MATHEUS CAMPOS MATTIOLI

THERMAL ENVIRONMENT IN DIFFERENT TYPES OF COVERING, LINING AND UNDERCOVERING WITH RECYCLED AND LOW-COST MATERIALS IN REDUCED-SCALE MODELS

LAVRAS-MG
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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, Ambiência e Tratamento de Resíduos, para a obtenção do título de Doutor.

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AMBIENTE TÉRMICO EM DIFERENTES TIPOS DE COBERTURA, FORRO E SUBCOBERTURA COM MATERIAIS RECICLADOS E DE BAIXO CUSTO EM MODELOS EM ESCALA REDUZIDA

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

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LAVRAS-MG
2021

To my parents, João and Elaine, for their support and trust. To my brother, Cristiano, for the example to be followed. To my family, Ana and Maria, who are the reason of my life,
I dedicate

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“One thing is for sure, the more deeply confused you become in your life, the more open your mind becomes to new ideas.”

Neil deGrasse Tyson

GENERAL ABSTRACT

The roof greatly influences the thermal environment of a facility, either by radiating heat to its interior or losing to the external environment. The use of alternative materials and techniques in these structures is a way to integrate affordable materials and, in some cases, to mitigate problems related to the thermal comfort of the occupants and the disposal of waste in the environment. The objective of the present study was to assess the behaviours of different roofs, ceilings, sub-roofs, and reflective paintings in reduced-scale distorted models in summer conditions. The work was divided into two stages. The first one tested the following materials: ceramic tiles, galvanized steel tiles, galvanized steel tiles with Tetra Pak® packaging sub-roof, galvanized steel tiles with Tetra Pak® packaging liner, galvanized steel with thatch grass lining, and galvanized steel tiles with thatch grass sub-roof. In the second stage, the roofs tested were ceramic tiles, aluminium tiles, galvanized steel tiles, corrugated fibre cement roofing tiles, galvanized steel tiles painted white, and corrugated fibre cement tiles painted white. The side faces were closed with aviary tarpaulins, in order to simulate the real conditions of a commercial aviary. Data were collected during the summer, from 9 a.m. to 5 p.m., at 15 minutes of intervals. The measurement instruments used were air temperature, relative humidity, and black globe temperature sensors coupled to a Hobo® U12-013 datalogger, with ± 0.35°C from 0 to 50°C, ± 2.5% relative humidity from 10% to 90% precision; and an Extech hot wire thermoanemometer, model Sdl350, with ± 0.01 ms^{-1} precision. The reuse of Tetra Pak® packaging as a lining or undercoating material resulted in a significant improvement in the thermal comfort indexes. Therefore, the use of alternative materials provided a significant reduction in the heat transfer from the tiles to the interior of the dwelling, showing that they are viable materials in economically vulnerable regions and under conditions of high solar radiation. Using the data collected in the second stage of this study, the black globe humidity index (BGHI), temperature and humidity index (THI), enthalpy (H), and effectiveness (ε) of each roofing material were calculated. The painting of fibre cement tiles white showed the lowest values of the thermal comfort indexes. The galvanized steel tiles painted white did not improve the indexes of the thermal environment. Thermal comfort is achieved by controlling heat fluxes localy or throughout the environment, therefore, we can conclude that the use of alternative materials with properties of thermal isolation like Tetra pak packaging or thatch grass for lining and undercovering improves the heat insulation, in addition, the use of reflective painting on fiber cement tiles can be an option for improving the thermal comfort of buildings.

Keywords: Rural Buildings. Animal Housing Environment. Environmental Indexes. Thermal Comfort Indexes. Shelter Environmental Assessment. Alternative Covering Materials.

RESUMO GERAL

As coberturas influenciam sobremaneira o ambiente térmico de uma instalação, seja irradiando calor para seu interior ou perdendo para o meio externo. A utilização de materiais e técnicas alternativas, nessas estruturas, são uma maneira de integrar materiais acessíveis economicamente, e em alguns casos, ainda, mitigar problemas relacionados ao conforto térmico dos ocupantes e à disposição de resíduos no meio ambiente. Nesse sentido, objetivou-se com o presente trabalho, avaliar as respostas de diferentes coberturas, forro, subcobertura e pintura reflexiva em modelos em escala reduzida e distorcida em condições de verão. O trabalho foi dividido em duas etapas, sendo a primeira constituida pelos seguintes materiais: telhas cerâmicas, telhas de aço galvanizado, telhas de aço galvanizado com subcobertura de embalagens Tetra Pak®, telhas de aço galvanizado com forro de embalagens Tetra Pak®, telhas de aço galvanizado com forro de capim sapé e telhas de aço galvanizado com subcobertura de capim sapé. Na segunda etapa as coberturas testadas foram: telhas cerâmicas francesas; telhas de alumínio; telhas de aço galvanizado; telhas onduladas de fibrocimento; telhas de aço galvanizado pintadas de branco e telhas onduladas de fibrocimento pintadas de branco. Os dados foram coletados durante o verão, das 9 às 17 horas, em intervalos de 15 em 15 minutos. Os instrumentos de medição utilizados foram sensores de temperatura do ar, umidade relativa e temperatura de globo negro acoplados a *Dataloggers* Hobo® modelo U12-013, com precisão ± 0,25 °C e termoanemômetro de fio quente da marca Extech, modelo Sdl350 com precisão de ± 0,01 ms^{-1}. O reaproveitamento de embalagens Tetra Pak®, como material de forro e subcobertura, resultaram em melhora significativa nos índices de conforto térmico. Portanto, a utilização de materiais alternativos proporcionaram redução significativa na transferência de calor das telhas para o interior da habitação, mostrando-se materiais viáveis principalmente em regiões economicamente vulneráveis e em condições de alta radiação solar. Em posse dos dados coletados na segunda etapa deste trabalho, foram calculados o Índice de Temperatura do Globo e Umidade (ITGU), Índice de Temperatura e Umidade (ITU), Entalpia e Efetividade de cada material de cobertura. A cobertura em telhas de fibrocimento pintadas na cor branca apresentou os menores valores para os índices de conforto térmico. Por outro lado, as telhas de aço galvanizado pintadas na cor branca não promoveram melhora nos índices do ambiente térmico. Diante disso, chegou-se à conclusão de que a pintura reflexiva nas telhas de fibrocimento se mostram como uma opção viável para a melhoria do conforto térmico das edificações.

Palavras-chave: Construções Rurais. Índices Ambientais. Conforto Térmico. Refugiados do ambiente. Telhas. Materiais Alternativos.

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SUMMARY

FIRST PART

1 GENERAL INTRODUCTION

The basic function of housing is to protect occupants from adverse weather conditions, especially when it comes to an environment that reaches extreme temperatures (LUCERO-ÁLVAREZ; MARTÍN-DOMÍNGUEZ, 2017). In this sense, constructions that promote environmental comfort for both humans and animals are necessary (when working with zootechnical constructions) (ALMEIDA; PASSINI, 2013).

Historically, man uses materials found in nature to build shelters and protect himself from the elements. In this context, building materials evolved in line with the growing need for greater comfort and higher standards established by man. Thus, materials such as stones, clay, wood, leather, plant fibers, among others, were later replaced by metals and products from industries (SILVA, 2000). However, in developing countries, there is still a need to use economically viable and easily obtainable materials, as the vast majority of the population is in a condition of social vulnerability (ALMEIDA; PASSINI, 2013).

Passive constructive systems aim to guarantee the comfort of life and are part of the technical-cultural heritage of several communities on the African continent. Over the centuries, they have developed low-tech solutions to combat severe weather in these areas (GRIFONI; OTTONE; PRENNA, 2018). The paradigms of current construction techniques often underestimate how ancient populations used local materials, architecture and geography, in order to increase the thermal comfort of their dwellings (MAZZONE, 2020).

The temperature of roofs can reach values from 75 to 80°C on hotter days, in certain regions (LEE et al., 2009). Furthermore, of all the thermal energy present inside a house, the roof can allow the passage of up to 70% of the incident thermal load, especially when there is no lining or the covering material has high emissivity (TINÔCO, 2001).

Thermal comfort can be defined as the mental condition in which the individual expresses satisfaction with the thermal environment. According to ANSI/ASHRAE (2004), people spend most of their time in built environments, in which their residence represents a significant portion of this period. In this context, it is extremely important to promote a comfortable and satisfactory residential environment for the occupants. Thermal discomfort can trigger stress and fatigue conditions as well as allergic symptoms and headaches (CHEN; CHANG, 2012).

On the African continent, for instance, a large portion of the population in some countries is dissatisfied with the thermal comfort of indoor environments, found in 70% of residential buildings, on average, reaching over 90% in certain places (ADAJI et al., 2019). These conditions are, in several cases, linked to the fact that the African continent is composed of developing countries, in which socioeconomic vulnerability makes living conditions inhumane.

A survey carried out in East African countries showed that climate is directly related to conditions of economic vulnerability. In Tanzania, risks associated with food insecurity, poverty and the incidence of disease are correlated with climate behavior, thus resulting in a fragile socioeconomic condition (GEBREYES; THEOBALD, 2018).

Simple alterations to residential buildings can cause a significant change in ambient temperature. According to Onyenokporo & Ochedi (2019), greater roof insulation is an alternative that can be done through the use of a lining. This method is shown to be an effective strategy for improving thermal comfort in homes, especially those used by the portion of the population in a vulnerable situation, in African communities.

Low-income homes in some African countries are usually built with more rustic materials of natural origin, such as cob, clay, acacia and daub (*pau a pique*). In this scenario, a survey carried out in Uganda with this category of residences showed that, among several experimental strategies aimed at improving internal thermal comfort, the one that proved most effective was the use of ceilings (HASHEMI, 2017).

Cabral *et al.* (2017) evaluated the use of ecological ceilings with unconventional materials and demonstrated the high potential of this category of materials due to the significant reduction in temperature provided by them. In this way, researches have been directed in the search for materials that cause less environmental impact and have characteristics of reuse. These products, when they have high reflectivity and insulating characteristics, have the potential to replace conventional materials used in ceilings (BARBIRATO et al., 2015).

In developing countries, the production of urban solid waste is a big problem when these materials are not destined for an environmentally correct purpose. In Brazil, packaging represents about a third of urban solid waste (NEVES; CASTRO, 2012), therefore, measures to reduce the amount of packaging and encourage its recycling should be considered, more specifically, with regard to the use of this material as an insulating agent in roofing. In a study with skimmers for piglets using Tetra Pak® packaging as insulating material, it was found that it has high thermal efficiency when used for this purpose (SARTOR et al., 2015).

In this context, another study investigated the use of Tetra Pak® packaging, or long-life package, as a lining material in its traditional form and also bordering the underside of corrugated fiber-cement sheets, or even as a material for manufacturing the corrugated sheet itself. The research showed interesting results when compared to the thermal performance of conventional tiles (SILVA et al., 2015).

Hahn (1993) emphasizes that trees make the most efficient shades. They provide protection from the sun combined with a beneficial cooling, caused by the evapotranspiration of the leaves. In this aspect, roof structures with tree-like characteristics can constitute an additional thermal barrier to help structures with low thermal inertia, such as metallic tiles, often used in countries with hot climates, which are financially vulnerable.

Air temperature, relative humidity and movement, and radiation are environmental factors that influence environmental thermal comfort. The isolated use of these factors, however, does not allow for an adequate characterization of the thermal environment. Therefore, several authors have proposed the use of environmental thermal indexes to characterize the thermal environment, such as the temperature and humidity index (THI), the black globe humidity index (BGHI) and the radiation heat load (RHL), that combine the effect of two or more factors (JENTZSCH et al., 2011).

In this context, researches have been carried out in order to alleviate the effect of the external temperature of the roofs on the internal environment. Therefore, the present work aimed to test the use of "sapé" grass materials and reused Tetra Pak® boxes, used as lining and undercovering of reduced-scale models, covered with galvanized steel tiles. Furthermore, in addition to assess the influence of different types of covering materials and reflective white paint on the thermal environment inside small-scale aviaries through the use of thermal environment indexes.

2 THEORETICAL FOUNDATIONS

Roofs has the function to protect buildings against the action of bad weather, such as rain, wind, sunlight, snow and also prevent the penetration of dust and noise inside. Thus, for the construction of roofs there are several types of materials, as long as they are impervious to rainwater and resistant to the action of wind and weather (TINÔCO, 2001). Some of the most used materials for roof construction are ceramic tiles, concrete tiles, corrugated fiber cement sheets, zinc-coated or galvanized steel, aluminum, aluminized wood, polyvinyl chloride (PVC) and fiber-glass.

According to Montenegro (1984), pottery or clay baked in ovens is an ancient technique, which emerged before the ancient civilizations of the valleys of the Nile and Euphrates rivers (Egypt and Mesopotamia). Despite its age, this technique is still used today for making ceramic tiles, which, even with the development of new materials, employing more technology and industrialization, are among the most effective in ensuring a thermally comfortable environment. Therefore, this fact reinforces that some techniques and materials, even if of ancient origin, may prove suitable for use in roofing.

Solar radiation is made up of short-wave radiation, which, when incident on the surface of the roof material, heats it up. A portion of this heat is passed to the external environment by convection, while the material that is later transmitted to the internal environment absorbs the other portion. Inside, the heat is transferred from the tiles to the ceiling surface by convection and radiation. The ceiling absorbs part of this heat and retransmits it to the building's internal space (MICHELS; LAMBERTS; GUTHS, 2008).

To reduce heat transfer to the internal space of the residence, it is necessary to use materials that delay the passage of heat flow through the installation by conduction, convection and radiation. This ability to reduce heat exchange is due to the thermal resistance that insulating materials provide, the so-called thermal inertia (AL-HOMOUD, 2005).

2.1 Roofs

One function of housing is to protect human beings against the elements (RASHAD et a., 2021). In this context, architecture and construction should be developed to offer thermal conditions compatible with human thermal comfort inside buildings (FROTA & SHIFFER, 2001). The thermal comfort of the interior of dwellings can be much improved by making roofs with passive construction techniques and using materials, an approach that is based on the use of favourable natural conditions for environmental conditioning. The following are some ways to implement such an approach (TINÔCO, 2001):

- Use of ceilings under the roof: the ceiling acts as a second physical barrier that allows the formation of a mobile air layer next to the roof, which greatly reduces heat transfer to the interior of the building. This reduction is 62% comparing a shelter without a ceiling to a shelter with a simple 6-mm nonventilated wooden ceiling, and 90% in the case of a ceiling with ventilation;
- Paintings with light colours enable high solar reflectivity. Currently, there are reflective paintings that are formulated to repel much of the solar radiation that hits the roof;
- Use of insulating materials: application of low-thermal-conductivity materials under the roof. The insulating materials are porous, and their high thermal resistance is based on the low thermal conductivity of the air. The most effective arrangement is the placement of an insulating liner, which takes advantage of the air layer formed between it and the roof. The other solutions are quite uneconomical for an effectiveness similar to that obtained by the simple roof with adequately ventilated lining;
- Materials with high thermal inertia (caloric capacity): these materials best protect against heat and insolation. Thus, when a roof has a high caloric capacity, the solar radiation that hits it during the day is initially consumed for its heating. At night, when the external temperature is usually lower than during the day, the roof that was initially heated again tends to cool, such that the process of heat transmission through it is greatly reduced.

Among the solutions presented, the most economical and efficient, as seen from the comparative study conducted by Costa (1982), was the use of a mobile air layer next to the roof, which is possible when the ceiling is properly designed. For the production of linings, several materials are efficient. Cravo *et al.* (2015) demonstrated the efficiency of agricultural waste–based composites in ceilings, as they have high thermal insulating potential.

In addition to choosing the most appropriate material, the designer should generally pay attention to the orientation of the constructions. According to Teixeira (1997), this is a factor that, logically, is closely related to the climate and the location of the facilities; therefore, a specific study is needed for each project. The facilities should be oriented in a north–south or east–west direction, according to the best thermal comfort recommendation for each case and depending on the type of installation, structure shape, and local climate (CAMPOS et al., 2012).

For the present study, which involves conditions of economic vulnerability, i.e., populations with difficulty accessing more elaborate construction standards and materials, it is essential that the cost per square metre of the built unit be lower than that of traditional buildings that follow popular standards. To achieve this, one possibility is using alternative materials that are more economically accessible. However, the vast majority of these materials do not have specific technical standards regulating their use, so the researcher must create their own original methodological procedures or adopt, by analogy, the technical standards of conventional materials. Alternative technology, therefore, encompasses the concepts of alternative materials and construction systems and refers, in turn, to the concept of appropriate technology. Not all alternative construction materials are necessarily appropriate, since the adaptation should be aimed at the interest, usually, of people in a vulnerable situation or in a rural environment near less capitalized producers (FREIRE; BERALDO, 2003).

Of the different materials roofs can be made of, the best choice to be used in the project is one whose properties of the material are compatible with the purpose of the building. The material should have the characteristics of a good roofing material, meaning it has mild surface temperatures when subjected to high solar radiation. For this goal, high solar reflectivity combined with high thermal emissivity on the surface and low solar absorptivity combined with low thermal emissivity on the lower part are needed. Some of the materials and their main characteristics are (TINÔCO, 2001):

- Special Styrofoam tiles between two aluminium sheets (sandwich tile): excellent thermal behaviour;
- Wood, plywood, 6 mm thick, corrugated, coated on top with aluminium foil, with durability of approximately 20 years: good thermal behaviour, but expensive;
- Simple aluminium: subject to damage by hail and winds when new, is subject to oxidation over time, thus losing its reflectivity. It can also make much noise, thus generating environmental discomfort in the housing or facility;
- Clay: good thermal behaviour but requiring high-cost crates, has many cracks that act as small air pockets and allow some ventilation, which is desirable for thermal comfort;

- Fibre-cement: unsatisfactory thermal behaviour but easy construction. It improves thermally when painted white, but commercial paints, with an approximate durability of 8 years, are expensive, and homemade paints last less than 1 year;
- Galvanized sheets and galvanized iron have poor thermal behaviour, good durability, and low cost. When new, they are almost as effective in reducing the thermal radiation load as aluminium foil, but with use, they undergo corrosive processes and loses effectiveness much more quickly. They are a type of tile widely used in much of Africa, which is also the object of concern in the present study;
- Sapé has good thermal behaviour due to the air layers formed between the leaves but is susceptible to fire.

2.2 Thermal behaviour of different materials

To ensure better thermal comfort within buildings, it is necessary to research which roofing materials are most suitable. Some authors consider the roof to be the most important building element of a building due to the large area of radiation interception (SAMPAIO et al., 2011). It is on the roof that solar radiation acts with greatest intensity, and the heat flow, when it reaches its peak, can be up to 5 times higher than that present in the internal environment. (NÄÄS, 1989).

In one study, roofs made with ceramic tiles, asbestos cement, and aluminium, a common combination in animal facilities, under winter conditions in the city of Viçosa, Minas Gerais, Brazil, were analysed. In the hours of the most intense cold, all of the covers had global temperature and humidity indexes below the minimum limit of the animal thermal comfort zone and relative humidity above the maximum tolerated. The roofs that best met the thermal comfort needs were those made with ceramic tiles and aluminium (SANTOS et al., 2004).

Roofs covered with asbestos cement tiles provide worse thermal comfort than roofs covered with ceramic tiles because part of the energy that falls on the surface of the ceramic tiles is spent in the process of water evaporation and absorbed during the night due to condensation of water vapour from the air (NÄÄS; MOURA; LAGANA, 1994).

Research has been conducted to find new construction materials. For example, the influence of recycled tiles, based on long-life packaging, on the thermal comfort of zootechnical facilities was evaluated, and their performance was compared with that of ceramic tiles, white ceramic tiles, and fibre cement tiles. The authors considered that recycled tiles can be a roofing option in zootechnical facilities because they have thermal comfort indexes similar to those found in more commonly used materials, such as ceramic tiles, in addition to being a sustainable material (FIORELLI et al., 2009). A similar study compared the thermal behaviour of ceramic tiles, fibre cement tiles, and tiles produced from the recycling of Tetra Pak® packaging. The prototype covered with the recycled tiles had the lowest surface temperature and thus the best thermal performance (HERRERA; VECCHIA; NOLASCO, 2010).

2.3 Thermal environment

An environment can be defined as any condition or influence outside the organism, group, or system under study. It can also be defined as the conditions under which any living being develops, being the total sum of influences that modify or determine the development of life or character (HOLZER, 1997).

From the concept of the environment, definitions of thermal comfort and discomfort can be sought to better understand the other factors involved in this topic. Thermal comfort can be defined as a mental condition that expresses satisfaction with the thermal conditions of the environment (ASHRAE, 2010). More succinctly, it is the full satisfaction of the living being with the thermal environment that surrounds it. In contrast, thermal discomfort is the individual's dissatisfaction with the surrounding thermal environment (OLIVEIRA JÚNIOR et al., 2015). According to ASHRAE (2010), the environment is evaluated subjectively. That is, even if they are in the same environment, different species may experience different sensations, since comfort does not depend only on air temperature. Ruas (1999a) clarifies that well-being is the result of a satisfactory combination, in the environment, between the average radiant temperature, the relative humidity, the air temperature, and the relative air velocity, among other factors.

2.4 Environmental thermal indexes

The need to know the thermal sensations experienced by individuals when exposed to certain combinations of environmental variables led to the development of thermal comfort assessment indexes. The indexes are parameters that represent the combined effect of the main intervening variables. Through them, we can evaluate the thermal comfort situation of an environment, as well as find ways to better adapt them to the needs (RUAS, 1999a).

There are several indexes whose fundamental objective is to determine the suitability of an environment with respect to an activity or a specific type of use (SILVA, 2000). The thermal comfort indexes were developed based on different comfort aspects and can be classified as (FROTA; SCHIFFER, 2001):

- Biophysical indexes: based on the heat exchanges between the body and the environment, correlating the elements of comfort with the heat exchanges that give rise to these elements;
- Physiological indexes: based on the physiological relationships originating from known conditions of air temperature, mean radiant temperature, air humidity, and wind speed;
- Subjective indexes: based on the subjective sensations of comfort experienced under conditions in which the elements of thermal comfort vary.

Some indexes are made both for the evaluation of materials and for the evaluation of the comfort of buildings. These include the temperature and humidity index (THI), the black globe humidity index (BGHI), and the radiant heat load (RHL).

Sampaio *et al.* (2011) considered that there is a tendency to use metal roofs, both for urban areas and for rural facilities, due to their low cost and easy installation. However, metal tiles have higher THI values than clay and fibre cement tiles, especially on warmer days. Black globe temperature (T_{bg}) indicates the combined effect of radiation, absolute air temperature, and, indirectly, wind speed (BOND; KELLY, 1955).

Several indexes have been developed to determine the levels of thermal comfort in the environment, which depend on the interrelationship between several variables, such as temperature, relative humidity, wind speed, and radiation in the environment (KAWABATA; CASTRO; SAVASTANO JÚNIOR, 2005). The more parameters are included in a given index of thermal comfort, the more accurate the evaluation of the environment will be. The most commonly used are:

- Black globe temperature (T_{bg}): found by the black globe thermometer. It indicates the combined effects of radiant energy, temperature, and wind speed (GOMES et al., 2011). It well represents the thermal sensation felt by the animals;
- Air dew-point temperature (T_{dp}): The air dew-point designates the temperature at which the water vapour present in the ambient air becomes liquid in the form of small drops via

condensation. The air dew-point is therefore the temperature at which the relative humidity of the air mass under consideration reaches 100% (MARGARIDO, 2014);

- Air dry-bulb temperature (T_{db}): the air dry-bulb temperature is the common air temperature, which should be measured with common thermometers. In hygrometers and psychrometers, T_{db} is measured by normal thermometers, while the air wet-bulb temperature is measured by a thermometer covered with some piece of wet tissue. Knowing these temperatures, it is possible to calculate the humidity and other psychrometric units of interest (REYES CAC, 2005).

2.5 Variables related to the thermal environment

To determine thermal comfort, it is necessary to understand not only the body heat dissipation mechanisms but also the four environmental factors that allow heat loss: air temperature, relative humidity, wind speed, and temperature radiant medium of the environment (LÓIS, 2001).

Air temperature: The body will give off heat to the environment when the air is cooler than the individual, thus cooling by convection, radiation and conduction occurs. If the air temperature is higher than the body temperature, the air will give heat to the body, requiring the action of the thermoregulatory system (CARVALHO; MICHALOSKI, 2018).

Relative humidity: As low relative humidity allows dry air to absorb moisture from the skin, body heat is rapidly removed. Conversely, high temperature and humidity hinder the evaporation of sweat, slowing the loss of heat to the environment. High temperature combined with high relative humidity thus promotes lower heat dissipation by the body (RUAS, 1999b; CARVALHO; MICHALOSKI, 2018).

Wind speed: It is necessary to know the temperature and relative humidity of the air to analyse the contribution capacity of ventilation to the removal of heat. Under conditions of unsaturated air and a temperature lower than that of the skin, when ventilation increases, there are more evaporation and convection because the body moisture is removed more quickly and the air exchange rate around the body is also higher (RUAS, 1999b).

Mean radiant temperature of the ambient: Radiant energy is emitted continuously by all bodies that are at a temperature higher than absolute zero. This means that if a person or animal in the environment continuously emits and receives radiant energy, the difference between the two energies is what defines whether the body is being heated or cooled by radiation. Thermal radiation does not depend on air or any other medium to propagate, and the amount of radiant energy emitted by a body depends on its surface temperature (RUAS, 1999b).

2.6 Temperature and humidity sensors

According to Valin Júnior *et al.* (2019), field studies aimed at obtaining data on air temperature, relative humidity, precipitation, and radiation, among others, should be done by using specific sensors and equipment to ensure the quality and standardization of these data. Automated systems for temperature control are one way to meet the need to monitor and supervise the functioning of physical systems in a safe, fast, and independent manner (Seo et al., 2009). As shown by Barbosa *et al.* (2008), the emergence of dataloggers, which are thermohygrometric recording and data storage devices, facilitated the measurement processes in the field. Silva and Choque (2017) consider that the automation processes used for the control and supervision of systems have generated significant advances, since remote sensors make it possible to have access to the climatic conditions in real time in a precise manner, enabling the producer to make decisions quickly. The development of these data acquisition systems allows us to receive information generated by the reading of sensors and, from it, generate commands for actuators or transmitting data via communication modules (TORRES et al., 2015).

2.7 Animal thermal comfort

It is extremely important to discern the influences of welfare conditions on animals. In general, each species is better adapted to a particular environment. The climatic conditions of tropical countries, such as Brazil, pose a problem for animal husbandry because these countries have high average temperatures during the year, causing thermal stress (SEVEGNANI; GHELFI FILHO; DA SILVA, 1994).

Heat stress occurs when an animal produces more heat than it can dissipate. Thus, for the animal to adjust to the temperature, it is forced to eat less, so its production necessarily declines. The comfort of the shelter for the animal is necessary to maximize its production;

therefore, this comfort will not be measured in the same way as it is in humans but rather in the form of production and productivity (SEVEGNANI; GHELFI FILHO; DA SILVA, 1994).

According to Tinôco (2001), in the poultry sector, as in other activities, the bird requires ideal conditions of the environment where it lives, such as an air temperature, relative humidity, atmospheric pressure, luminosity, and sound level appropriate for its development. Thermal factors most directly affect birds because they keep the internal body temperature of the animal constant. In situations in which the bird needs to control its internal body temperature, either due to excess heat or to compensate for the cold of the environment, the animal will use them to produce or dissipate heat. When the bird is in full thermal comfort, it does not waste energy; consequently, it is at its maximum productivity level. Outside of this situation, the production will be lower, and its reproduction and resistance functions will be suboptimal, which can lead to critical and even lethal situations (TINÔCO, 2001). Cravo *et al.* (2012), in a literature review, describe studies in which the digestive enzymes of birds, under temperatures of 32 to 35°C, have reduced performance. They showed a delay of 4 to 11 days for slaughter when compared to the results from birds that were in environments with temperatures of approximately 25°C.

When seeking greater efficiency in production, the animal-environment interaction should also be taken into account, as the different responses of the animals to the climatic peculiarities of each region are determinant for the success of the activity. Climatic factors that directly affect thermal exchanges and heat losses to the environment can lead animals to thermal stress. This occurs due to the lack of thermal balance between the animal and the environment, causing serious problems, both in animal production and in reproduction (NAVARINI et al., 2009).

2.8 Roofing alternative materials

For buildings in general, materials are used in the form in which they are found in nature or as the result from processing and transformation. Thus, the materials can be classified as (BERALDO; NAÃS; FREIRE, 1991):

- Natural, used in the form in which they are found in nature, such as sands and boulders;
- Artificial, resulting from an industrial transformation process, such as tiles, bricks, and cement.

Tetra Pak® packaging is used to package consumer products and is mainly used for dairy products, beverages, and processed foods. They are made from three components: 75% paper, 20% plastic (polyethylene), and 5% aluminium (PEDROSO; ZWICKER, 2007). The paper gives the packaging stability and resistance, the polyethylene protects against external moisture, and the aluminium acts as a barrier against the passage of oxygen and light.

One way packaging is recycled is through companies that separate the three components, paper, aluminium, and polyethylene. In this system, electrical energy is used to apply a plasma jet to heat the mixture. The plastic is transformed into paraffin, and the aluminium is recovered in the form of billets, whereas the paper is sold to cellulose companies (MARCHI, 2011).

Another reuse method is to remove only the paper from the packaging using a device called a hydrapulper. The paper can be used to produce cardboard and paper tablets, for example. The aluminium and the plastic are sent to a hot press, where heat is applied to melt the plastic, which functions as a glue that sticks to the aluminium. The resulting material has several applications, such as the manufacture of recycled tiles, ceilings, and furniture (HERRERA; VECCHIA; NOLASCO, 2010).

It was esteemed that approximately 25% of the Tetra Pak® packages produced in Brazil were recycled, totalling approximately 50,000 tons. The worldwide recycling rate was 20% of postconsumer packaging (NEVES, 1999). Aiming to solve the problem of packaging reuse, a study proposed the manufacture of alternative construction materials, such as plates and panels containing packaging waste. The plates were 30% waste residue. Test reports showed that the product had high heat resistance and low water absorption (XIE et al., 2011).

2.9 Painting on roofs

In countries whose climates are equatorial, tropical, desert, or Mediterranean, the summer has high temperatures and intense solar radiation, as in Brazil. The materials to be used in roofs should allow good thermal insulation, minimizing the impact of climatic variations on the internal environment of the facilities (ABREU; ABREU; COSTA, 2001). Shao, Ma and Zhang (2019) found that approximately half of the heat absorbed by the installation came from the roof. Thus, the roof is a relevant element when it is desired to obtain thermal comfort for animals in hot climate regions. Sampaio *et al.* (2011) considered the roof to be the most important building element of a building due to the large area of radiation interception. The roof is the site of the most intense solar radiation, and the heat flow through it, at the peak of heat, is on the order of five times greater than that dispersed in the internal environment (NÄÄS, 1989).

When adequate levels of thermal comfort are desired, it is vital to study the construction materials used in residences and agricultural sheds, as well as to determine the ideal types of roof for these constructions. One solution to improve the thermal comfort of roofs is painting the roofs white (SEVEGNANI; GHELFI FILHO; DA SILVA, 1994). A dark roof can absorb up to 80% of the radiated heat, or even more, making it an aggravating factor for heat retention (PASSINI et al., 2013). Therefore, Sarmento *et al.* (2005) highlight that white paint on the external faces of roofs can decrease the temperature of the internal faces of tiles by up to 9°C, making it a simple and efficient cooling strategy. According to Sevegnani *et al.* (1994), the use of white paint on fibre cement tiles causes a reduction in the amount of heat generated by roof radiation due to the reflection of solar radiation caused by the white colour. This reduction may lower the internal temperatures compared to those recorded for ceramic tiles in natural colour.

2.10 Models of reduced-scale constructions (similitude theory)

Similitude theory aims to make real-world predictions from observations made in a model. Physical models on reduced or distorted scales reproduce a prototype, where scales are used to represent the real size. Four types of models can be considered (MURPHY, 1950):

- True models: those in which all important characteristics are reproduced to scale and meet all design criteria and operating conditions;
- Adequate models: allow an improved prediction of one characteristic, but not necessarily of any others;
- Distorted models: reproductions of real models with the use of two or more scales in their dimensions;
- Dissimilar models: the original and the model have different basic physical qualities, with no similarity between the reduced model and the real model, only an analogy.

For technical reasons, in practice it is typical to work with partial similarity through appropriate models. It is often not possible to accurately reproduce all the physical and geometric details, especially when models with very small scales are used. The full-scale installations have large dimensions, and when doing experiments, there is a need to perform statistical repetitions, which makes their use unfeasible. In addition, the use of models to do research with new materials can contribute significantly to reducing the cost of research and allow the different tests to be done merely by changing a single model. It is possible to predict the environmental thermal conditions of a prototype from physical models built on a scale with up to a 12 times reduction (JENTZSCH et al., 2011).

In modern poultry farming, where the sheds are responsible for the internal microclimate in poultry houses, the rearing environment is extremely important because it is one of the main factors responsible for the loss of animal production on an industrial scale. Thus, it is necessary to know the main risk points for thermal comfort and animal welfare, allowing producers to be supported, making them more efficient and competitive in this activity (SILVA et al., 2015). As put forth by several authors, poultry houses should follow some typological recommendations to provide adequate thermal comfort to broilers. The ridges of the roof of the shed should usually be pointed in the east–west direction. Thus, the trajectory of the sun for most of the year will pass through the sheds, keeping as much radiation as possible out of the facility (TINÔCO, 1996; FURTADO et al., 2005; PAULA et al., 2012).

According to Nääs *et al.* (2001), Furtado *et al.* (2005) and Paula *et al.* (2012), the roof is one of the most important building elements of the facilities and must have roofing materials with high reflectivity and good thermal damping. The eaves of the sheds, located on the north–south faces, should have length between 1.2 and 2.5 meters, as they are responsible for preventing the penetration of rains, winds and solar rays (TINÔCO, 1996). The ceiling height should vary according to the natural ventilation and the amount of desirable solar radiation within the premises. The same can be achieved, according to Tinôco (1996), by a width/height ratio equal to 2.9, but the minimum recommended width/height ratio should be 3 meters (FURTADO et al., 2005; PAULA et al., 2012). Curtains on the sides of the sheds are used to keep rain and sun out of the poultry house, in addition to being fundamental to the control of ventilation and for the productive performance of birds (ABREU et al., 2006).

The length of poultry facilities is often greater than 100 meters, aiming to make management more efficient and increase equipment optimization (FURTADO et al., 2005). The most common widths are 8 to 12 meters, and this dimension has a great influence on the thermal conditioning and the cost of poultry houses (PAULA et al., 2012). Furtado *et al.* (2005) considered that the global trend was to design sheds with widths of 10 to 12 meters and lengths of 100 to 125 meters to optimize the use of automatic equipment such as drinkers and feeders.

As a last typological recommendation, the sheds should be far enough from each other, as it is extremely important that one not act as a natural ventilation barrier for the other. The distances used are at least 30 meters, where the most common are distances are 10 times the height of the construction (FURTADO et al., 2005; PAULA et al., 2012).

To do research on materials used in poultry facilities, it is often necessary to adopt small-scale shed models so that the research becomes economically viable. According to Conceição *et al.* (2008), reduced-scale and distorted models with a large discrepancy between the horizontal and vertical dimensions are adopted to reproduce the actual installations. Thus, the scales used should follow the ratio of 1:2 in the vertical direction and 1:10 in the vertical direction. horizontal. The theory of scale models, proposed by Murphy (1950), where prototypes are used on a small scale, holds that sometimes dimensions are distorted to estimate the physical responses without the limitations caused by the actual size of the facilities. Over the years, these scale models have been used by many researchers to simulate agricultural facilities (SEVEGNANI, 1997).

Small-scale models are used due to the high cost of implementing full-scale prototypes and difficulties with their management in the field. The models can be structured with steel profiles, type “U”, on reduced and distorted scales at proportions of 1:10 horizontally and 1:2 vertically. Also having dimensions of 1.25 m high, 1.20 m wide, and 1.50 m long (SEVEGNANI, 1997; CONCEIÇÃO et al., 2008).

The models can be covered with ceramic tiles having a roof with a 30° slope, while others prototypes can be covered with other roofs having a 15° slope and had 20-cm eaves (SANTOS et al., 2005). The east and west faces of the models are usually completely closed with 1-cm-thick wood plates. The models must be arranged on flat ground, free of shading, oriented in the east–west direction and positioned with a minimum distance of two meters from each other (FONSECA; ALMEIDA; PASSINI, 2011).

2.11 Thermal comfort indexes

From data collected at predetermined times, we can calculated the thermal indexes described below to evaluate the environment inside any habitation or habitat. Despite the existence of more complete indexes, THI is one of the most commonly used indexes, as it needs information normally available in weather stations and databases filled out from satellite images

(OLIVEIRA et al., 2006). According to Kelly and Bond (1971), the THI can be calculated based on the values of Tdb and Tdp according to Equation (1), below:

$$THI = T_{db} + 0.36 \, . \, T_{dp}\text{-}330.08 \tag{1}$$

where:

THI = temperature and humidity index (dimensionless);

T_{db} = air dry-bulb temperature (K);

T_{dp} = air dew-point temperature (K).

The THI was initially developed by Thom (1959) and was calculated from T_{db} and T_{dp}. It was modified by McGregor and Nieuwolt (1998) as a function of air temperature and relative humidity (Equation 2):

$$THI = 0.8 \, . \, T_{db} + \frac{RH \, . \, T_{db}}{500} \tag{2}$$

where:

THI = temperature and humidity index (°C);

T_{db} = air dry-bulb temperature (°C);

RH = relative humidity of the air (%).

Buffington *et al.* (1981) proposed an index that considers in a single value, the effects of air dry-bulb temperature, air humidity, radiation level, and, indirectly, air movement, aiming to be the most accurate indicator of thermal comfort and animal production (SAMPAIO et al., 2004). The mathematical model proposed by Buffington *et al.* (1981) is found in Equation 3:

$$BGHI = T_{bg} + 0.36 \, . \, T_{db} - 330.08 \tag{3}$$

where:

BGHI = black globe humidity index (dimensionless);

T_{bg} = black globe temperature (K);

T_{dp} = air dew-point temperature (K).

The effective temperature index (ETI) (Equation 4) was developed by Missenard (1937) to evaluate internal conditions. The index represents the sensations of a human isolated from the movement of air and solar radiation (OM, 2015).

$$ETI = T_{db} - 0.4 \, . \, (T_{db} - 10) \, . \, (1 - \frac{RH}{100}) \tag{4}$$

where:

T_{db} = air dry-bulb temperature (°C);

RH = air relative humidity (%).

RHL, which can be determined by Equation 5, is another indicator of the thermal environment that, under steady state conditions, expresses the total radiation received by the black globe from all spaces or neighbouring parts. (ESMAY, 1974).

$$\mathrm{RHL} = \sigma\,.\ \mathrm{MRT}^4 \qquad (5)$$

where:

RHL = radiant heat load (W m^{-2});

σ = Stefan-Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-1});

MRT = mean radiant temperature (K).

The mean radiant temperature (MRT), which is part of the RHL, can be expressed by Equation 6 (BOND; KELLY, 1955):

$$\mathrm{MRT} = 100\sqrt[4]{2.51\sqrt{v}\left(T_{bg} - T_{db}\right) + \left(T_{bg}/100\right)^4} \qquad (6)$$

where:

v = wind speed (m s^{-1});

T_{bg} = black globe temperature (K);

T_{db} = air dry-bulb temperature (K).

The wet-bulb globe temperature index (WBGT) is calculated using Equation 7, established by Regulatory Standard number 15 – NR 15 (BRASIL, 2019). This index is suitable for the evaluation of indoor environments without solar charge:

$$\mathrm{WBGT} = 0.7\,.\,T_{db} + 0.3\,.\,T_{bg} \qquad (7)$$

where:

T_{db} = air dry-bulb temperature (°C);

T_{bg} = black globe temperature (°C).

The enthalpy (H) is a psychrometric quantity that indicates the amount of heat present in a given dry air mass and thus can be used to characterize the environmental conditions. Its value is obtained from the air temperature and the mixture ratio between dry and wet air, expressed in kJ kg^{-1} of dry air (CONCEIÇÃO et al., 2008). The enthalpy can be calculated, according to Conceição *et al.* (2008), through Equation 8, which was developed by Albright (1990):

$$\mathrm{H} = 1.006\,.\,T_{db} + W\,.\,(2501 + 1.805\,.\,T_{db}) \qquad (8)$$

where:

H = enthalpy (kJ kg^{-1});

T_{db} = air dry-bulb temperature (°C);

W = mixing ratio (kg water vapour kg dry air $^{-1}$).

The mixing ratio can be calculated by Equation 9:

$$W = \left(\frac{0.622 \ . \ RH \ . \ 0.6108 \ . \ e^{\frac{17.3 \ . \ T_{db}}{237.3 + T_{db}}}}{100 \ . \ P_{atm}} \right) \quad (9)$$

where:

RH = relative humidity (%);

e = Euler’s number;

P_{atm} = atmospheric pressure (kPa).

Effectiveness is a parameter that indicates the ability of each roofing material to provide a better thermal environment. The concept of effectiveness, defined in relation to the RHL or the THI, has been used to classify the diversity of materials used in roofs (SANTOS et al., 2005). According to Moraes (1999), the use of BGHI is better for calculating effectiveness because it is the most commonly used index in the quantification of thermal comfort conditions in zootechnical facilities, so the mathematical model specified in Equation 10 is the most commonly used:

$$\varepsilon = \frac{\text{BGHI (in sun)} - \text{BGHI (tested tile)}}{\text{BGHI (in sun)} - \text{BGHI (aluminium tile)}} \quad (10)$$

where:

ε = effectiveness (dimensionless);

BGHI = black globe humidity index (dimensionless).

2.12 Statistical analysis

Experiments with reduced-scale models can be set up in a randomized in n blocks design with n repetitions (days), in a scheme with split plot design in time. The factors involved can be coverage, scheduled times, lining and any other ones. For the analysis, the averages can be obtained per hour, yielding in n schedules. The data can be subjected to analysis of variance using the F test (0.05). The Scott-Knott test can be applied (0.05) when necessary to separate groups with different means. The normality of the residuals and homogeneity of variances can be verified by the Shapiro-Wilk (0.05) and Bartlett tests (0.05), respectively. All of the analyses can be performed using R software (R CORE TEAM, 2019).

3 GENERAL CONSIDERATIONS

Thermal comfort for humans and animals, promoted by buildings, should be sought from the planning and project stages of the work, ensuring the well-being of the worker and greater productive efficiency of animal husbandry systems. For example, sheds for broiler chickens are highly dependent on energy, either for heating or cooling the environment, allowing the animal to express its full genetic production potential.

Roofing materials should always be empirically examined because, in addition to suffering the action of the weather, they receive solar radiation during most of the day, especially in socioeconomically vulnerable regions. Being one of the main factors responsible for the internal heating of the environment increases the demand for alternative materials and economically viable techniques to replace conventional thermal packaging options. Thus, the use of a lining or sub-covering with high thermal inertia and the painting of roofs with reflective paints are feasible options.

In the specific case of poultry farming, due to the large size of the facilities, the construction of full-scale prototypes is impractical, which often hinders the advancement of research. However, small-scale models have proven useful in these studies, reducing costs and allowing analogies with field conditions.

In this sense, the search for more technically efficient and more accessible materials drives the development of construction materials that provide better conditions to users, especially for roofs.

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SECOND PART - ARTICLES

ARTICLE 1 - SUSTAINABLE LINING AND LOW-COST SUB-COVERINGS FOR HOUSES OF SOCIAL INTEREST

ARTICLE FORMATTED ACCORDING TO THE GUIDELINES OF THE JOURNAL RESOURCES, CONSERVATION AND RECYCLING

ABSTRACT

Alternative roof materials play important role in social-economic vulnerable regions with high solar radiation incidence to provide thermal comfort in dwelling indoors. The objective of the present study was to evaluate the thermal conditions provided by the use of thatch grass and reused Tetra Pak® packaging boxes in liners and sub-covers for small-scale construction models covered with metal tiles. The evaluations were done by means of thermal indexes. Six models were constructed on a distorted scale using the following materials for the roof: ceramic tiles (C_{CT}), galvanized steel tiles (C_{GS}), galvanized steel tiles with Tetra Pak® packaging sub-roof (C_{GS-TPS}), galvanized steel roof tiles with Tetra Pak® packaging liner (C_{GS-TPL}), galvanized steel roof tiles with thatched grass sub-covering (C_{GS-ThS}), and galvanized steel roof tiles with thatched-grass lining (C_{GS-ThL}). Data were collected during the summer, from 9 a.m. to 5 p.m., at 20-min intervals. Air temperature and relative humidity, and black globe temperature were measured through sensors coupled to the Hobo® U12-013 datalogger, with ± 0.25°C precision. Air velocity was measured by Extech hot wire thermoanemometer, model Sdl350, with ± 0.01 ms^{-1} precision. The reuse of Tetra Pak® packaging as a lining and undercoating material resulted in significantly lower thermal comfort index values. We conclude that the use of alternative materials provides a significant reduction in the heat transfer from the tiles to the interior of the dwelling, making them viable materials for economically vulnerable regions with high solar radiation.

Keywords: Coverage. Alternative materials. Thermal comfort. Housing.

1 INTRODUCTION

Thermal comfort can be defined as the mental condition in which a being expresses satisfaction with the thermal environment. According to Carlucci *et al.* (2021), people spend most of their time in built environments, especially their homes. In this context, it is of paramount importance to improve the thermal performance of low-income households, since psychological disorders, allergies, and health problems are more important in environments with higher levels of thermal stress (HADDAD et al., 2019).

On the African continent, for example, some countries have high dissatisfaction with thermal comfort in internal environments, especially in residential buildings. This average level of dissatisfaction reaches 70% and even above 90% in some places (ADAJI et al., 2019). Such environmental conditions are often found in developing countries such as those of Africa where a state of socioeconomic vulnerability prevails. A study conducted in East African countries showed that climate is directly related to vulnerability conditions. In Tanzania, risks associated with food insecurity, poverty, and diseases are correlated with climatic conditions, resulting in a situation of vulnerability of the community (GEBREYES; THEOBALD, 2018).

In other parts of the world we seen the same environmental conditions, as the northeast region of Brazil, that presents extreme temperatures on roof most of year, compromising the health and the socioeconomic situation of the local populations (SANTOS et al., 2019). It is estimated that 1.8 to 4.1 billion people are potentially exposed to thermal stress due to the lack of access to some cooling technology, especially in India, Southeast Asia, and sub-Saharan Africa. It is estimated that more than 1 billion people still do not have access to electricity. The use of passive construction techniques could be feasible within this socioenvironmental context (MASTRUCCI et al., 2019).

Passive construction systems aimed at ensuring the comfort of life are part of the technical-cultural heritage of various communities on the African continent. Over the centuries, these people have developed low-tech solutions to combat the severe climate of these areas (GRIFONI; OTTONE; PRENNA, 2018). The paradigms of current construction techniques often underestimate how ancient populations used local materials, architecture and geography as a way to increase the thermal comfort of their homes (MAZZONE, 2020).

Simple changes in residential buildings can cause a significant change in room temperature. The roof can be insulated through the use of lining. This method has proven to be an effective strategy to improve thermal comfort in economically vulnerable African communities (ONYENOKPORO; OCHEDI, 2019). Low-income dwellings in several African countries are usually made using more rustic and natural materials such as cobs, clay, acacia, and daub (*pau-pique*). A study conducted in Uganda on such dwellings showed that, among several strategies tested, liners were the most effective at improving internal thermal comfort (HASHEMI, 2017).

Materials of natural origin are used in the construction of various types of housing around the world. This is due not only to the culture and tradition passed down through the generations but also because they are more economically accessible materials and, in many cases, efficiently their occupants against the weather, ensuring some comfort to the inhabitant. The use of plant materials in roofs has demonstrated satisfactory thermal performance when compared to materials more commonly used in civil construction (ALMEIDA; PASSINI, 2013).

Tetra Pak® packages are used worldwide to hold perishable foods, allowing the foods to be transported and stored for long times without the need for refrigeration (TEKIN; UCAR; KARAGÖZ, 2019). In 2019, approximately 190 billion Tetra Pak® packages were sold worldwide, but their global recycling rate was only 26% (TETRA PAK, 2020). Recent studies have sought new ways to reuse these solid wastes. Studies evaluating the thermal behaviour of Tetra Pak® packages have shown the high efficiency of this material as a thermal insulator (SARTOR et al., 2015). Seeking to take advantage of this material property, Silva *et al.* (2015) evaluated the reuse of Tetra Pak® packaging as liner material in certain types of roofing. They found an increase in the thermal comfort condition of the evaluated models. Thus, the reuse of Tetra Pak® packaging is an economically accessible option for vulnerable populations living with high levels of thermal stress, and it would have a very low cost of implementation.

In this context, the objective of the present study was to assess the use of alternative materials for communities in vulnerable situations in the form of ceilings and sub-roofs of physical models constructed on a small scale. More specifically, the efficiency of these materials in improving the environmental conditions of buildings was analysed.

2 MATERIALS AND METHODS

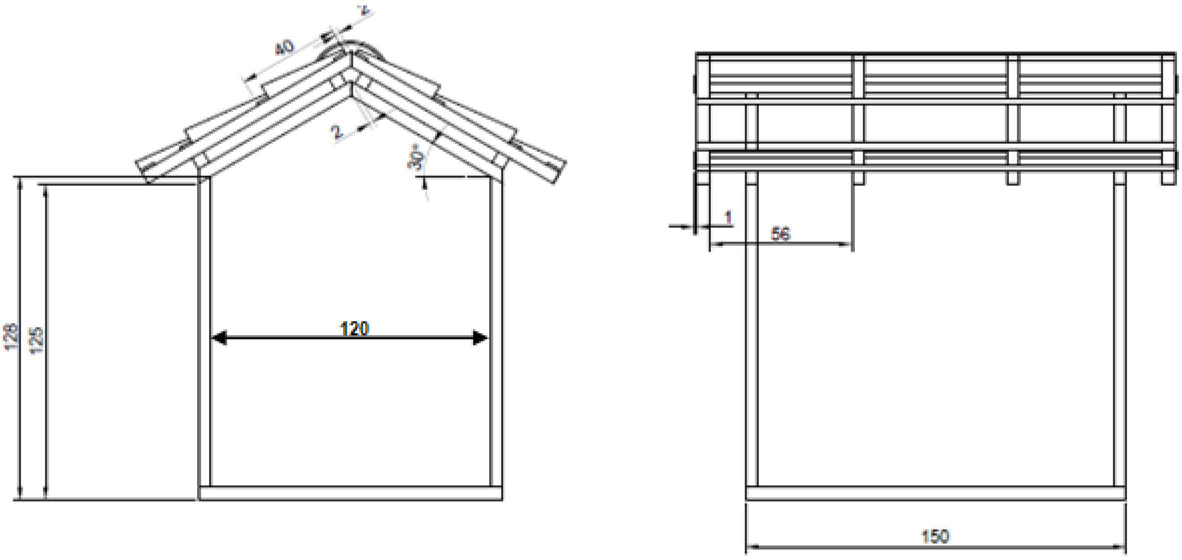
The experiment was conducted in the municipality of Lavras, Minas Gerais, during the summer season of 2017. The municipality is located in the south of the state of Minas Gerais, at the geographical coordinates of 21°14′ S latitude and 45°00′ W longitude, located at 930 m altitude. The climate of the municipality, according to the Köppen climate classification, is of the Cwa type, temperate humid with dry winters (DANTAS et al., 2007).

Small-scale physical models were used due to the high cost of implementing full-scale prototypes and difficulties in their management in the field. The following roofing materials were compared: C_{CT} - roofing with ceramic tiles; C_{GS} - roofing with galvanized steel roof tiles (0.5 mm); $C_{GS\text{-}TPS}$ - roof with galvanized steel roof tiles (0.5 mm), with a sub-roof made of recycled Tetra Pak® packaging, installed against the inner side of the roof tiles; $C_{GS\text{-}TPL}$ - roofing with galvanized steel roof tiles (0.5 mm), with lining made of recycled Tetra Pak® packaging; $C_{GS\text{-}ThL}$ - roof with galvanized steel roof tiles (0.5 mm), with thatched-grass lining against the underside of the roof tiles; $C_{GS\text{-}ThS}$ - roof with galvanized steel roof tiles(0.5 mm), with thatched-grass sub-roof.

Physical models were constructed (Figures 1 and 2) with steel profiles, scaled down to 1:3 in the horizontal direction and 1:3 in the vertical direction. The models were 1.25 m high, 1.20 m wide, and 1.50 m long. It should be emphasized that the only purpose of the physical models was to evaluate the thermal performance of the tile and not the thermal performance of the social housing as a whole. The ceramic tile roof had a slope of 30°, while the others were slopes 15°. All models had 20 cm eaves. The east and west faces of the models were completely closed with 1 cm thick wood plates. The physical models were mounted on flat ground, free of shading, oriented in the east–west direction and positioned at least 2 m from each other to avoid interference between it caused by shading or ventilation (FONSECA; ALMEIDA; PASSINI, 2011).

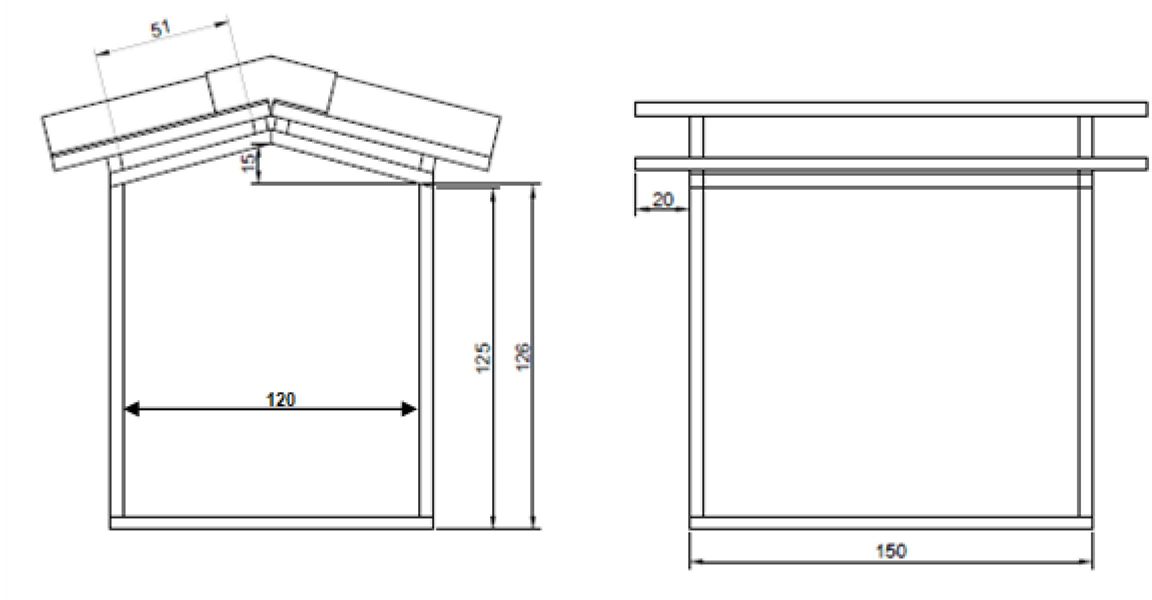
The data were obtained during the summer period, from 9 a.m. to 5 p.m. in 20 minute intervals. The black globe temperature (T_{bg}), air dry-bulb temperature (T_{db}), air dew-point temperature (T_{dp}) and relative humidity (RH) data were acquired through sensors coupled to the Hobo® U12-013, with a temperature accuracy of ± 0.35°C between 0 and 50°C and a relative humidity accuracy of ± 2.5% between 10% and 90%. The wind speed was measured using an Extech digital thermoanemometer, model Sdl350, with a precision of ± 0.01 ms^{-1}, and the measurements were collected near each globe inside the models.

Figure 1 - Cross-sectional views of the cross-sections of the physical model constructed on a small scale for ceramic tile coverage (unit of dimensions: cm).



Source: Author.

Figure 2 - Cross-sectional views of the cross-sections of the physical models constructed on a small scale for the roofs with galvanized steel (unit of the elevations: cm).



Source: Author.

To determine the black globe temperature, black globes externally painted in matte black were calibrated using reference equipment. The sensors were installed at the height corresponding to the geometric centre of each model, approximately 80 cm. As a way to evaluate the environmental thermal conditions provided by each of the roofs, a method also used and recommended by several authors (GUO; BART, 2020; CORDEIRO et al., 2020; MAGALHÃES et al., 2020; MAHGOUB et al., 2020), the following indexes were calculated: temperature and humidity index (THI); wet-bulb globe temperature index (WBGT); effective temperature index (ETI); and radiant heat load (RHL).

The THI was initially developed by Thom (1959) and was calculated from T_{db} and T_{dp}. It was modified by McGregor and Nieuwolt (1998) as a function of air temperature and relative humidity (Equation 2):

$$\mathrm{THI} = 0.8 \cdot \mathrm{T_{db}} + \frac{\mathrm{RH} \cdot \mathrm{T_{db}}}{500} \tag{1}$$

where:

T_{db} = air dry-bulb temperature (°C);

RH = air relative humidity (%);

THI = temperature and humidity index (°C).

The wet-bulb globe temperature index (WBGT) was calculated using Equation 2, established by Occupational Hygiene Standard no. 06 (BRASIL, 2017) in compliance with Regulatory Standard number 15 – NR 15 (BRASIL, 2021) and Occupational Hygiene Standard Number 6 – NHO 06 (BRASIL, 2017). This index is suitable for the evaluation of indoor environments without solar charge:

$$\mathrm{WBGT} = 0.7 \cdot \mathrm{T_{db}} + 0.3 \cdot \mathrm{T_{bg}} \tag{2}$$

where:

T_{db} = air dry-bulb temperature (°C);

T_{bg} = black globe temperature (°C).

The effective temperature index (ETI) (Equation 3) was developed by Missenard (1937) to evaluate internal conditions. The index represents the sensations of a human isolated from the movement of air and solar radiation (OM, 2015).

$$\mathrm{ETI} = \mathrm{T_{db}} - 0.4 \cdot (\mathrm{T_{db}} - 10) \cdot (1 - \mathrm{RH}/100) \tag{3}$$

where:

T_{db} = air dry-bulb temperature (°C);

RH = air relative humidity (%).

Radiant heat load, which can be determined by Equation 4, is another indicator of the thermal environment that, under steady state conditions, expresses the total radiation received by the black globe from all spaces or neighbouring parts (ESMAY, 1974).

$$\text{RHL} = \sigma \,.\, \text{MRT}^4 \tag{4}$$

where:

RHL = radiant heat load (W m^{-2});

σ = Stefan-Boltzmann constant (5.67 . 10^{-8} W m^{-2} K^{-1});

MRT = mean radiant temperature (K).

The mean radiant temperature (MRT), which is part of the RHL, can be expressed by Equation 5 (BOND; KELLY, 1955):

$$\text{MRT} = 100\sqrt[4]{2.51\sqrt{v}\left(T_{bg} - T_{db}\right) + \left(T_{bg}/100\right)^4} \tag{5}$$

where:

v = wind speed (m s^{-1});

T_{bg} = black globe temperature (K);

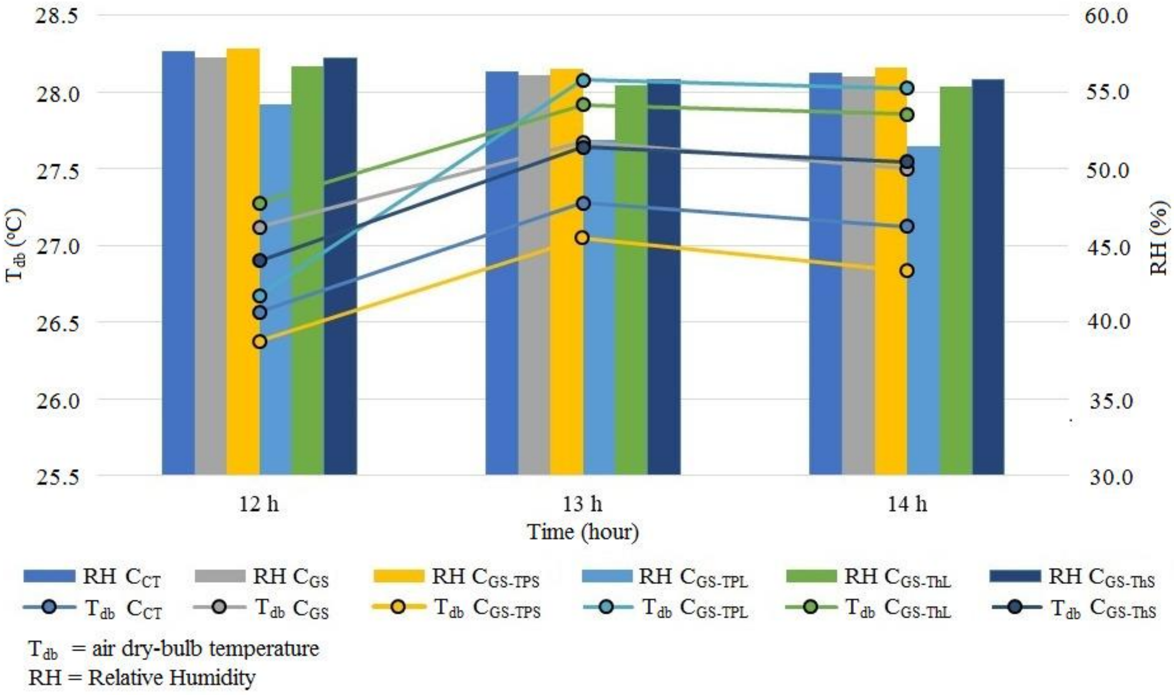
T_{db} = air dry-bulb temperature (K).

The experiment was set up in a randomized block design with 18 replicates (days), in a scheme in split plot design in time, and the factors involved were coverage, with six levels, and timetable, with eight levels. For analysis, the averages per hour were obtained, yielding eight schedules. The data were subjected to analysis of variance using the F test (0.05). The Scott-Knott test was applied (0.05) when necessary to separate groups with different means. The normality of the residuals and homogeneity of variances were verified by the Shapiro-Wilk (0.05) and Bartlett tests (0.05), respectively. The analyses were performed using R software (R CORE TEAM, 2019).

3 RESULTS AND DISCUSSION

The lowest mean temperatures at the hottest part of the day were obtained in the C_{CT} and $C_{GS\text{-}TPS}$ roofs (ceramic tile and galvanized steel tile with Tetra Pak® packaging sub-roof, respectively), highlighting the significant reduction in the internal temperature of the $C_{GS\text{-}TPS}$ model due to the use of Tetra Pak® packaging as a sub-cover (Figure 3). This reduction is probably explained by the highly reflective aluminium foil present on one side of the Tetra Pak® packaging, so the thermal radiation that was emitted by the galvanized steel tile to the interior of the model was reflected back by the layer of packaging positioned along the side of the tile.

Figure 3 - Average air dry-bulb temperature (T_{db}) per hour and mean air relative humidity (RH%) per hour of the roofs: C_{CT} - ceramic tile; C_{GS} - galvanized steel sheet; $C_{GS\text{-}TPS}$ - galvanized steel roof tile with Tetra Pak® packaging sub-roof; $C_{GS\text{-}TPL}$ - galvanized steel roof tile with Tetra Pak® packaging lining; $C_{GS\text{-}ThL}$ - galvanized steel roof tile with a lining of thatched grass; $C_{GS\text{-}ThS}$ - galvanized steel roof tile with thatched grass sub-roof.



Source: Author.

However, the $C_{GS\text{-}TPL}$ coating (galvanized steel with Tetra Pak® packaging liner) showed its worst thermal performance for T_{db} at 1 p.m., the time when the highest mean temperature was recorded. The air relative humidity ranged from 55.4 to 57.8% for the other roofs at the hottest times, with the exception of the $C_{GS\text{-}TPL}$ roof, which showed lower values, ranging from 51.5% to 54.2%.

In the evaluation of the thermal behaviour of a model with a palm straw roof cover, Barnabé *et al.* (2015) observed a delay in the temperature increase inside the prototype in relation to the other roofs evaluated. This behaviour was explained by the fact that part of the energy from the sun is spent on the evaporation of water absorbed by the straw. Straw is an organic and fibrous material that absorbs water resulting from condensation on the surface of the roof during the night.

However, this performance was not observed in the use of thatch grass as a lining or sub-roof, which had temperatures inside the model similar to those of the galvanized steel roof

(C_{GS}). As the thatch was not exposed to direct radiation or moisture, it did not behave as described by Barnabé *et al.* (2015). It was expected that the thatch layer would form an additional barrier to act as an insulator, reducing the temperature inside the physical models. However, probably because the physical models were open, this effect was not as pronounced during the study period.

3.1 THI

As seen in Table 1, the times with the highest mean THI values were noon to 3 p.m., except in the C_{GS-TPL} model, where the highest temperatures were between 1 and 3 p.m. regarding the thermal performance of the roofs. THI differed significantly ($p<0.05$, F test) between the roofs, so the test provided evidence that there was a significant effect of roof within each time period.

Table 1 **-** Average temperature and humidity index (THI)* per hour of each roof: C_{CT} - ceramic tile; C_{GS} - galvanized steel sheet; C_{GS-TPS} - galvanized steel roof tile with Tetra Pak ® packaging sub-roof; C_{GS-TPL} - galvanized steel roof tile with Tetra Pak ® packaging lining; C_{GS-ThL} - galvanized steel roof tile with thatched-grass lining; C_{GS-ThS} - galvanized steel roof tile with thatched-grass sub-roof.

Time (hour)	**Roofs**					
	C_{CT}	C_{GS}	C_{GS-TPS}	C_{GS-TPL}	C_{GS-ThL}	C_{GS-ThS}
9	19.28 bD	20.14 aD	19.62 bD	18.35 cE	19.98aD	19.29 bD
10	21.30 bC	22.07 aC	21.52 bC	20.88 cD	21.93 aC	21.39 bC
11	23.31 bB	23.83 aB	23.34 bB	22.76 cC	23.88 aB	23.43 bB
12	24.29 bA	24.78 aA	24.14 bA	24.20 bB	24.89 aA	24.58 aA
13	24.87 bA	25.22 aA	24.68 bA	25.34 aA	25.41 aA	25.17 aA
14	24.72 bA	25.06 aA	24.48 bA	25.27 aA	25.34 aA	25.08 aA
15	24.32 cA	24.65 bA	24.19 cA	25.06 aA	25.03 aA	24.75 bA
16	23.11 aB	23.25 aB	22.88 aB	23.10 aC	23.45 aB	23.16 aB

*The means followed by the same lowercase letter in each row and the means followed by the same uppercase letter in each column do not differ at the 5% probability level by the Scott–Knott test.
Source: Author.

In the morning, from 9 to 11 a.m., the C_{CT}, C_{GS-TPS}, and C_{GS-ThS} roofs showed statistically equal mean THI values, while the C_{GS-TPL} showed the lowest mean THI value. At noon, treatments C_{CT}, $C_{GS\text{-}TPS}$, and $C_{GS\text{-}TPL}$ began to stand out with the lowest mean THI values, and from 1 p.m. to 2 p.m., only the C_{CT} and $C_{GS\text{-}TPS}$ groups were statistically equal among the lowest mean THI values.

Analysing the times of highest mean THI, noon to 3 p.m., in general the C_{CT} and $C_{GS\text{-}TPS}$ roofs were among those with the lowest mean THI, while the roofs of $C_{GS\text{-}TPL}$ and $C_{GS\text{-}ThL}$ stood out for having the highest mean THI values within this period.

Air dry-bulb temperature increased each day until 1 p.m., while air relative humidity behaved oppositely, reaching its lowest values at the hottest times of the day. This relationship was also observed by Mushore *et al.* (2019) in their work evaluating the thermal comfort conditions of the University of Zimbabwe. Due to the colder conditions where the University of Zimbabwe is located, it was in the summer that the best comfort conditions were obtained during the hottest hours of the day, reaching THI values between 21 and 24°C.

In a study conducted in Malaysia, the effect of urbanization tended to increase the physiological discomfort caused by the increase in air temperature, where THI increased by 0.7°C, probably corresponding to the increase in urbanization (MORRIS et al., 2017). This phenomenon shows that for the C_{GS}, $C_{GS\text{-}TPL}$, $C_{GS\text{-}ThL}$, and $C_{GS\text{-}ThS}$ roofs, which presented mean THI values close to the 26°C limit, effects such as the increase in urbanization may lead these roofs to enter the discomfort scale for 100% of the occupants (Table 2). By the same approach, in a study conducted in Nigeria, the variability of thermal comfort over the years was examined, and it was concluded that developing countries in tropical regions should prepare for a significant increase in the level of stress thermal efficiency due to the increase in urbanization and the warming of the planet (OM, 2015). The author also points out that most developing countries are not prepared for climate change, mainly due to the lack of technology and misallocation of resources.

Table 2 - Comfort conditions in relation to the temperature and humidity index (THI).

THI scale (°C)	Comfort conditions
THI < 15	100% of individuals feel uncomfortable due to cold stress.
15 < THI < 21	50% of individuals feel comfortable and 50% are under cold stress.
21 < THI < 24	100% of individuals feel comfortable.
24 < THI < 26	50% of individuals feel comfortable and 50% are under heat stress.
THI > 26	100% of individuals feel uncomfortable due to heat stress.

Source: Adapted from Polydoros and Cartalis (2015).

The Tetra Pak® packaging sub-covering model ($C_{GS\text{-}TPS}$) yielded significantly lower mean THI values than the galvanized steel (C_{GS}) roof, so new technologies should be studied to find accessible materials and sustainable materials. CARNEIRO *et al.* (2015), evaluated the thermal comfort provided by roofs with recycled tile and green roofs (roofs that allow the growth of vegetation) and obtained reductions in the THI values, which were more significant for the roofs of green roofs, emphasizing the importance of studying alternative technologies to improve the thermal comfort of dwellings.

3.2 WBGT

As seen in Table 3, there was a significant difference between the mean WBGT between the different roofs according to the F test at the 5% probability level.

Table 3 - Average wet-bulb globe temperature index (WBGT)* per hour of each roof: C_{CT} - ceramic tile; C_{GS} - galvanized steel sheet; $C_{GS\text{-}TPS}$ - galvanized steel roof tile with Tetra Pak® packaging sub-roof; $C_{GS\text{-}TPL}$ - galvanized steel roof tile with Tetra Pak® packaging liner; $C_{GS\text{-}ThL}$ - galvanized steel roof tile with thatched-grass sub-roof; $C_{GS\text{-}ThS}$ - galvanized steel roof tile with thatched-grass lining.

Time (hour)	**Roofs**					
	C_{CT}	C_{GS}	$C_{GS\text{-}STP}$	$C_{GS\text{-}FTP}$	$C_{GS\text{-}SS}$	$C_{GS\text{-}FS}$
9	18.37 bD	18.99 aD	18.47 bD	17.67 cD	18.78 aE	18.36 bD
10	20.17 bC	20.79 aC	20.41 bC	19.62 cC	20.67 aD	20.36 bC
11	21.91 aB	22.28 aB	21.83 aB	21.12 bB	22.35 aB	22.09 aB
12	22.54 bA	23.04 aA	22.49 bA	22.10 bA	23.25 aA	23.06 aA
13	22.99 bA	23.35 aA	22.82 bA	22.93 bA	23.67 aA	23.42 aA
14	22.95 bA	23.15 aA	22.44 cA	22.88 bA	23.51 aA	23.24 aA
15	22.27 bB	22.72 aA	22.20 bA	22.73 aA	23.05 aA	22.88 aA
16	21.46 aB	21.49 aB	21.11 bB	20.78 bB	21.51 aC	21.41 aB

* The means followed by the same lowercase letter in each row and the means followed by the same uppercase letter in each column do not differ at the 5% probability level by the Scott–Knott test.
Source: Author.

According to the data presented, the highest mean WBGT values were within the range of noon to 3 p.m. This is when the solar radiation hitting the facilities is usually at its highest.

The C_{CT}, C_{GS-TPS}, and C_{GS-TPL} roofs stood out with the lowest mean WBGT values.

The C_{GS-TPL} roof had the best thermal behaviour, with the lowest mean WBGT value. In addition, at 11 a.m., the C_{GS-TPL} coverage was the only one significantly different from the others, with the lowest mean WBGT value of the schedule, which reinforces the significant improvement provided by the use of the liner with recycled packaging Tetra Pak®. On the other hand, the C_{GS}, C_{GS-ThL}, and C_{GS-ThS} covers had the highest mean WBGT values.

To evaluate the thermal comfort conditions, NR 15 (BRASIL, 2021) and NHO 06 (BRASIL, 2017) (National School of Labour Inspection (ENIT)), which expresses the tolerance limits for exposure, was used to heat the models. The continuous work regime and the classification of the type of activity as heavy were determined to evaluate the comfort conditions based on the WBGT. All roofs fit within the thermal comfort region, with values lower than 25, so all treatments had a thermal condition that would not expose its occupants to thermal stress (Table 4).

Table 4 - Limits of thermal stress according to the wet-bulb globe temperature index (WBGT).

INTERMITTENT WORK REGIME WITH REST IN THE WORKPLACE	**TYPE OF ACTIVITY**		
	LIGHT	**MODERATE**	**HEAVY**
Continuous work	up to 30.0	up to 26.7	up to 25.0
45 minutes of work 15 minutes of rest	30.1 to 30.5	26.8 to 28.0	25.1 to 25.9
30 minutes of work 30 minutes of rest	30.7 to 31.4	28.1 to 29.4	26.0 to 27.9
15 minutes of work 45 minutes of rest	31.5 to 32.2	29.5 to 31.1	28.0 to 30.0
Work is not allowed without the adoption of measures under control	up to 32.2	up to 31.1	up to 30.0

Source: Adapted from Regulatory Standard no. 15 (BRASIL, 2021) and Occupational Hygiene Standard no. 6 (BRASIL, 2017).

In an experiment conducted in poultry facilities by Carvalho *et al.* (2014), in a climate region similar to the present one, WBGT values close to 30 were found, characterizing a situation of discomfort according to NR 15 (BRASIL, 2021; BRASIL, 2017). Contrasting with the values obtained in this study, in which the WBGT value closest to the limit established by the standard was 23.67, in the C_{GS-ThL} group at 1 p.m. According to Carvalho *et al.* (2012), especially for activities in hot environments where the WBGT values reach a thermal overload according to NR 15, attention should be given above all to ergonomic factors, food, and rest periods for the occupants, as these factors can lead to greater physical exhaustion and thus can trigger health problems.

3.3 ETI

The times that showed the highest mean effective temperature index (ETI) values were generally noon to 3 p.m., except in the C_{GS-TPL} group, in which the times with the highest ETI were 1 p.m. to 3 p.m. In the interval from 9 a.m. to 11 a.m., the C_{GS-TPL} group was statistically isolated from the others ($p<0.05$, F test), with the lowest mean ETI values (Table 5). With higher and statistically similar values, the C_{CT}, C_{GS-TPS}, and C_{GS-ThS} groups followed. At noon, the C_{CT}, C_{GS-TPS}, and C_{GS-TPL} roofs had the lowest mean ETI values. However, in the interval from 1 p.m. to 3 p.m., the C_{GS-TPL} roofs ceased to be among the lowest mean ETI groups, and only the C_{CT} and C_{GS-TPS} roofs began to have the lowest values. The C_{GS}, C_{GS-ThL}, and C_{GS-ThS} groups had the highest ETI values.

Table 5 - Mean effective temperature index (ETI)* per hour of the roofs: C_{CT} - ceramic tile; C_{GS} - galvanized steel sheet; C_{GS-TPS} - galvanized steel roof tile with Tetra Pak ® packaging undercoating; C_{GS-TPL} - galvanized steel roof tile with Tetra Pak ® packaging lining; C_{GS-ThL} - galvanized steel roof tile with thatched-grass sub-roof; C_{GS-ThS} - galvanized steel roof tile with thatched-grass lining.

Time (hour)	**Roofs**					
	C_{CT}	C_{GS}	C_{GS-STP}	C_{GS-FTP}	C_{GS-SS}	C_{GS-FS}
9	19.24 bD	20.03 aD	19.55 bD	18.37 cE	19.88 aD	19.24 bD
10	21.08 bC	21.77 aC	21.27 bC	20.65 cD	21.64 aC	21.15 bC
11	22.86 bB	23.33 aB	22.89 bB	22.31 cC	23.37 aB	22.97 bB
12	23.72 bA	24.16 aA	23.58 bA	23.56 bB	24.25 aA	23.97 aA
13	24.21 bA	24.53 aA	24.04 bA	24.53 aA	24.69 aA	24.47 aA
14	24.07 bA	24.38 aA	23.86 bA	24.44 aA	24.62 aA	24.39 aA
15	23.71 bA	24.01 aA	23.60 bA	24.25 aA	24.33 aA	24.08 aA
16	22.69 aB	22.79 aB	22.46 aB	22.57 aC	22.96 aB	22.69 aB

*The means followed by the same lowercase letter in each row and the means followed by the same uppercase letter in each column do not differ at the 5% probability level by the Scott–Knott test.

Source: Author.

According to values proposed by Santos, Amorim, and Cavalcante (2014) (Table 6), all treatments showed mean ETI values at all times below the comfort limit in relation to heat, thus ensuring a thermally comfortable environment. In a study conducted in Cairo, Egypt, a significant impact of urban growth on the microclimate of developing cities was demonstrated through ETI evaluation, revealing several heat stress zones in the urban perimeter (MAHMOUD; GAN, 2018).

Table 6 - Limits for thermal comfort according to the effective temperature index (ETI).

ETI (°C)	**THERMAL SENSATION**
ETI < 25	Limit for comfort with relation to heat
25 ≤ ETI ≤ 29.2	Feeling of moderate heat

Source: Adapted from Santos, Amorim and Cavalcante (2014).

A survey conducted in the tropical region of Africa concluded that countries in this region should be well prepared for the future increases in thermal stress is recommended because, in certain regions, ETI values of 26.1°C are already reached, which characterize a situation of thermal discomfort, which should even intensify in the coming years. In addition to the increase in thermal stress, there is evidence that the increase in temperature in different cities around the world is significantly associated with increased mortality and morbidity (OSTRO; RAUCH; GREEN, 2011). Coelho, Gonçalves, and Latorre (2010) show that in developing countries, there is a correlation between ETI and human health. Under certain environmental conditions, ETI is also correlated with several groups of diseases. Therefore, it is of utmost importance to adopt construction techniques that make it easier to achieve thermally comfortable environments to ensure the health of their occupants.

As observed for the C_{GS} roof, in which the use of the ceiling or sub-roof was not applied, at the hottest times of day the average ETI was close to the comfort limit proposed by Santos, Amorim, and Cavalcante (2014). It can therefore be concluded that in places or times where it is warmer that it was in this study, coupled with the increase in global temperature, the use of ceilings is a viable alternative for reducing the internal temperature of buildings.

3.4 RHL

The average daily RHL results, listed in Table 7, show a significant difference ($p<0.05$) by covering and study time. In the period from 11 a.m. to 3 p.m., the highest mean RHL values were observed in the $C_{GS\text{-}ThL}$ and $C_{GS\text{-}ThS}$ groups. Conversely, with the C_{CT} roof, the highest mean RHL values were only between 1 p.m. and 2 p.m. In the $C_{GS\text{-}ThL}$ group, the highest RHL interval was from noon to 3 p.m. Analysing different types of coverage, Akamine and Passini (2017) also saw higher RHL values at 1 p.m., which according to the authors is explained by the high incidence of solar radiation during this time.

Table 7 - Average radiant heat load (RHL)* per hour of the roofs: C_{CT} - ceramic tile; C_{GS} - galvanized steel sheet; $C_{GS\text{-}TPS}$ - galvanized steel roof tile with Tetra Pak® packaging undercoating; $C_{GS\text{-}TPL}$ - galvanized steel roof tile with Tetra Pak® packaging liner; $C_{GS\text{-}ThL}$ - galvanized steel roof tile with thatched-grass sub-roof; $C_{GS\text{-}ThS}$ - galvanized steel roof tile with thatched-grass lining.

Time	**Roofs**					
(hour)	C_{CT}	C_{GS}	$C_{GS\text{-}STP}$	$C_{GS\text{-}FTP}$	$C_{GS\text{-}SS}$	$C_{GS\text{-}FS}$
9	434.34 aD	437.84 aC	432.59 aC	432.38 aC	432.24 aD	433.82 aC
10	448.50 aC	452.62 aB	448.97 aB	447.39 aB	450.14 aC	450.89 aB
11	463.90 aB	464.56 aA	461.69 aA	459.24 aA	466.33 aB	465.19 aA
12	466.78 bB	470.93 aA	466.63 bA	465.44 bA	474.79 aA	472.99 aA
13	471.28 bA	473.65 bA	469.44 bA	471.77 bA	479.49 aA	476.48 aA
14	474.27 aA	471.75 aA	465.96 bA	468.29 bA	477.80 aA	474.19 aA
15	462.84 bB	467.29 bA	462.84 bA	465.55 bA	474.29 aA	470.69 Aa
16	459.81 aB	456.17 aB	453.44 bB	451.86 bB	460.74 aB	456.89 aB

*The means followed by the same lowercase letter in each row and the means followed by the same uppercase letter in each column do not differ at the 5% probability level by the Scott–Knott test.
Source: Author.

In the morning, between 9 to 11 a.m., there was no significant difference between the mean RHL of the roofs ($p<0.05$). At noon, the C_{CT}, $C_{GS\text{-}TPS}$, and $C_{GS\text{-}TPL}$ roofs began to stand out for their lower mean RHL values. At 1:00 p.m. and 3:00 p.m., the C_{CT}, C_{GS}, $C_{GS\text{-}TPS}$, and $C_{GS\text{-}TPL}$ roofs had the lowest values, whereas at 2 and 4 p.m., only the $C_{GS\text{-}TPS}$ and $C_{GS\text{-}TPL}$ roofs had the highest values because they had a lower thermal load. Thus, the treatments $C_{GS\text{-}TPS}$ and $C_{GS\text{-}TPL}$, with sub-roofs and liners of Tetra Pak® packaging, presented the best (lowest) RHL values, especially at times of higher temperatures, thus demonstrating greater thermal efficiency. In contrast, the $C_{GS\text{-}ThL}$ and $C_{GS\text{-}ThS}$ groups, with sub-roofs and liners of thatched grass, showed the worst thermal performance, with the highest RHL values at all times analysed.

Note that the use of Tetra Pak® packaging resulted in a significant decrease in the thermal load in the models. This improvement was also observed in a similar experiment conducted by Silva *et al.* (2015), in which the use of Tetra Pak® packaging as a lining of roofs made of asbestos cement resulted in a lower RHL of the internal environment of the model.

Taking as reference the RHL 498.3 of W m^{-2} indicated by Rosa (1984) for ceramic roofing, our C_{CT} values were lower than that, even at times of the warmest weather. Sampaio *et al.* (2011) obtained data that corroborate the results presented in this study, namely, a lower RHL with ceramic tile roofing than metal tile roofing, whose RHL ranged from 406.7 to 479.2 W m^{-2} and from 406.2 to 518.3 W m^{-2}, respectively. These findings support the use of ceilings, since in the $C_{GS\text{-}TPS}$ and $C_{GS\text{-}TPL}$ groups, with the use of Tetra Pak® material, RHL values were obtained that were close to and, at certain times, lower than those of the C_{CT} roof.

4 CONCLUSION

The use of alternative materials such as reused Tetra Pak® packaging has promising insulating characteristics that justify its use in low-cost buildings. The use of packaging as lining or sub-roof provided a considerable reduction in the heat transfer from the tiles to the interior of the facilities, especially under conditions of high solar radiation, thus increasing the thermal comfort of the environment. Likely due to the fully open configuration of the models used in the experiment, no significant improvements in thermal comfort were detected inside the facilities that had thatched grass as lining and sub-lining materials.

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ARTICLE 2 – THERMAL PERFORMANCE PROVIDED BY DIFFERENT COVER MATERIALS IN AVIARY MODELS

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ABSTRACT

Covers are determinant elements for the thermal comfort of a facility and absorb up to 80% of the heat radiated in buildings. Nonconventional alternative materials and techniques can be used in these structures to integrate economically accessible materials and contribute to environmental conservation. The objective of this study was to compare the thermal conditions provided by different cover materials and to analyse the application of white reflective paint in small-scale building models through thermal indexes. For this purpose, six small- and distorted-scale models were constructed with Ceramic tiles (T_{CE}), aluminium tiles (T_{AL}), galvanized steel tiles (T_{GS}), corrugated fibre cement tiles (T_{FC}), galvanized steel tiles painted white (T_{GSPW}), and corrugated fibre cement tiles painted white (T_{FCPW}). The experiment was conducted in the vicinity of the Engineering Department of the Federal University of Lavras (UFLA). Data were collected during January and February of 2019, from 9 a.m. to 5 p.m., at 15-minute intervals. Based on the calculations, the days on which the greatest enthalpy occurred were selected for a total of nine non-consecutive days. Based on the selection, the black globe humidity index (BGHI), the temperature and humidity index (THI) and the effectiveness of each cover were analysed. The cover with corrugated fibre cement tiles painted in reflective white showed the lowest values for the thermal comfort indexes. In turn, the galvanized steel tiles painted white did not improve the thermal comfort indexes. By considering the enthalpy values, the cover with galvanized steel tiles was shown to produce a greater thermal amplitude, which compromises the performance of the birds.

Keywords: Thermal environment indexes. Thermal comfort. Tiles. Cover material. Rural buildings. Reflective paint.

INTRODUCTION

In 2020, Brazil exported approximately 4 million tons of chicken meat to more than 140 countries worldwide, though only six of those countries accounted for almost 60% of all exports. These numbers rank the country as the top chicken meat exporter in the world. In terms of poultry production, Brazil produces approximately 14 million tons of meat, ranking it third behind only the United States and China (USDA, 2020).

In recent years, poultry farming has been widespread due to the great dynamism of the chicken industry in Brazil, which receives constant investments to support innovation and research into new concepts and rearing systems. Research efforts aim to improve industrial production because increases in the stocking density change the environment inside production facilities, which endangers animal development, production efficiency, and animal welfare (AKAMINE; PASSINI, 2017).

The high density of birds within the same system of poultry house (above 30 kg m^{-2} or 19 birds m^{-2}), combined with high temperatures and intense solar radiation in Brazil during the summer, directly influence the thermal comfort of chickens. The lack of animal welfare is an important factor in terms of performance and production (OLIVEIRA JÚNIOR et al., 2015). Thus, facilities should provide thermal comfort according to each of the life stages of the birds and an adequate thermal environment inside the poultry house. By doing so, the animals are able to express their full genetic production potential (STAUB et al., 2016).

In modern poultry farming, the design of poultry houses is responsible for the internal microclimate, and the lack of an adequate thermal environment during rearing is one of the main factors that affects animal production losses on an industrial scale. Understanding the main factors that affect thermal comfort and animal welfare enables producers to become more efficient and competitive (SILVA et al., 2015).

Because most sheds are east-west oriented, cover materials are among the most important factors that affect the building environment because they receive solar radiation throughout the day. This radiation can lead to a considerable increase in the internal temperature of poultry houses, which occurs due to heat transfer from the heated external surface of the cover to the internal environment when the cover material does not have the desirable thermal characteristics (VALADARES et al., 2018).

The cover can absorb up to 80% of the heat irradiated by the sun. In covers with darker tiles, this value may be even higher, which makes it an aggravating factor for heat retention. One of the ways to reduce heat transfer to the internal environment is by using white paint on the tiles, which improves thermal comfort indexes by reflecting solar rays and reducing their absorption (PASSINI et al., 2013).

Valin Júnior *et al.* (2019) stated that data such as the air temperature and relative humidity, rainfall, and radiation should be collected with specific sensors and equipment to ensure its quality and standardization. As shown by Silva and Choque (2017), the automation processes used for systems control and supervision have generated significant advances because climatic conditions can be determined in real time using remote sensors.

Studies have been conducted to mitigate the effect of the external temperature of covers on the internal environment. The objective of the present study was to evaluate the influence of different types of cover materials and the use of reflective white paint on the upper part of buildings on the thermal environment inside small-scale poultry houses based on thermal comfort indexes.

MATERIALS AND METHODS

The study was carried out in the Southern microregion of Minas Gerais state (21º14' south latitude and 45º00' longitude and an altitude of 918 meters). According to the Köppen climate classification, the climate of the region is classified as Cwa, mesothermal, with dry winters, rainy summers, and temperatures in the hottest month of higher than 22°C (DANTAS et al., 2007).

Six physical models were used on a reduced and distorted scale, with proportions of 1:2 in the vertical direction and 1:10 in the horizontal direction. The models were built with a ceiling height of 1.25 m, a width of 1.20, and a length of 1.50 m. These proportions were used because the physical space for the tests was limited. The models were covered with different types of tiles, namely, ceramic tiles (T_{CE}), aluminium tiles (T_{AL}), galvanized steel tiles (T_{GS}), fibre cement tiles (T_{FC}), galvanized steel tiles painted white (T_{GSPW}), and fibre cement tiles painted white (T_{FCPW}).

The structure of the models was made from steel profiles with 0.20-m-long eaves, and the east and west faces were completely closed with 0.01-m-thick wood. The north and south side closings were made with waterproof blue/grey tarpaulin, with the blue side facing the outside of the model. The T_{GSPW} and T_{FCPW} tiles were painted with waterproof plastic paint that is resistant to ultraviolet rays, rain, and low temperatures, is a liquid membrane type, and is suitable for covers.

The physical models were arranged on flat terrain, with their ridges oriented in the east-west direction where they were free of shading and spaced at least 2.00 m apart to avoid interference due to shading or ventilation (Figure 1). In all, seven dataloggers were used for data collection, one for each physical model covered with different tiles and one exposed to full sun conditions.

Figure 1 - Arrangement of the models on a reduced and distorted scale.

Source: Author.

Data were collected in January and February (summer) of 2019, from 9:00 a.m. to 5:00 p.m., at 15-minute intervals. The sensors were installed in the geometric centre of the models. The days on which the greatest enthalpy occurred were selected based on the calculations, for a total of nine non-consecutive days.

The temperature and humidity indexes (THI), the black globe humidity index (BGHI), enthalpy index (H) and the effectiveness (ε) as well as the methodology recommended by several authors were used to analyse the thermal environment inside the physical models (DA SILVA et al., 2019; FOŘT et al., 2020; MAGALHÃES et al., 2020; MUSHORE et al., 2019).

According to Kelly and Bond (1971), the THI can be calculated based on the values of T_{db} and T_{dp} according to Equation (1), below:

$$\mathrm{THI} = T_{db} + 0.36 \cdot T_{dp} - 330.08 \tag{1}$$

where:

THI = temperature and humidity index (dimensionless);

T_{db} = air dry-bulb temperature (K);

T_{dp} = air dew-point temperature (K).

The mathematical model proposed by Buffington *et al.* (1981) for the BGHI is found in Equation 2:

$$\mathrm{BGHI} = T_{bg} + 0.36 \,.\, T_{dp} - 330.08 \tag{2}$$

where:

BGHI = black globe humidity index (dimensionless);

T_{bg} = black globe temperature (K);

T_{dp} = air dew-point temperature (K).

The enthalpy (H) is a psychrometric quantity that indicates the amount of heat present in a given dry air mass and thus can be used to characterize the environmental conditions. Its value is obtained from the air temperature and the mixture ratio between dry and wet air, expressed in kJ kg^{-1} of dry air (CONCEIÇÃO et al., 2008). The enthalpy can be calculated, according to Conceição *et al.* (2008), through Equation (3), which was developed by Albright (1990):

$$H = 1.006 \cdot T_{db} + W \cdot (2501 + 1.805 \times T_{db}) \tag{3}$$

where:

H = enthalpy (kJ kg^{-1});

T_{db} = air dry-bulb temperature (°C);

W = mixing ratio (kg water vapour kg dry air $^{-1}$).

The mixing ratio can be calculated by Equation 4:

$$W = \left(\frac{0.622 \ . \ RH \ . \ 0.6108 \ . \ e^{\frac{17.3 \ . \ T_{db}}{237.3 + T_{db}}}}{100 \ . \ P_{atm}} \right) \tag{4}$$

where:

RH = air relative humidity (%);

e = Euler's number;

P_{atm} = atmospheric pressure (kPa).

Effectiveness (ε) is a parameter that indicates the ability of each roofing material to provide a better thermal environment. The concept of effectiveness, defined in relation to the RHL or the BGHI, has been used to classify the diversity of materials used in roofs (SANTOS et al., 2005). According to Moraes (1999), the use of BGHI is better for calculating effectiveness because it is the most commonly used index in the quantification of thermal comfort conditions in zootechnical facilities, so the mathematical model specified in Equation 5 is the most commonly used:

$$\varepsilon = \frac{\text{BGHI (in sun)} - \text{BGHI (tested tile)}}{\text{BGHI (in sun)} - \text{BGHI (aluminium tile)}} \tag{5}$$

where:

ε = effectiveness (dimensionless);

BGHI = black globe humidity index (dimensionless).

The experiment was planned in a randomized block design (RBD), with nine replicates (days), in a scheme of split plot designed in time. The considered factors included the covers, with six levels, and the time points, with eight levels. It is important to note that the means per hour were obtained for the analysis, for a total of eight time points. The data were subjected to analysis of variance using the F test (0.05). The Scott-Knott test was applied (0.05), when necessary, to separate groups with different means. The normality of the residuals and homogeneity of variances were verified by the Shapiro-Wilk (0.05) and Bartlett tests (0.05), respectively. The analyses were performed using R software (R CORE TEAM, 2019).

RESULTS AND DISCUSSION

The interaction between the cover and the time points was significant at the 5% significance level based on the F test for all evaluated indexes, which demonstrates dependence between the two factors. Therefore, Tables 1, 2 and 3 show the values of the daily means per hour of all collection days for the BGHI, THI and H indexes, respectively, from 9:00 to 16:00.

Table 1 shows that the lowest values for the mean BGHI occurred at 9:00 for all covers. The cover with aluminium tiles (T_{AL}) and that with fibre cement tiles (T_{FC}) had similar thermal responses, except in the 16-hour period. There was a significant difference for the cover with galvanized steel tiles (T_{GS}) and that with galvanized steel tiles painted white (T_{GSPW}) during most of the study period, demonstrating the lower absorption of incident solar radiation or the higher thermal inertia of the cover that received a layer of white paint.

Table 1 - Mean* hourly values of the black globe humidity index (BGHI) for all treatments: Cover with ceramic tiles - T_{CE}; Cover with aluminium tiles - T_{AL}; Cover with galvanized steel tiles - T_{GS}; Cover with fibre cement tiles - T_{FC}; Cover with galvanized steel tiles painted white - T_{GSPW}; Cover with fibre cement tiles painted white - T_{FCPW}.

Time (hour)	**Roofs**					
	T_{CE}	**T_{AL}**	**T_{GS}**	**T_{FC}**	**T_{GSPW}**	**T_{FCPW}**
09:00	76.91 cC	77.29 bC	77.76 aC	77.31 bC	77.61 aC	76.34 dC
10:00	79.67 bB	79.82 bB	80.39 aB	79.74 bB	80.30 aB	78.80 cB
11:00	81.73 bA	81.40 cA	81.98 bA	81.37 cA	82.41 aA	80.66 dA
12:00	82.82 bA	82.18 cA	82.73 bA	81.95 cA	83.24 aA	81.47 dA
13:00	83.16 bA	82.48 cA	83.00 bA	82.17 cA	83.63 aA	81.75 dA
14:00	83.55 bA	82.96 cA	83.37 bA	82.79 cA	84.27 aA	82.23 dA
15:00	83.43 bA	82.92 cA	83.09 cA	82.75 cA	84.07 aA	82.02 dA
16:00	81.73 bA	81.46 bA	81.50 bA	81.18 cA	82.24 aA	80.59 dA
Média	81.62	81.31	81.73	81.16	82.22	80.48

*The means followed by the same lowercase letter in the rows and the means followed by the same uppercase letter in the columns do not differ at the 5% probability level based on the Scott–Knott test.
Source: Author.

Table 2 shows that the lowest mean THI values also occurred at 9:00 for all covers. However, the cover with fibre cement tiles painted white (T_{FCPW}) yielded values that were statistically significantly lower than those of the other covers.

Table 2 - Hourly mean values* of the temperature and humidity indexes (THI) for all treatments. Cover with ceramic tiles - T_{CE}; Cover with aluminium tiles - T_{AL}; Cover with galvanized steel tiles - T_{GS}; Cover with fibre cement tiles - T_{FC}; Cover with galvanized steel tiles painted white - T_{GSPW}; Cover with fibre cement tiles painted white - T_{FCPW}.

Time (hour)	Roofs					
	T_{CE}	**T_{AL}**	**T_{GS}**	**T_{FC}**	**T_{GSPW}**	**T_{FCPW}**
09:00	76.70 bC	77.19 aC	77.44 aC	77.12 aC	77.33 aC	76.29 cC
10:00	79.28 bB	79.65 aB	79.92 aB	79.37 bB	79.87 aB	78.52 cB
11:00	81.22 cA	81.14 cA	81.50 bA	80.97 cA	81.93 aA	80.29 dA
12:00	82.20 bA	81.84 bA	82.20 bA	81.50 cA	82.69 aA	80.98 dA
13:00	82.50 bA	82.15 bA	82.47 bA	81.70 cA	83.02 aA	81.19 dA
14:00	82.85 bA	82.65 bA	82.76 bA	82.27 cA	83.60 aA	81.62 dA
15:00	82.76 bA	82.53 bA	82.58 bA	82.29 bA	83.45 aA	81.48 cA
16:00	81.20 bA	80.99 bA	81.25 bA	80.84 bA	81.71 aA	80.19 cA
Média	81.09	81.02	81.27	80.76	81.70	80.07

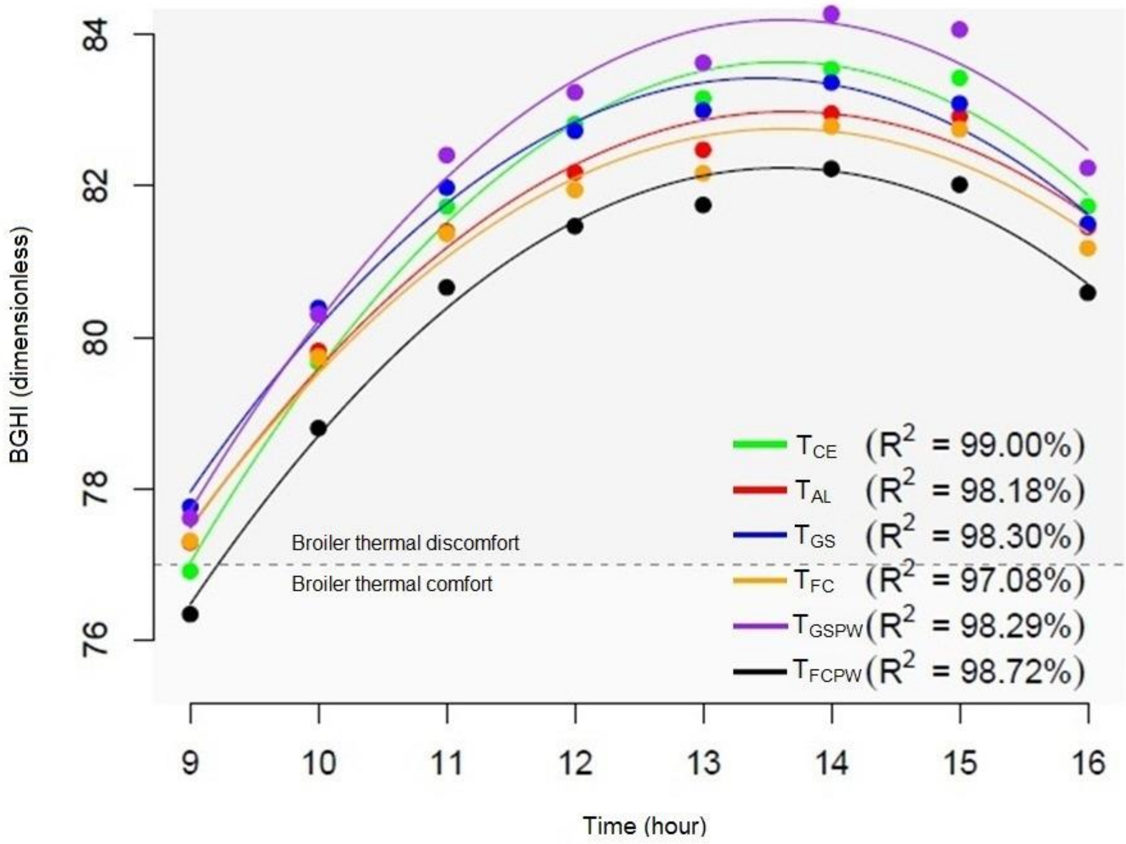
*The means followed by the same lowercase letter in the rows and the means followed by the same uppercase letter in the columns do not differ at the 5% probability level based on the Scott–Knott test.
Source: Author.

According to Figure 2, the cover with fibre cement tiles painted white (T_{FCPW}) showed the lowest BGHI values. On average, the cover with aluminium tiles (T_{AL}) had lower indexes than the cover with ceramic tiles (T_{CE}), notably after 11:00; however, this difference was not significantly different. Similar results were found by Silva *et al.* (2015), who obtained mean BGHI values of 78.44 for aluminium tiles and 78.75 for ceramic tiles.

Figure 2 and Table 1 show that the cover with ceramic tiles (T_{CE}) had higher thermal index values than the cover with corrugated fibre cement tiles (T_{FC}), which has not been reported in other studies, such as those by Rocha *et al.* (2010), Sampaio *et al.* (2011) and Silva *et al.* (2015). This result may have occurred due to a presanitization step that was performed on the tiles used in the T_{FC} cover. All the materials used in this study were in similar conditions of use; however, during cleaning, the texture and colour of the fibre cement tiles changed, and a whitish colour was observed.

Different results were observed for the covers painted white. Painting the galvanized steel tiles white did not reduce the BGHI value. In turn, painting the corrugated fibre cement tiles white improved the environmental conditions, decreasing the BGHI value.

Figure 2 - Mean black globe humidity index (BGHI) for all collection days at each observation time point.



Legend: Cover with ceramic tiles (T_{CE}); Cover with aluminium tiles (T_{AL}); Cover with galvanized steel tiles (T_{GS}); Cover with fibre cement tiles (T_{FC}); Cover with galvanized steel tiles painted white (T_{GSPW}); Cover with fibre cement tiles painted white (T_{FCPW}). The thermal discomfort condition for broilers is above the dashed line, and the thermal comfort condition is below the dashed line (MEDEIROS et al., 2005).
Source: Author.

Figure 2 shows that the cover with galvanized steel tiles painted white (T_{GSPW}) provided greater discomfort than the cover with galvanized steel tiles (T_{GS}), with higher values for the indexes except between 9:00 and 10:00. Sarmento *et al.* (2005) also found that external paint did not substantially decrease the thermal indexes; instead, it only decreased the tile temperature, which alone did not influence the indexes.

The cover with corrugated fibre cement tiles painted white (T_{FCPW}) presented lower values for the indexes and improved the internal environmental conditions compared to the other covers. A similar result was found by Passini *et al.* (2013), who observed a reduction in the BGHI values from 78.0 to 77.5 when fibre cement tiles were painted white.

Furthermore, it can be inferred from the BGHI analyses (Table 1 and Figure 2) that only the T_{EC} and T_{FCPW} treatments were within the thermal comfort limit for birds between 22 and 42 days of age in the first hour of collection – at 9:00. Medeiros *et al.* (2005) reported that birds between 22 and 42 days of age were calm, normally dispersed, and highly productive when the BGHI value varied from 69 to 77.

However, Oliveira *et al.* (2006) worked with birds in the first weeks of life and reported that the ideal BGHI value for poultry production is between 77.0 and 81.3. Figure 2 and Table 1 show that all the covers were within the thermal comfort range at 10:00. However, the covers with fibre cement tiles (T_{FC}) and with fibre cement tiles painted white (T_{FCPW}) were the best options for birds at the beginning of life and were more frequently within the comfort range (10:00, 11:00, and 16:00).

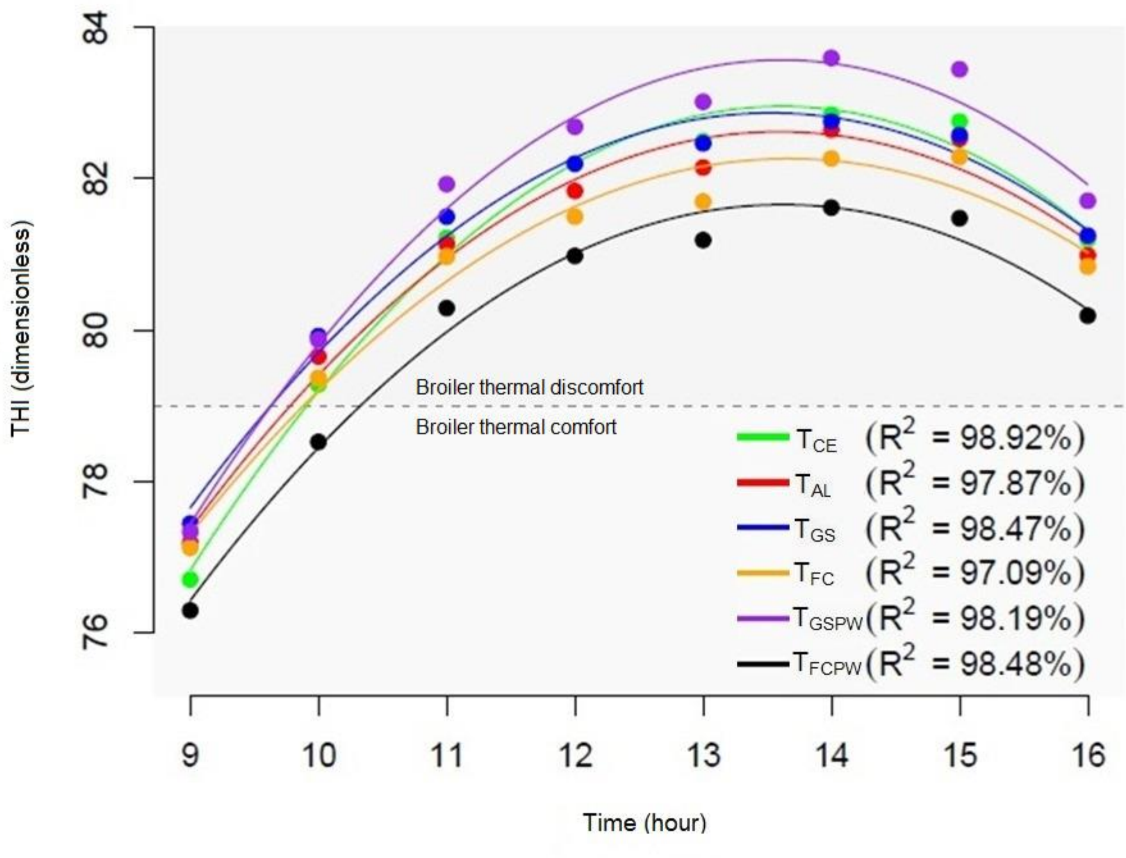
Figure 2 also shows that the maximum BGHI value occurred at 14:00 in all treatments, corroborating the results obtained by researchers such as Jacome *et al.* (2007), Rocha *et al.* (2010), and Passini *et al.* (2013). Figure 2 shows that the value of the index declined after 14:00. Thus, it was inferred that the highest level of thermal discomfort in bird facilities occurs at 14:00.

Although the sensitivity of THI for predicting environmental thermal comfort conditions is lower than that of the BGHI, which is corroborated by other animal environment studies (SANTOS et al., 2005; SAMPAIO et al., 2011), the temperature and humidity indexes were used because the parameters required for their calculation are easier to acquire based on the simplicity of the associated equipment; thus, aviaries can easily acquire the instruments needed to calculate this index.

Table 2 and Figure 3 show that the cover with aluminium tiles (T_{AL}) presented lower but statistically equal values for the temperature and humidity indexes from 11:00 compared to the cover with ceramic tiles (T_T). This result agrees with the findings of Sampaio *et al.* (2011), who observed lower THI values for ceramic tiles. However, Silva *et al.* (2015) found mean values of 77.49 for aluminium tiles and 77.51 for ceramic tiles; these results are similar to the mean THI values of 81.01 and 81.09 for covers with aluminium and ceramic tiles, respectively, found in this study.

Figure 3 also shows that, as observed for the Globe Temperature and Humidity Index, the lowest THI values were found for the cover with corrugated fibre cement tiles (T_{FC}) compared to the cover with ceramic tiles (T_{CE}) starting at 11:00. The opposite results were found by Sampaio *et al.* (2011) and Silva *et al.* (2015); in addition, Fiorelli *et al.* (2009) found that the mean THI on the days analysed was lower for the cover with fibre cement tiles than for the cover with ceramic tiles, in agreement with the results of the present study.

Figure 3 - Mean temperature and humidity index (THI) for all collection days at each time point.



Legend: Cover with ceramic tiles - T_{CE}; Cover with aluminium tiles - T_{AL}; Cover with galvanized steel tiles - T_{GS}; Cover with fibre cement tiles - T_{FC}; Cover with galvanized steel tiles painted white - T_{GSPW}; Cover with fibre cement tiles painted white - T_{FCPW}. The thermal discomfort condition for broilers is above the dashed line, and the thermal comfort condition is below the dashed line (OLIVEIRA et al., 2019; NASCIMENTO et al., 2011).
Source: Author.

The changes in the THI values obtained inside the models with covers of fibre cement tiles painted white (T_{FCPW}) and galvanized steel tiles painted white (T_{GSPW}) were similar to those that occurred for the BGHI values but with different values, as expected. In addition, painting the fibre cement cover yielded lower daily means compared to the daily means for the covers with ceramic tiles; this finding agrees with the results of Conceição *et al.* (2008).

Abreu and Abreu (2011) found that birds in the first week of life are in a thermal comfort condition only from 9:00 to 10:00 for all types of covers. According to the same researchers, the THI values can range from 72.4 to 80.0. Thus, the results of the present study indicate that all covers yielded values for growing birds (regardless of age) above the comfort limits for other time points, provided the same thermal discomfort conditions, and led to a consequent decrease in productivity, which may cause death.

The results in Table 3 are variable, and a lower mean H value at 9:00 was not observed because the mean enthalpy index (H) is characteristically distinct from the other indexes and in this case encompasses RH%. Regardless, there was no significant difference in the covers at this time point, as observed.

Table 2 - Mean* hourly enthalpy (H) values for all treatments. Cover with ceramic tiles - T_{CE}; Cover with aluminium tiles - T_{AL}; Cover with galvanized steel tiles - T_{GS}; Cover with fibre cement tiles - T_{FC}; Cover with galvanized steel tiles painted white - T_{GSPW}; Cover with fibre cement tiles painted white - T_{FCPW}.

Time (hour)	Roofs					
	T_{CE}	**T_{AL}**	**T_{GS}**	**T_{FC}**	**T_{GSPW}**	**T_{FCPW}**
09:00	65.31 aC	65.09 aC	69.20 aA	66.81 aB	66.32 aB	66.54 aA
10:00	71.18 aB	71.51 aB	69.58 aA	72.64 aA	73.05 aA	68.81 aA
11:00	74.58 aA	74.26 aA	64.95 bB	75.29 aA	76.46 aA	66.62 bA
12:00	75.84 aA	75.22 aA	61.63 bB	75.58 aA	76.76 aA	63.88 bB
13:00	75.93 aA	75.17 aA	58.90 bC	75.23 aA	76.22 aA	61.32 bB
14:00	76.16 aA	75.48 aA	54.72 bD	75.35 aA	75.74 aA	56.63 bC
15:00	75.58 aA	74.57 aA	52.93 bD	74.24 aA	74.33 aA	53.54 bC
16:00	72.16 aB	70.57 aB	52.51 bD	69.96 aB	69.85 aB	52.62 bC
Média	73.34	72.73	60.55	73.14	73.59	61.25

*The means followed by the same lowercase letter in the rows and the means followed by the same uppercase letter in the columns do not differ at the 5% probability level based on the Scott–Knott test.
Source: Author.

Table 3 shows the mean enthalpy (H) results of the time points for each cover. The T_{GS} (galvanized steel tile) cover presented the greatest variation in the value of H, at approximately 17.06 kJ kg^{-1}. According to Guimarães *et al.* (2014), environments with very high thermal amplitudes affect the performance of birds because they are forced to adapt to variations in a short period of time, which compromises the maintenance of their physiological indexes. Thus, because the cover with corrugated fibre cement tiles (T_{FC}) showed the smallest variation in amplitude, at approximately 8.77 kJ kg^{-1}, T_{FC} is the cover that least compromises bird performance.

The highest H values for each cover occurred at different time points. The highest enthalpy values for the models covered with ceramic tiles (T_{CE}) and aluminium tiles (T_{AL}) occurred at 14:00 and were considered statistically equal between 11:00 and 15:00. The highest values for the covers with fibre cement tiles (T_{FC}) and galvanized steel tiles painted white (T_{GSPW}) were found at 12:00. The highest values for the models covered with galvanized steel tiles (T_{GS}) and fibre cement tiles painted white (T_{FCPW}) were occasionally observed at 10:00.

The exact highest mean enthalpy was found for the cover with galvanized steel tiles painted white (T_{GSPW}), followed by the cover with ceramic tiles (T_{CE}), corrugated fibre cement tiles (T_{FC}), and aluminium tiles (T_{AL}). The cover with the lowest mean daily enthalpy was the cover with galvanized steel tiles (T_{GS}), followed by the cover with corrugated fibre cement tiles painted white (T_{FCPW}). Consequently, the models with these covers occasionally showed peak values at 10:00.

Barbosa Filho *et al.* (2007) developed enthalpy tables based on the age of a bird to assist in the monitoring of the internal environment of broiler breeding sheds. Following the comfort ranges developed by the researchers, the H values were not in the comfort range for birds during the first week of life in any of the collected time points, and the values ranged from 77.0 to 88.3 kJ kg^{-1}. For the second week of life, the comfort condition ranged from 66.9 to 77.0 kJ kg^{-1}, with T_{CE} (ceramic), T_{AL} (aluminium), T_{FC} (fibre cement) and T_{GSPW} (galvanized steel painted white) in thermal comfort condition from 10:00 to 16:00.

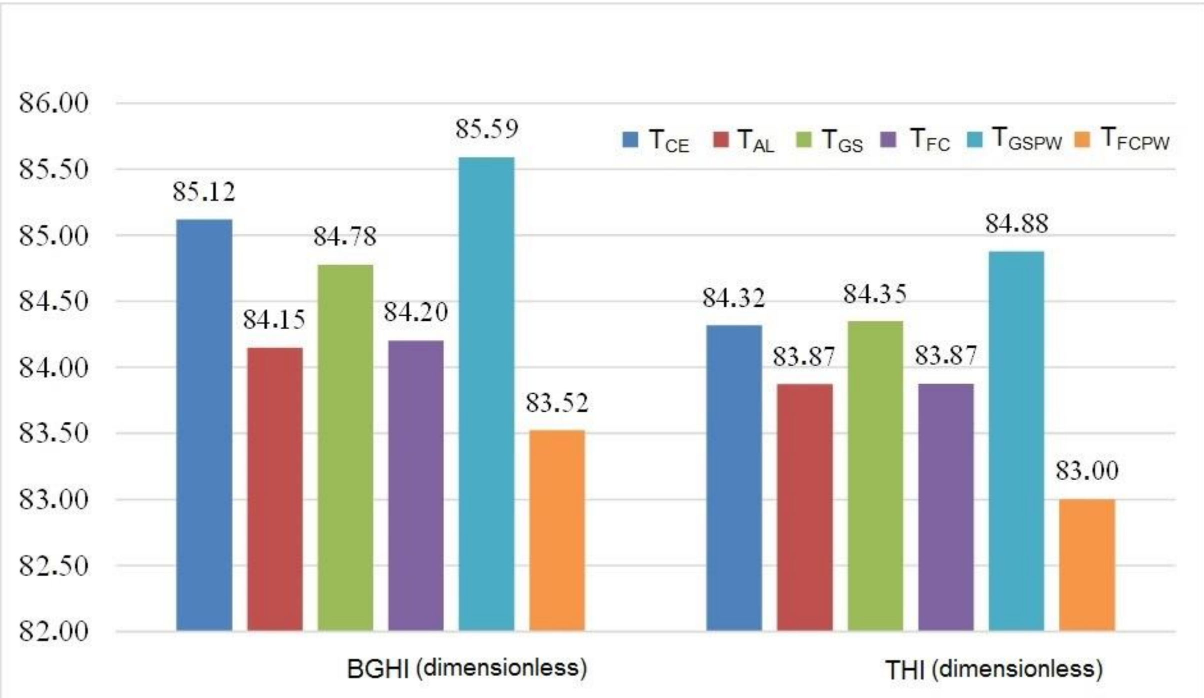
According to the results, the cover with galvanized steel (T_{GS}) showed thermal comfort conditions between 9:00 and 10:00, and the cover with fibre cement tiles painted white (T_{FCPW}) showed thermal comfort conditions only at 10:00. In the third week of life, the comfort condition ranged from 57.7 to 66.9 kJ kg^{-1}, and the covers with ceramic, aluminium, fibre cement, and galvanized steel tiles painted white were within the comfort range only at 9:00. The covers with galvanized steel tiles and fibre cement tiles painted white showed thermal comfort conditions from 11:00 to 13:00. At 14:00 to 16:00, the T_{GS} and T_{FCPW} treatments remained in the thermal comfort range for chickens in the fourth week of life, and the values ranged from 49.5 to 57.7 kJ kg^{-1}; the other covers did not yield comfort conditions for this age.

Chickens in the last two weeks of life would not be under thermal comfort conditions in the facilities analysed.

Regarding the mean value in time, which is also presented in Table 3, the T_{CE}, T_{AL}, T_{FC} and T_{GSPW} covers yielded values within the thermal comfort range of enthalpy for the two-week-old birds. The same behaviour was observed by Akamine and Passini (2017) when analysing prototypes with aluminium tiles, for which the mean enthalpy was 67.11 kJ kg^{-1}. The mean enthalpy for the T_{GS} and T_{FCPW} covers showed thermal comfort conditions only for three-week-old birds; this result agrees with the results of Fonseca *et al.* (2011), who used a prototype with galvanized steel tiles and obtained a mean H value of 66.90 kJ kg^{-1}.

Figure 4 was developed by using the day of highest enthalpy among the nine days when data were collected, and the mean enthalpy was 74.72 kJ kg^{-1}; according to the enthalpy tables reported by Barbosa Filho *et al.* (2007), this value represents an uncomfortable environment for broilers of most ages, except for those that are two weeks old.

Figure 4 - Mean BGHI (Black Globe Humidity Index - dimensionless) and Mean THI (Temperature and Humidity Index - dimensionless) of all treatments for the day of highest enthalpy (H).



Legend: Cover with ceramic tiles (T_{CE}); Cover with aluminium tiles (T_{AL}); Cover with galvanized steel tiles (T_{GS}); Cover with fibre cement tiles (T_{FC}); Cover with galvanized steel tiles painted white (T_{GSPW}); Cover with fibre cement tiles painted white (T_{FCPW}).
Source: Author.

The thermal environment indexes were observed for the day with the highest enthalpy because that day is when the highest temperatures occur, and it is the most critical day in terms of the thermal environment.

Based on a comparison of the BGHI and the THI for the day with the highest enthalpy (Figure 4) and the mean BGHI (Table 1 and Figure 2) and the mean THI (Table 2 and Figure 3), the values obtained for all covers were higher on the day of highest enthalpy, and the variation in the means of the indexes showed a minimum increase of 2.83 in the BGHI for the cover with aluminium tiles (T_{AL}). The other covers showed even greater variations in both indexes, which confirms that the day with the highest enthalpy is related to the day with the greatest thermal discomfort.

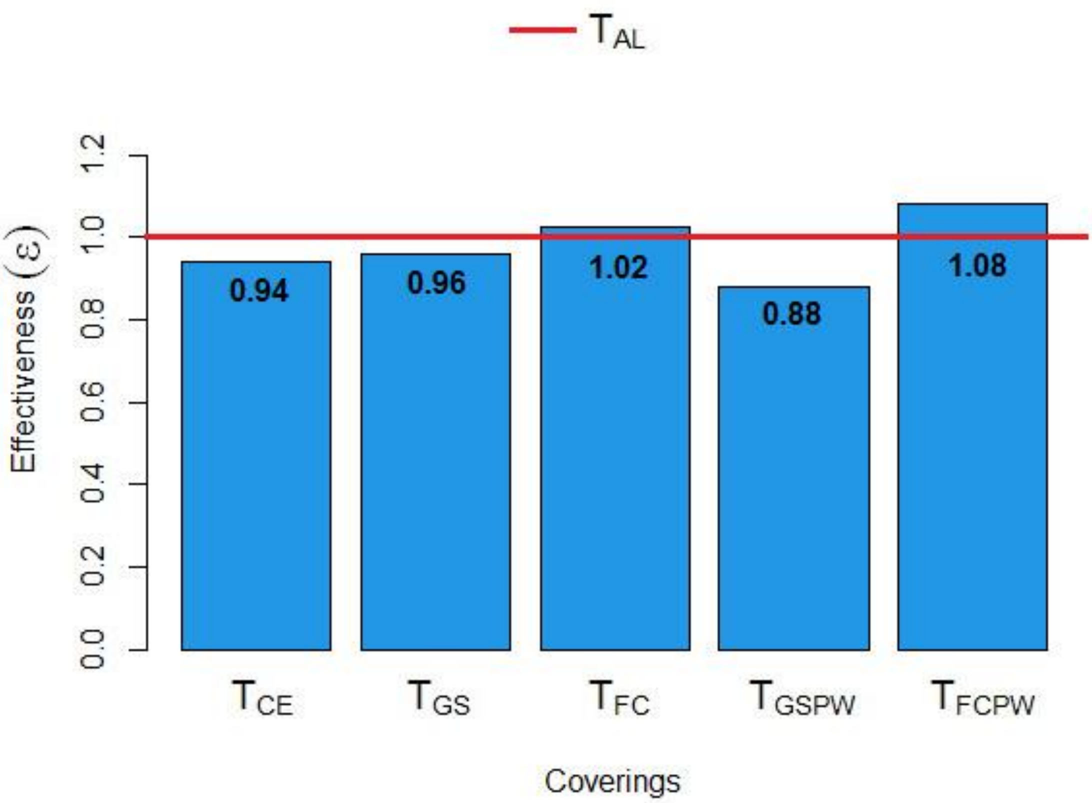
Figure 4 also shows that for both indexes, the most efficient cover in terms of thermal comfort was the one with corrugated fibre cement tiles painted white (T_{FCPW}), and the most uncomfortable cover was the one with galvanized steel tiles painted white (T_{GSPW}).

Figure 5 shows the mean values of thermal effectiveness for all covers, which were determined based on the results of the Globe Temperature and Humidity Index. Unlike what was found for the indexes discussed above, the interaction between the cover and time point factors in terms of effectiveness (ε) was not significant at the 5% probability level based on the "F" test, which confirms that they are independent. However, the analysis of the main effects showed that there was no significant difference at the 5% probability level between the mean effectiveness described in Figure 5, considering the hottest time points (12:00 to 15:00).

As recommended in the effectiveness equation, the cover with aluminium tiles (T_{AL}) was used as a standard and had a mean thermal effectiveness equal to 1.00. Covers with values greater than 1.00 performed better than covers with aluminium tiles, and those with values less than 1.00 performed worse than covers with aluminium tiles (CARDOSO et al., 2011).

Based on Figure 5, the coverings with fibre cement tiles and fibre cement tiles painted white showed greater thermal effectiveness, and the former was 2% more effective than the cover with aluminium tiles, while the latter was 8% more effective than the cover with aluminium tiles. Thus, the T_{FC}, T_{CE} and T_{GSPW}, covers showed 4%, 6% and 12% less thermal inertia effectiveness than the T_{AL} cover, respectively. The T_{GSPW} presents the less effectiveness betwen the others, the opposite of the expected for an external painting white, contrary to related from Michels *et al.* (2021).

Figure 5 – Mean (dimensionless) effectiveness of the covers for the hottest time points (12:00 to 15:00).



Legend: Cover with ceramic tiles – T_{CE}; Cover with aluminium tiles – T_{AL}; Cover with galvanized steel tiles – T_{GS}; Cover with fibre cement tiles – T_{FC}; Cover with galvanized steel tiles painted white – T_{GSPW}; Cover with fibre cement tiles painted white – T_{FCPW}.
Source: Author.

Silva *et al.* (2015) also researched the thermal effectiveness of different cover materials and found that the cover with corrugated fibre cement tiles had the worst thermal effectiveness performance; these results are opposite to those of the present study. However, the cover with ceramic tiles had different characteristics, and results lower than those found for the aluminium tiles were obtained.

Ferreira Júnior *et al.* (2009) found that covers with corrugated fibre cement tiles yielded results that were similar from those found in this study, beeing more effective than covers with aluminium tiles. Santos *et al.* (2005) compared the results obtained for a cover with ceramic tiles and found divergent values to those of this study, and the variation in the cover with ceramic tiles was from 2 to 8% more effective than that of the control treatment.

CONCLUSIONS

By evaluating the Globe Temperature and Humidity Index (THI) and the Temperature and Humidity Index (THI), white reflective paint on corrugated fibre cement tiles was shown to satisfactorily reduce the thermal environmental indexes inside the models when compared to the prototype with corrugated fibre cement tiles without paint. The same cannot be concluded for the galvanized steel tiles, which did not show improvements in the thermal conditions after painting.

The best cover option for thermal comfort was dependent on the age of the birds; however, the cover that yielded values that were more often in the comfort ranges of the thermal indexes was the one with corrugated fibre cement tiles painted white, which confirms the improvement provided by the reflective paint.

By considering the enthalpy values, the cover with galvanized steel tiles was shown to produce a greater thermal amplitude, which compromises the performance of the birds.

Finally, the covers that obtained the highest thermal efficiency were those with fibre cement tiles and fibre cement tiles painted white, which were rated as having a lower performance for the other indexes. In addition, painting the cover with galvanized steel tiles decreased their effectiveness.

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