result close to those found by Amaral et al. (2011) and Miller (2012), with an average weekly value of 2.66 kg.

4.2 Variability of the thermal system

Table 3 presents the results from studies conducted in Brazil since 2009. Not many studies were found regarding the BGHI studied in a nursery environment.

Considering the specificities of nursery facilities within the production cycle and the demand in terms of handling, they require specific features from the constructive and heating systems' perspectives.

Table 3 **-** Comparative between the BGHI found in various phases, periods, and floors.

(continues)

YEAR	AUTHOR	PHASE	PERIOD	FLOOR	BGHI (dimensionless)
2019	DAMASCENO et al.	maternity	summer	Concrete	70.73 to 85.58
2018	NEPOMUCENO	nursery	-	Metal/mash	65.9
			-	Metal/mash	66.0
2017	MIRANDA et al.	nursery	winter 2017	Metal and mesh/elevated polyethylene (PE)	67.0 to 73.9
2017	SOARES et. al	maternity	autumn	Concrete	74.8 to 81.9
2016	FERREIRA et al	termination	winter	Concrete	66.3±5.6
2016	ABREU et al.	growth and termination	summer	-	72.9 to 78.6
2013	CASTRO et al.	maternity	April and May	Slate	66.33 to 75.5

Table 3 - Comparative of BGHI found in various phases, periods, and floors.

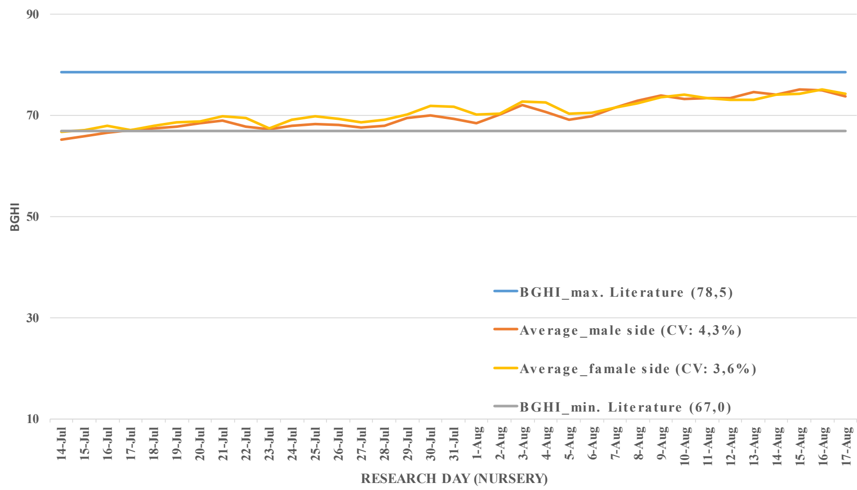
(conclusion)

YEAR	**AUTHOR**	**PHASE**	**PERIOD**	**FLOOR**	**BGHI** (dimensionless)
2009	CAMPOS et al	nursery I	winter 2005	suspended metallic cages	68.9 to 78.4
		nursery II			70.7 to 78.5
2008	CAMPOS et al.	growth	-	typology	78.4 and 78.5
				typology	68.9 and 70.7
2008	NUNES et al	growth	-	-	74.5
2007	TINOCO	growth and termination	summer	shavings	68.6 to 82.2
				rice peel	67.5 to 81.9
				concrete	67.9 to 81.7
2005	MANNO et al	15 to 30kg	-	-	71.1 to 84.9.
2005	VAZ et al	15 and 30kg	-	-	81.2
1997	TURCO	termination	-	-	72.0
1997	OLIVEIRA et al	15 to 30kg	-	-	70.2 and 74.5

Source: The Author (2020).

Figure 13 shows the variation of the average daily values of BGHI for both sides of the facility, south side (male) and north side (females). The results are close to those found in the literature.

Figure 13 - Average daily values of BGHI for both sides of the nursery facility, males (SOUTH) and females (NORTH), in the winter experimental period.



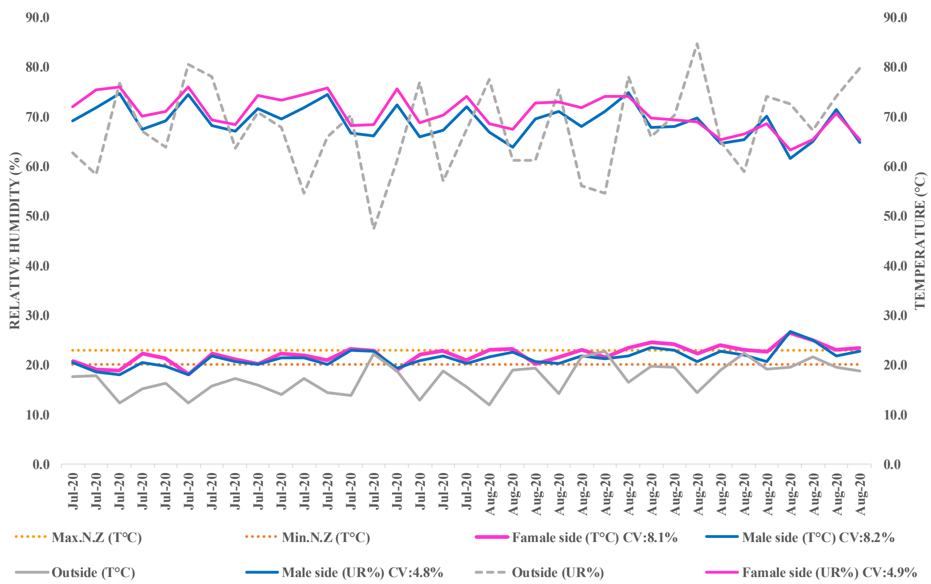
Source: The Author (2020).

Since the facility is not thermally and hermetically insulated, there was a small variation in the results obtained for the different observed points.

Ferreira (2012), when using heating systems of fluorescent lamps, found BGHI amplitudes with intervals between 64.26 and 71.54 in the winter period.

Variables related to BGHI, such as relative humidity (RH, %) (FIGURE 14), showed a natural tendency, with reduced values during the day and higher values at night.

Figure 14 - Variability of the daily averages of Relative Humidity (%) and Temperature (°C).



Source: The Author (2020).

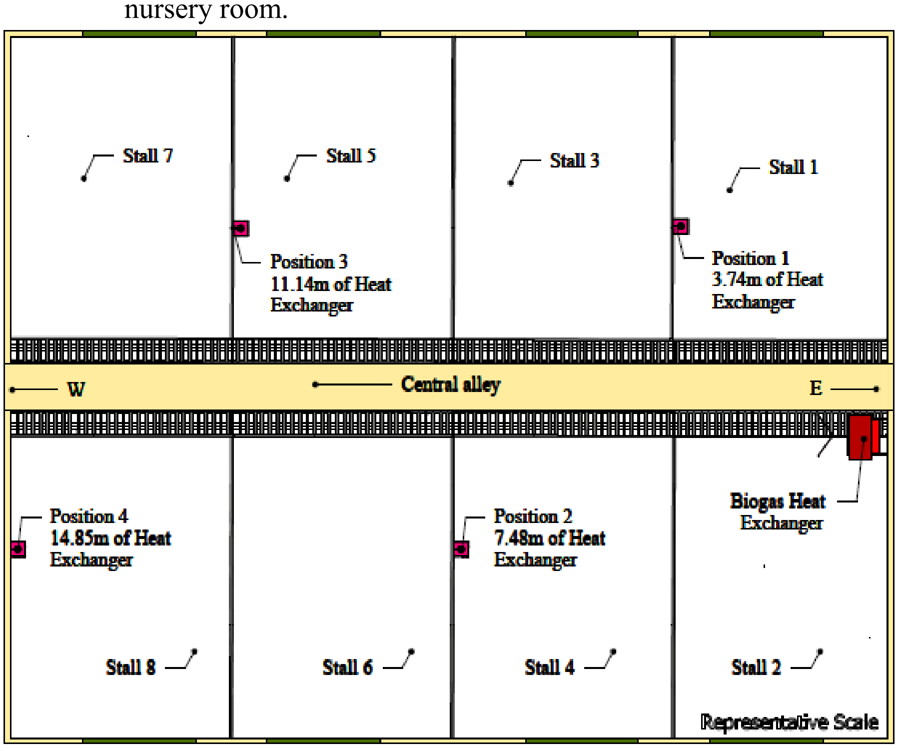
Nepomuceno et al. (2018) found an average interval of average relative humidity in a nursery with mesh metal floors between 68.9% and 69.2%. Sampaio et al. (2004) showed that, at this phase, piglets should not be subjected to relative humidity higher than 70%. In this study, in confinement with a heated environment and raised and mesh floor, the average RH value was 70.76%.

The ambient temperature inside the facilities for the nursery phase must remain within the recommended ranges (MORELLO et al., 2018). Silva-Miranda et al. (2012) defined thermoneutrality amplitudes in the temperature range between 20 °C and 23 °C by applying noise analysis in piglets in the nursery.

Despite the importance of maintaining temperature averages constant during the experiment, there was a considerable variation on the external temperature, and the biogas heat exchange system kept BGHI values within an acceptable range inside the nursery room.

Figure 15 shows the positions of each set of sensors (Ps1, Ps2, Ps3, and Ps4) in the environment for a better representation of the stalls per area, according to longitudinal distances in relation to the heat exchanger. The sensors were arranged in parallel in the longitudinal direction and alternating in the transverse direction for better coverage in the temperature readings throughout the room. This arrangement corresponded to the positioning of the stalls for female piglets, Ps1 and Ps3, on the north side, and on the south side, the Ps2 and Ps4, corresponding to the stalls for male piglets.

Figure 15 - Schematic representation of the position of the sensors within the stalls and their respective distances from the heat exchanger of the nursery room.

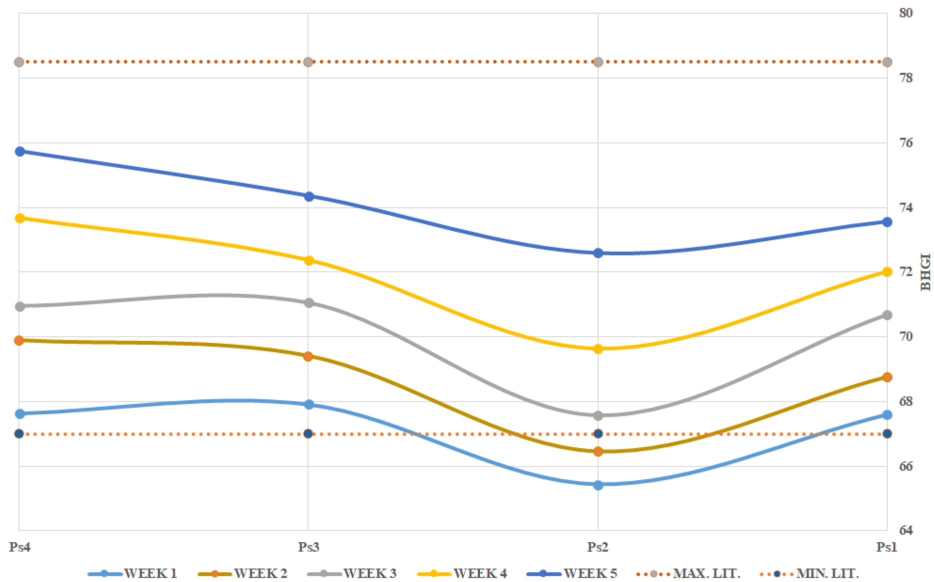


Source: The Author (2020).

The heat flow begins at the heat exchanger towards the opposite wall within the nursery.

Figure 16 shows the variations in BGHI for each point over the five monitored weeks.

Figure 16 - BGHI values obtained for each black globe thermometer set, relating to its distance from the heat exchanger device.



Source: The Author (2020).

The set located in the Ps2 position, at 7.48 m from the heat exchanger, showed a tendency towards lower values when compared with the other points for all five weeks, which may have occurred due to some turbulence in the distribution of hot air that happened inside the room. However, the average values of the thermal environment parameters obtained from the third week are within the range of BGHI values recommended in the literature.

Figure 16 shows that there was a higher concentration of heat in the most distant positions in relation to the heat exchanger for all five weeks, notably, the values found in position four (next to the wall opposite to where the heat exchanger is located).

Campos et al. (2009) performed a similar experiment in a nursery of a confined system during the winter, where the piglets were found in metal cages indoors, at a location with the same Cwa classification, and obtained an expressive range of BGHI, ranging between 68.9 and 78.5.

4.3 Statistical analysis of the BGHI values

The periods adopted for analysis are 3-hour portions derived from the temperature-reading time in the experiment, which occurred for 24 hours.

The Scott-Knott Test was performed for the main effect of PERIODS. The SEX*PERIODS interaction was not significant at the level of 5% probability ($p > 0.05$) by the F *Scott-Knott test at 95% confidence. Therefore, the sex and period factors are independent.

The Scott-Knott test was applied at 95% confidence for the effect PERIODS, obtaining $p < 0.05$.

Table 4 presents the averages of the analyzed periods for the analysis of variance.

Table 4 - BGHI (dimensionless) means per period.

Periods	Means*
3	67.1**F**
2	67.5**F**
1	68.5**E**
8	70.1**D**
4	70.4**D**
7	71.9**C**
5	73.1**B**
6	73.9**A**

Source: The Author (2020).

* Means followed by the same letter in the columns do not differ from each other at 5% probability level by the Scott-Knott test.

For periods that correspond to the times of maximum daily temperature, the results showed that period 6 has the highest average BGHI value, followed by periods 5 and 7.

On the other hand, periods 2 and 3 presented the lowest average BGHI values, which also correspond to the times of minimum daily temperatures.

Campos et al. (2008), found BGHI intervals between 78.4 and 78.5, and averages between 68.9 and 70.7.

The highest average BGHI value, corresponding to 70.73, was found in the stalls where the females were confined, stalls 1, 3, 5, and 7, opposite the stalls of the males, with 69.94 ($p < 0, 05$).

Manno, Oliveira & Donzele (2005) obtained a BGHI value of 71.1 and concluded that this value indicates the animals' thermal comfort and that the value of 84.9 is an indicator of thermal stress.

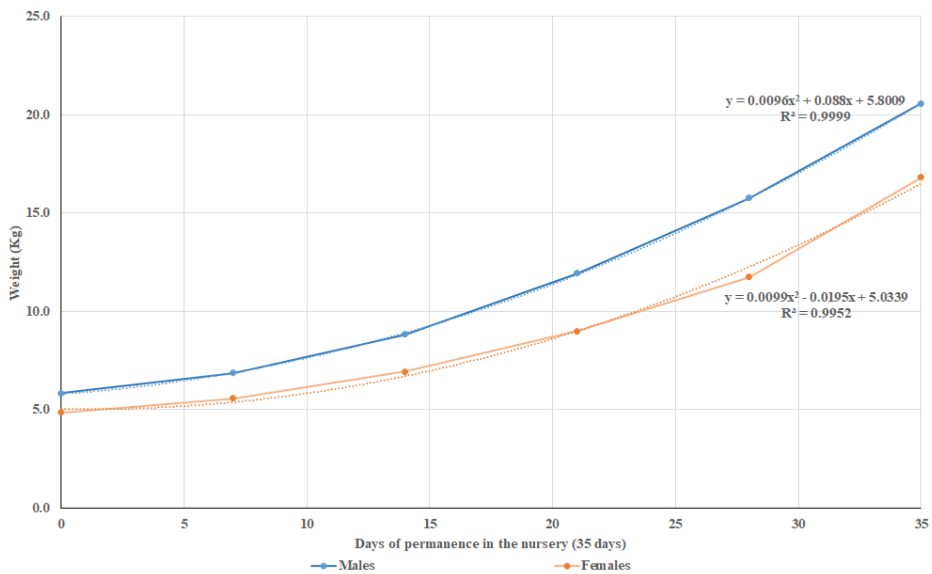
4.4 Weight gain rate

The analysis of variance showed that the effect of the DAY*SEX interaction was significant at the 5% probability level by the F test, which represents a dependence between the factors DAY and SEX. The same occurs for the interaction DAY*STALL (SEX), which represents a dependence between DAY and STALL (SEX) (Reads Stall within Sex).

Because of this, developments were made regarding both interactions.

The DAY factor is quantitative, with levels 0, 7, 14, 21, 28, and 35. Therefore, regression analysis was performed to unfold the DAY factor within each SEX (FIGURE 17).

Figure 17 - Day*Sex interaction.



Source: The Author (2020).

Figure 17 illustrates the general evolution of the weights in the room since the first day (D_0) with the weight gain of chemically castrated male piglets significantly higher than that of females (R^2).

Silva et al. (2002) observed significant weight gain (p <0.05) between the sexes in favor of the males piglets when compared with females, with daily averages of 0.865 kg and 0.783 kg, respectively, in the entire experimental period.

By accompanying the pig rearing throughout the nursery phase, for both sexes, Lovatto et al. (2004) evaluated free access or not to the feeder, and obtained a total average gain of 6.6% higher for males than for females, with values of 0.724 kg and 0.679 kg per day for male and female pigs, respectively, at the end of the experiment.

By calculating the weekly weight gain in the present study, males showed better performance than females in almost every period, with the accumulated weight of the order of 176% for males when compared with females. However, in the last week, females exceeded the average weight of males by 4.8%.

Table 5 lists the data for the period from the first (D_0) to the last day (D_{35}) (north side of the facility). There was no statistical difference in weight on the first day of weighing the lot for both sides, which denotes uniformity.

Table 5 - Evolution of the weights of female piglets - north side of the facility (stalls 1,3,5,7).

FEMALES: AVERAGE WEIGHTS (Kg) PER WEEK											
Stall in D_0		**Stall in D_7**		**Stall in D_{14}**		**Stall in D_{21}**		**Stall in D_{28}**		**Stall in D_{35}**	
5	4.288A	5	4.78A	5	5.90A	5	7.79A	5	10.07B	5	13.51C
1	4.80A	1	5.45A	1	6.63A	1	8.71A	7	11.71A	1	16.96B
7	5.08A	7	6.04A	3	7.50A	7	9.26A	1	11.81A	3	17.44B
3	5.22A	3	6.06A	7	7.72A	3	10.18A	3	13.42A	7	19.32A

Source: The Author (2020).

Means followed by the same letter in the columns do not differ from each other at 5% probability level by the Scott-Knott test.

Table 6 lists the results for the period from the first (D_0) to the last day (D_{35}) (south side of the facility). The stalls located on the south side of the facility began showing weight gains that differentiated them from the end of the first week (D_7). The similarities did not occur sequentially, but rather alternated between the alignment of the stalls, where the animals in two of these stalls presented lower weight gain.

Table 6 - Evolution of the weights of male piglets - south side of the facility (stalls 2, 4, 6, 8).

MALES: AVERAGE WEIGHTS (kg) PER WEEK											
Stall in D_0		**Stall in D_7**		**Stall in D_{14}**		**Stall in D_{21}**		**Stall in D_{28}**		**Stall in D_{35}**	
2	4.97A	2	5.65B	2	6.85B	2	9.22B	2	12.10C	2	16.00D
6	5.03A	6	5.98B	6	7.71B	6	10.63B	6	14.29B	6	19.01C
4	6.31A	4	7.43A	4	9.78A	4	13.11A	4	17.38A	4	22.32B
8	6.99A	8	8.4A	8	11.00A	8	14.83A	8	19.25A	8	24.95A

Source: The Author (2020).

Means followed by the same letter in the columns do not differ from each other at 5% probability level by the Scott-Knott test.

After five weeks of the time spent in the nursery, the readings from the fourth week (D_{28}) demonstrated the difference between the averages of the female piglets on the north side of the facilities.

In this context, stall 5, containing female piglets, which is located on the north side of the room, maintained its minimum average when compared with the entire lot in the experimental room.

5 CONCLUSION

Based on the results, the studied heating system using the biogas-fueled heat exchanger maintained a satisfactory general average BGHI during winter for the nursery phase.

During the entire study period, the male piglets presented a slightly higher weight gain when compared with females.

The heat supplied by the biogas-fueled heat exchanger system showed good heat distribution within the studied nursery room. However, there was a slight concentration of heat in the nursery room opposite the location where the heat exchanger was installed.

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