Review

Not peer-reviewed version

Understanding Compost-Bedded Pack Barn Systems in Tropical Climate Regions: A Review of the Current State-of-the-Art

Rafaella Resende Andrade * , Ilda de Fátima Ferreira Tinôco , Flávio Alves Damasceno , Carlos Eduardo Alves Oliveira , Mariana Silva Concha , Ozana de Fátima Zacaroni , Gianluca Bambi , Matteo Barbari

Posted Date: 28 April 2024

doi: 10.20944/preprints202404.1841.v1

Keywords: animal welfare; dairy cattle; housing systems; compost-bedded pack barns; heat stress doi:10.20944/preprints202404.1841.v1

Review

Understanding Compost-Bedded Pack Barn Systems in Tropical Climate Regions: A Review of the Current State-of-the-Art

Rafaella Resende Andrade [1,*], Ilda de Fátima Ferreira Tinôco [2], Flávio Alves Damasceno [3], Carlos Eduardo Alves Oliveira [2], Mariana Silva Concha [4], Ozana de Fátima Zacaroni [4], Gianluca Bambi [5] and Matteo Barbari [5]

[1] Department of Biosystems Engineering, College of Agronomy, Federal University of Goiás, Goiânia 74690-900, GO, Brazil (R.R.A.)
[2] Department of Agricultural Engineering, Federal University of Viçosa (UFV), Viçosa 36570-900, MG, Brazil; iftinoco@ufv.br (I.F.F.T.); carloseoliveira@ufv.br (C.E.A.O.)
[3] Department of Engineering, Federal University of Lavras (UFLA), Lavras 37200-900, MG, Brazil; flavio.damasceno@ufla.br (F.A.D.)
[4] Department of Animal Science, School of Veterinary and Animal Science, Federal University of Goiás, Goiânia 74690-900, GO, Brazil; marianaconcha@discente.ufg.br (M.S.C); ozacaroni@ufg.br (O.F.Z.)
[5] Department of Agriculture, Food, Environment and Forestry, University of Firenze, 50145 Firenze, Italy; gianluca.bambi@unifi.it (G.B.); matteo.barbari@unifi.it (M.B.)
* Correspondence: rafaella.andrade@ufg.br

Simple Summary: The search for breeding systems that contribute to increases in productivity and milk quality with the meticulous use of resources is one of the main challenges with modern livestock. In this sense, the compost-bedded pack barn (CBP) is a promising alternative for raising dairy cattle. However, answers regarding the applicability of this system to the conditions of tropical and subtropical climates are lacking, focusing on Brazil. The objective of this study was to gather and describe the most recent information on open and closed CBPs for dairy cattle. Properly designed, open CBP facilities with suitably designed ventilation systems and effective bedding management show potential for the climatic conditions and building typologies in Brazil. Most studies on the closed CBP system have provided only preliminary impressions because limited amounts of data have been collected. The first results demonstrate serious challenges with bedding management. The discussed results can be used to guide decision-making processes to create suitable environmental conditions for CBP systems.

Abstract: The main challenge in milk production has been to maintain a focus on efficient processes that enhance production outcomes, while aligning with animal welfare and sustainability and being valued by society. As an alternative to improve cow welfare in production and provide better handling of the waste generated by the activity, the system called compost-bedded pack barn (CBP) is an alternative that has been widely adopted in countries with temperate climates and higher milk production. This CBP has been attracting global interest, including from countries with tropical and subtropical climates, such as Brazil, where many producers have started to use it due to the response in terms of milk productivity. A CBP can be designed either in a) an open facility with natural ventilation or positive pressure ventilation system or b) totally closed facilities, equipped with negative pressure ventilation systems and permanent thermal control. The latter system is being implemented in Brazil, despite insufficient knowledge about its efficiency. The objective of this study was, through a review, to gather and describe the most recent information on the use of open and closed CBP systems for dairy cattle housing, mainly how it is applied in tropical climate regions. To achieve the proposed objective, this review study included the following topics related to CBPs: (i) implementation; (ii) bedding; (iii) general construction and architectural characteristics; iv) ambient thermal conditioning. Knowledge gaps and directions for future research are also identified.

Keywords: animal welfare; dairy cattle; housing systems; compost-bedded pack barns; heat stress

1. Introduction

One of the major concerns in the dairy farming sector worldwide is to alleviate the negative effects of inadequate breeding environments on cows during their lactation period. In addition to the adoption of modern technologies to improve the internal environment of livestock facilities, a demand exists for facilities that ensure the sustainability of animal production, highlighted by the trend of preservation of the environment and animal welfare currently signaled by consumers.

Simultaneously, a search is ongoing for breeding systems that reduce emissions, reuse waste, and ensure efficiency of the return on invested capital [1]. Notably, the livestock sector represents an important source of ammonia emissions, greenhouse gases, and other impacts on the environment [2].

Another challenge in future housing for dairy cows is the creation of projects that resolve conflicts in existing systems, one of which is the amount of surface area required per animal [1]. More space per animal offers the possibility for more natural behavior but tends to increase ammonia emissions per cow due to the larger emission surface per cow [3]. Additionally, when the lay public is introduced to the types of animal management systems, they think that living a natural life is an important part of animal welfare, reflecting their wishes for animals to live in natural environments, with space and the ability to engage in species-specific behaviors [4].

When considering the aforementioned factors, the confinement of dairy cattle in compost-bedded pack barn (CBP) systems has shown promise for dairy farming. The system has been successfully used for several years with dairy cattle in temperate regions [5,6] and, recently, in tropical and subtropical countries, such as Brazil [7,8].

The main reasons that aroused the interest of dairy farmers in the CBP system include to increased comfort, health, and longevity of animals; improved waste management; and ease of completing daily tasks [5]. In this alternative animal husbandry system, the cows remain in an extensive resting area, where they are offered a pasture-like environment in which they may lie down and stand up [9,10]. Producers use the conventional bedding system and incorporate composting methods, through the periodic addition of carbon source material and daily turning of the bedding, promoting the composting of the organic material [6,11].

Most CBP facilities are open on the sides and can be ventilated naturally or with mechanical positive pressure ventilation [8]. Recently, some closed CBP facilities have been built in Brazil, equipped with mechanical negative pressure ventilation systems [12,13]. However, as the adoption of this milk production system technology has expanded in Brazil, concerns have also arisen from producers regarding the real applicability of totally closed facilities for the construction type and climatic conditions present in the country, due to the limited research on this type of system. In view of the above, the objective of this review was, through a review, to gather and describe the most recent information in the literature on the open and closed CBP systems for dairy cattle housing, mainly how it is applied in tropical climate regions. The following topics related to the CBP system were discussed: (i) implementation; (ii) bedding; (iii) general construction and architectural characteristics; iv) ambient thermal conditioning. Knowledge gaps and directions for future research were also identified.

2. Methods

A literature search was conducted using the WoS and ScP database, and all the results returned in the searches were included in the Mendeley® software, from which duplicates were identified and excluded. The search was not limited by the year of publication and all relevant papers were included up to August 2023. Only experimental articles written in English and peer-reviewed were considered. Criteria for inclusion and exclusion of articles were defined a priori.

In order to carry out a more comprehensive study of the available literature in relation to the proposed theme, no additional restrictions, such as publication period, sample size or quality of the journal, were imposed. Microsoft Excel® was used to extract and organize information of interest contained in the selected studies.

3. Compost-Bedded Pack Barn Systems

3.1. Implementation of Compost-Bedded Pack Barn Systems

3.1.1. Globally

With the improvement in loose housing (LH) in the 1980s, the first CBP system reported in the literature was built by dairy farmers in Virginia, USA. Later, in October 2001, in southern Minnesota, USA, producers from that region had the idea of building a different facility, with a new concept and without re-producing any of the intensive milk production systems that had been previously adopted [6].

In Israel, the first CBP system was developed in 2006 and was quickly adopted among dairy farmers, where no organic material is added to the bedding area in the facility, other than cow feces and urine [14]. This method of operating the CBP system in this region was possible due to its arid conditions, where the bed does not require additional material [15].

In the USA, the composting process within CBP was improved by adding sawdust or wood chips as bedding material, which is turned over two or three times a day, enabling aerobic degradation, which results in an increase in the internal temperature of the bed [15]. The increase in bed temperature is important to assist in the composting process, that is, the aerobic degradation of organic material. In Israel, the first CBP system was developed in 2006 and was quickly adopted among dairy farmers, where no organic material is added to the bedding area in the facility, other than cow feces and urine [14]. The bed stirring was mechanized. This method of operating the CBP system in this region was possible due to its arid conditions, where the bed does not require additional material [15].

As described, the concepts of the CBP systems used in the USA and Israel are quite different and have provided a basis for the development of other systems worldwide [1]. Thus, the CBP system has been disseminated to several regions, arousing the interest of several producers, especially in the United States, Canada, New Zealand, Germany, Italy, the Netherlands, Austria, Denmark, and South Korea [11,14,16–18].

Recently, CBP systems have started to be adopted in countries in South America, mainly in Brazil, Argentina, Colombia, Paraguay, and Uruguay, with variations in the characteristics and commonly used construction materials and ventilation systems [18–22]. However, few studies have been conducted regarding its applicability and efficiency for the specific climatic conditions of these countries. Since it is a system that has recently been adopted in these regions.

Differences exist in the models of CBP systems developed around the world. However, no standard solution is available for all agricultural, climatic, economic, and social contexts. The CBP system has the potential to increase animal welfare and longevity and improve soil quality [1].

3.1.2. In Brazil

Facilities located in tropical and subtropical climates face different challenges than those in temperate countries, as they must deal with both high temperature and relative humidity during much of the year [8,23]. The main difficulty experienced by milk producers in these regions is maintaining a monthly high average productivity throughout the year to make production more financially attractive. This has led producers to look for more adequate facilities to overcome the challenges arising mainly from the weather conditions [9,13].

For this purpose, the first open (conventional) CBP system was built in Brazil in 2012, located in the state of São Paulo [10,13]. The project conventional CBP system was implemented following the design of the North American model, being recommended, therefore, as a low-cost and economically

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 April 2024 doi:10.20944/preprints202404.1841.v1

viable animal confinement method for Brazilian producers, as the building is open on the sides, favoring internal ventilation [1,13].

Although the conventional CPB system (with open sides) has been widely adopted by Brazilian dairy farmers some producers started to build closed and climate-controlled CBP systems. Through the implementation of closed CBP systems, producers sought to mitigate variations in the thermal environment between seasons and facilitate system management [8,13]. Figure 1, to detail the characteristics of open and closed CBP facilities, depicts images of the internal part of each type of system.


(a) (b)

Figure 1. Interior of (a) open and (b) closed compost-bedded pack barn systems. Source: The authors.

The pressure ventilation of closed and climatized CBP system is negative in tunnel mode, which is associated with an evaporative cooling system (ECS). The first climatized closed CBP system project was built in the state of Minas Gerais, Brazil, in 2015; since then, this method has been adopted in several regions of the country [13]. The main objective of the closed and climatized CBP system is to ensure more uniform ventilation and to provide better comfort conditions inside the facility, especially during the hottest periods of the day. However, the lack of insulation of the side enclosures and roofs can drastically compromise the effectiveness of the system.

Studies evaluating the thermal behavior of closed and climatized CBP facilities in Brazil are scarce [24]. Concomitantly in these systems, some undesirable welfare critical points of dairy cattle, internationally recognized as harmful to dairy cows, may arise, but seem likely to be circumvented by the CBP system in Brazilian climatic conditions.

This breeding system has only recently been scientifically tested, as questions have been raised by producers, researchers, and technicians about the management of the system as well as the impacts on the environment and product quality [8,24]. The structure of the closed CBP system causes many problems, especially after the increased adoption of the system by Brazilian producers, with numerous facilities constructed without consulting a specialist/designer in the area [13].

Currently, the exact number of open and closed CBP systems in Brazil is unknown, but the number of new systems has rapidly grown [1,24]. Closed CBP systems already exist in the southeastern and southern regions of Brazil, with a few in the northeast [8,13]. The scientific data in the literature indicate that, to date, only the closed CBP system is found in Brazil.

Based on the above, to assess the applicability of open and closed CBP systems in Brazil, some relevant points must be discussed: bedding management practices, the constituent material of bedding, area of bed per animal, construction characteristics, ventilation systems, among others, which are discussed in this paper.

3.2. Bedding for Compost-Bedded Pack Barn Systems

3.2.1. Materials

When choosing the best bedding material, nutrients for microorganisms, animal comfort, availability, and cost-effectiveness should be considered [5]. In open and closed CBP systems for dairy cows, sawdust and shavings have been commonly used as bedding material [1,7,8]. The use of materials, as carbon sources, has been satisfactory, mainly due to the combination of absorbency and structural form, indicating their suitability for CBP systems [25].

However, in some regions in southeastern Brazil, a mixture of wood shavings and dry coffee husk has been used [13,26,27]. In the central-west region of Brazil, rice husks are predominantly used. Radavalli et al. [28] observed that in the west of the state of Santa Catarina, Brazil, the most-used materials producing adequate results as bedding in open CBPs were 70% sawdust, 26.7% a mixture of sawdust and shavings, and only 3.3% wood shavings.

However, on many commercial dairy farms, bedding materials are selected based on economic feasibility [29]. Additionally, the selection of bedding is dependent on its availability and cost at different times of the year. Attention must be paid to the type and management of the chosen bedding material, as it is the main source of cow exposure to the mastitis pathogen [18,30].

The success of the bedding component of open and closed CBP systems depends on the management of the composting process, the application of the material in the field, and its acquisition cost [1]. When materials are widely available, the system can substantially contribute to the globally discussed circular economy [2].

3.2.2. Animal Bed Surface

In a study carried out in Brazil, in open CBP systems, 10.4 $m^2 \cdot cow^{-1}$ is adopted as the bedding area in the south of the state of Minas Gerais [26]. From 11 to 19 $m^2 \cdot cow^{-1}$ is used in the state of São Paulo [18], 14.6 $m^2 \cdot cow^{-1}$ in the west of the state of Santa Catarina [28], and 16.4 $m^2 \cdot cow^{-1}$ in Paraná [7]. In Brazil, for lactating cows, the minimum bedding area per animal is 10-14 $m^2 \cdot cow^{-1}$ [24]. For closed CBP systems in Brazil, the bedding area was 10 $m^2 \cdot cow^{-1}$ in the Zona da Mata region, state of Minas Gerais [13] and 10.5 $m^2 \cdot cow^{-1}$ in the west of the state of Minas Gerais [8].

The differences observed for the bedding area per animal are due to several factors, such as the climate in each location, construction of the facility, adopted ventilation system, ventilation rate for drying the bedding, rate of turning the bed, and the type of compost material. In hot, dry, well-ventilated climates, bedding is likely to dry faster, resulting in reduced space available per cow [11]. However, in cold and wet weather conditions, large amounts of material may be required to keep the surface adequately dry and comfortable for cows [1].

Eckelkamp et al. [31], in CBPs, observed the influence of the environment on bed temperature, finding that the annual variations in the surface temperatures of the bed in CBP facilities were similar to those of ambient temperatures. Likewise, Black et al. [16] evaluated CBP facilities and observed an average bed surface temperature of 10.5 ± 8.0 °C. According to the authors, evaporation and ventilation cool and dry the surface of the bed of a CBP facility, causing the surface temperature level of the bed to be close to the ambient temperature. The larger the number of cows and, consequently, the larger the amount of feces and urine, the higher the need to expand the bedding area per animal so that microbial activity and surface drying are balanced according to the daily amount of deposited manure [11,32].

3.2.3. Management Practices

Producers must manage their facilities to keep the bedding area dry and thus avoid worsened cow hygiene scores and increased somatic cell counts [33]. For open CBP systems, the literature recommends turning the bed once, twice, or three times per day, preferably during the period when the animals are milking [1,11]. In a study conducted in a closed CBP system during summer and winter, located in the state of Minas Gerais, Brazil, bed turning was performed twice a day; however,

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 April 2024 doi:10.20944/preprints202404.1841.v1

the problem of excessive bedding moisture still occurred [13]. As the best strategy for the operation of this system with tunnel ventilation, under the specified conditions, a larger bedding area per animal and more frequent bed turning should be adopted [8,10,13].

The turning depth varies according to the management practices of the producer and the type of implement used; however, for open CBP facilities, studies recommend depths of 0.18 to 0.30 m [5,11]. Silva et al. [34], in an open CBP in Rio Grande do Sul, Brazil, found that turning depth was influenced by bed height. In most of the investigated facilities (60%), the turning depth was between 0.20 and 0.30 m.

In both types of CBP systems (open and closed), the main objective of the turning process is to introduce oxygen into the upper layers of the bedding, promoting aerobic microbial degradation, which causes the heat produced from the process to help with drying the surface of the material [5,35]. Klaas et al. [14] emphasized that the generation of heat from the composting processes is crucial for the functioning of the system. Another important point is avoiding turning the compacted soil base together with the bedding material; this is more likely when the bedding depth is less than 0.30 m [11].

The duration between additions of new layers of bedding material depends on the available area per animal, weather conditions, ventilation rate (air exchange), and type of bedding material. More bedding replacement is necessary during the rainy season and when there is insufficient air exchange inside the bedding [11,16,36]. Eckelkamp et al. [31] and Llonch et al. [37] indicated that more bedding material must be added when the bedding humidity is above 60%. The bedding management practices for the closed and open CBP systems are the same, with more material being added when the bedding humidity is above 60% [13,27].

In open and closed CBP systems, specific management is required of both solid (bed area) and liquid (from cleaning the feeding corridor) waste [11,13]. Waste disposal must comply with legislation on proper destination. Generally solid and liquid residues are being used as fertilizers in Brazil [8,10].

Typically, in open CBP systems located in temperate countries, the bedding is completely renewed every 6 to 12 months [1]. In countries with a tropical climate, the entire bed is renewed every 12 to 36 months. For closed CBP systems in Brazil, a shorter period between bedding replacements was observed, with an average period of 6 months [13]. This shorter time is probably related to the increased difficulty of bedding management due to the high moisture content of the bed.

The renewal period of the bedding material depends on the construction characteristics of the facility, available bedding area per animal, adopted ventilation systems, moisture content, and management practices, among other factors. According to Klaas et al. [14], the compost removed from a facility can be directly spread on the fields, when necessary, and the transport costs are lower than those of liquid manure from other types of facilities. In open and closed CBP systems, additional benefits include the use of composted material to store animal waste, and the possibility of marketing the material to generate additional income for the farm [32,36,38]. In the traditional confinement systems for dairy cattle (free stall and tie stall), manure management represents a growing challenge for producers, requiring high investment in systems for the proper treatment of waste. CBP facilities with a supply corridor (with a concrete floor) generate approximately 30% less liquid effluent than traditional free stall systems [39]. Subsequently, the generated liquid waste can be used to produce biofertilizers, thereby reducing the use of chemical fertilizers on the fields, reduces expenses, and helps mitigate environmental issues.

The success of integrating bedding material into the system largely depends on the skills of those managing the composting process, the application of the material on the field, and the cost of acquiring the material [2]. Importantly, the incidence of mastitis in CBP is directly linked to the quality of the bedding. One of the indications that the bedding is not of adequate quality is the animals' cleanliness score and the incidence of mastitis: clean animals experience less dirt adherence, reducing the probability of mastitis [38,40,41].

3.3. Construction and Architectural Characteristics in Brazil

The adequacy of CBP systems, with evidence in better comfort conditions for dairy cattle, has been demonstrated [42,43]. Structural components have a substantial effect on the cow's microenvironment [44]. A wide variety of construction options exist for CBP systems; however, an ideal solution has not yet been identified. An extensive open resting area (bed) and the daily turning of the material seem to be the only common features of CBP systems worldwide [1].

Firstly, the producer needs to remember that the appropriate design of an animal building must consider all points of the construction, from the choice of site, orientation of the building, earthworks, the definition of the foundation, and the budget and details of the material, in addition to s electrical and hydraulic planning and finishing the concrete floor [45].

In general, the physical structure of open and closed CBP facilities is composed of a rest area (bed), food corridor, treatment track, feeders, drinkers, walls, and an access passage to the food corridor. In both types of CBP, cows have free access to the feeder, drinkers, and rest area [8,13]. Open CBPs have sometimes been combined with access to pasture [6].

The first design criterion to be considered for open CBP facilities is the orientation of the structure. For Brazilian climatic conditions, they should be built with the longitudinal axis of the ridge oriented in the east–west direction [8,10]. This avoids direct solar radiation on the bedding area during the hottest hours of the day and can prevent the grouping of animals in certain areas, a factor that can compromise the quality of the bedding [18].

For closed CBPs located in Brazil, in relation to the orientation of the systems, in the west of the state of Minas Gerais, northeast–southwest orientation is best [8]; in the region of Zona da Mata, Minas Gerais, northwest–southeast orientation is recommended [13]. However, for CBP facilities with cross-ventilation or tunnels, the positioning is not as relevant, as the sides are closed.

The roof type used varies between countries and depends on climate, precipitation, wind speed, and snow load, among other factors [3]. In Brazil, to reduce construction costs, for open and closed CBP facilities, galvanized steel or aluminum tiling is commonly used; this type of material has a low absorption coefficient when new (high reflective power) and a high value of thermal conductivity, and, therefore, low insulating power [24].

The use of materials with increased thermal resistance on the roof allows an efficient increase in the control of the internal temperature of the facility [46]. In hot climates, these materials can reduce the heat flow from the roof to the facility, allowing for improved thermal comfort [47]. Low-quality materials and the general inadequacy of the structures lead to further difficulties in controlling the internal microclimate. A roof pitch between 15° and 25° is satisfactory for open CBP systems. The roof slope in closed CBPs with climate control may also be lower than that of open systems because the air outlet is mechanically powered by the exhaust fans [13]. In addition, closed CBP systems have a lining that helps with the thermal conditioning inside the facility.

In open CBP systems, to prevent excess moisture from entering the bed, roof eaves should not be less than 1.0 m [48]. Oliveira et al. [26] observed the predominance of 2.0 to 3.0 m eaves in open CBP facilities in the south of the state of Minas Gerais, Brazil. For closed CBP installations, which have negative pressure ventilation, side closure with tarpaulins consequently prevents the ingress of rainwater, avoiding the need for wide eaves [40]. This finding was confirmed by Andrade et al. [13], who observed that the eaves were 0.8 m wide. In the same study, the side closure and ceiling lining of the facility (without insulation) were made of blue polypropylene. In addition to the characteristics of the materials of the side enclosures, other factors that influence the internal thermal environment of the animal facility, such as ventilation, penetration of solar radiation, and processes or equipment that release heat inside the building, must be considered [48].

In Brazil, the adoption of an open CBP facility width of approximately 20.0 m has been often used [24,26]. In the south of the State of Minas Gerais, Brazil, a facility length of 73.3 m was common [26]. In the case of a closed CBP facility located in the State of Minas Gerais, Andrade et al. [13] observed a width and length of 26.4 m and 55.0 m, respectively. To date no consensus has been reached on the ideal size of the bed in the closed CBP facility; however, to reduce the cost of earthworks and the difficulties with the management of the animals and bedding, facilities with longer than 200 m should be avoided.

Regarding the ceiling height of open CBP systems, in Brazil, as observed by Oliveira et al. [26] and Radavelli [28], the average ceiling height for open CBPs is taller than 4.3 m. In the case of a closed CBP, Andrade et al. [24] observed a ceiling height was 4 m. The ceiling height of a closed CBP system must be shorter to reduce the volume of internal air. A taller ceiling requires a larger number of exhaust fans. However, opening the system later will be difficult due to the lower ceiling height of the facility.

When deciding to build a shed with a controlled environment, the height of the ceiling should be lower than that of open sheds, facilitating the control of the internal temperature by the cooling system. However, for open and closed CBPs, the selected height should consider the execution of routine work, such as the entrance of wagons and tractors, require a height of approximately 4.0 m [49].

Equally important when planning the facility is defining whether structures such as the milking parlor, waiting room, and waste pit will be attached to the cow housing shed [45]. This decision will affect the positioning of the corridors needed for the animals to move to these structures. In addition, the dimensioning of these structures must be linked to the objective of the final project, so that the facilities do not have to be readjusted in the future, generating undue expenses.

The bedding area ($m^2 \cdot cow^{-1}$) is one of the key aspects of the design of open and closed CBP systems. Smaller bedding areas per animal concentrate larger volumes of urine and feces, generating more moisture in the bedding and posing management difficulties. The floor level under the bed area must be designed to keep the bed surface level with the floor of the feed aisle, with the bed depth varying from 0.20 m to more than 1.0 m. Depending on the country and legislation, the floor under the bed may or may not be paved [1].

In open and closed CBP systems, the bed area is normally separated from the feed aisle by a short wall, usually 1.2 m high [30]. To prevent the bedding material from leaving the facility, in open CBP systems, a masonry wall with a height between 0.3 m and 0.5 m, associated with a steel cord fence, has commonly been implemented to guarantee the proper circulation of indoor air properly [26]. This wall can also prevent rain ingress and the bed from spreading out of the facility. In addition, in Brazil, lower wall heights have been adopted to favor natural ventilation. In closed CBP systems, the side closure prevents excess bedding from spreading out of the facility and the rain from entering.

The length of the feeder also strongly influences the design, as it is related to the length of the facility. In open and closed CBP systems, feeders should be easily accessible to animals, and a linear feeder space of 0.7 to 1.4 m per cow is recommended [48].

The length of the handling lane (aisle where the food is offered) must be the same as the length feeding aisle, and the width must be sufficient for machines (such as tractors) to be able to work. Generally, widths of 4.0 m are sufficient. The food aisle must be at least 4.0 m wide [11]. Another recommendation is for the entire area of the feed aisle and treatment lane to be concreted. A CBP system potentially requires less concrete than an FS system. In open and closed CBP systems, the supply aisle can be positioned in the facility on only one side, laterally on both sides, or centrally [40].

In most open and closed CBP facilities, drinking fountains are located along the walls that divide the feeding aisle and bedding area, facing the feeding aisle [24,48]. Radavelli et al. [28] investigated the construction aspects of 30 open CBP systems located in western Santa Catarina, Brazil. The results showed that some of the open CBP systems contained drinking fountains in the bedding area or nearby, so the animals could drink while in the bedding area. Drinkers in this region are not recommended as they can add more moisture to the bedding and negatively influence the composting process. In a study on closed CBPs in the State of Minas Gerais, Brazil, the drinking fountains were located on the walls that divided the bed area from the food corridor and facing the food corridor [13,50].

Another important point for both system types is cleaning the floor of the food aisle, which must be cleaned daily. The feeding corridor, with a concrete floor, collects 25 to 30% of the manure and urine produced by the animals [6].

Attention should also be paid to the lighting provided in open and closed CBP systems, mainly to facilitate the operators' work and the inspection of animals, as well as to assist in handling tasks. A well-lit facility can increase animal movement and improve food intake and, consequently, increase milk production [10,13].

In places where continuous general lighting is used or areas with simple visual tasks (for example, in the bed region) the illuminance must be 100 to 200 lx. For the feeder region, a minimum light level of 200 lx is recommended [47,51]. Andrade et al. [51] evaluated the spatial distribution of luminosity in a closed CBP. According to the study results, the luminosity values were below the recommended (average of 84.96 lx, varying between 3.0 and 492.67 lx) for dairy cows during the lactation period. Closing the sides of the facility influenced the luminosity intensity, indicating that the intensity and distribution of luminosity needed to be changed.

The other facilities that are essential for the production process in open and closed CBP systems include the milking parlor, waiting room, calf stall, bull stall (when artificial insemination is not used), chute or trunk for vaccination and spraying, silos, feed deposit, and forage chopper compartment [45]. Another important aspect is determining whether structures such as the milking room, waiting room, and waste pit will be attached to the cow housing shed during the planning phase. This decision will affect the placement of corridors to take the animals to these structures [40].

The milking parlor, normally automated, must be connected to the confinement facility, so that two or three milkings can be performed daily under hygienic conditions. Some properties that have closed CBPs have opted to place the milking parlor and waiting room inside the facility, located next to the evaporative plates. As such, the animals remain in a controlled environment throughout the lactation period.

3.4. Effects of the Environment on the Thermal Comfort and Welfare of Dairy Cows

Facilities that provide more space per cow, soft bedding and allow free movement to have been beneficial for animal comfort and well-being [52]. Fávero et al. [18] suggest that managing the CBP system bedding to provide dry, loose surface results in cleaner animals with a lower incidence of mastitis. According to the same authors, the cow's hygiene score can be a useful and efficient indicator to help manage bedding and assess the risk of subclinical mastitis in CBP systems.

According to Blanco-Penedo et al. [52], the hygiene of the animal's body and udder reflects the cleanliness of the surface where the animal lies. In a study conducted in open CBP and Free Stall (FS) facilities, hygiene levels were assessed on a 5-point scale (1 = clean and 5 = very dirty) [41]. Mean hygiene scores for open CBP facilities were better when compared to FS facilities, averaging 1.95 ± 0.09 versus 2.18 ± 0.06, respectively. However, Eckelkamp et al. [31] did not observe differences between the average hygiene score of cows between CBP (2.19 ± 0.05) and FS (2.26 ± 0.06) facilities, which indicated that animals in both systems remained clean throughout the study.

Marcondes et al. [53] evaluated the productive characteristics of dairy farms, located in the state of Minas Gerais, Brazil, that switched from a confinement system (dry-lot, DLS) to open CBP facilities and compared with similar farms that did not change their rearing system. The authors observed that farms with open CBP facilities increased milk production per cow by 13.3% compared to farms with DLS confinement and concluded that these results are probably due to the better environmental conditions and greater animal comfort provided by open CBP facilities.

Burgstaller et al. [54] noted that open CBP facilities were a good alternative compared to FS facilities in terms of lameness, hoof health and animal welfare. Bran et al. [20] conducted a study on intensive farms in southern Brazil to investigate factors associated with lameness in dairy cows. The same authors observed that farms that used mattresses as a base had a higher prevalence of lameness than farms that used composted bedding.

3.5. Ambient Thermal Conditioning System Used in Compost-Bedded Pack Barn Facilities

The thermal environment is a composite of a series of factors that characterize the microclimate inside the facilities, which interact with each other and reflect the real thermal sensation of the animals [55]. Concomitantly, the appropriate thermal environment can optimize the feed efficiency of the animals [52]. However, facilities without adequate control of microclimatic variables may struggle to provide thermal comfort, and heat stress conditions can affect animal productivity. Under these conditions, animals use mechanisms to regulate body temperature, which can lead to a high level of stress, resulting in reduced well-being and further reductions in milk production [56]. Although the effect of cold stress on milk production is minimal, the effect of heat stress on milk production can be extremely harmful [53,54].

Adequately sized ventilation in both open and closed CBP systems is necessary to remove excessive heat and humidity from the ambient air, as well as the heat and humidity generated by the bedding, and to ensure the hygienic quality of the ambient air [1,35]. The ventilation process varies according to the design of the facility adopted for the dairy cows in Brazil. The two main categories of CBP are as follows:

a) CBP systems designed in open facilities, in which internal air renewal naturally occurs through natural ventilation or supplemented with positive pressure ventilation (Figure 2a).
b) CBP systems designed in closed facilities, where the sides are closed, and the volume of internal air, as well as the volume and flow of air that enters and leaves, are controlled. The ventilation is achieved through a negative pressure system (Figure 2b).

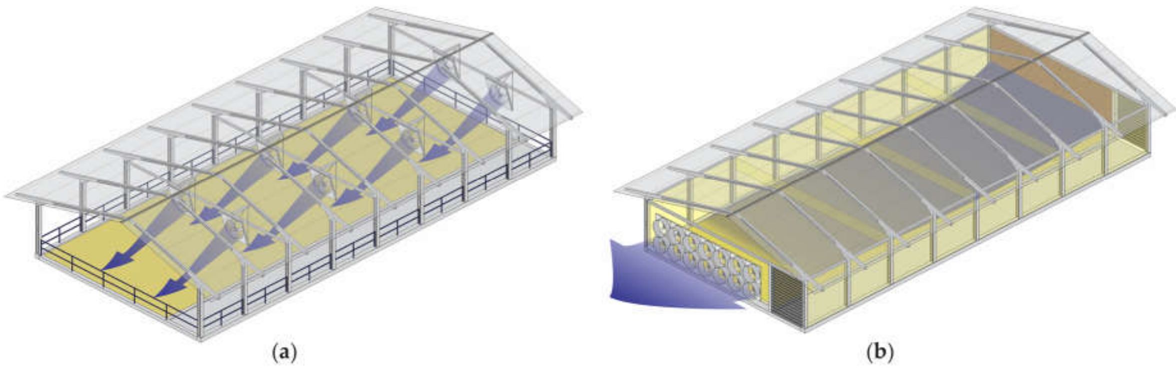
(a) (b)

Figure 2. Compost-bedded pack barn systems with (**a**) open sides and positive pressure ventilation, and (**b**) closed sides and negative pressure ventilation associated with an adiabatic evaporative cooling system. Source: The authors.

3.5.1. Positive Pressure Ventilation Systems

When natural ventilation is insufficient to improve the indoor environment of a facility, fans over the bed area and the food aisle must be used to reduce ambient heat, improve air quality, and promote bed drying [49]. According to Leso et al. [1], the main types of fans found in open CBP systems are high-volume and low-speed (HVLS) or low-volume and high-speed (LVHS) fans. Should be mentioned that in Brazil most CBP facilities are open and use positive pressure ventilation, with LVHS fans [8,13,26,50].

Oliveira et al. [26] analyzed twenty CBP facilities located in the south of Minas Gerais, Brazil, and they observed a predominance of facilities with LVHS fans (76.4%). The mean values of air velocity at the bed surface and at 1.5 m height were 1.3 ± 0.7 $m \cdot s^{-1}$ and 1.7 ± 0.8 $m \cdot s^{-1}$, respectively. According to Black et al. [16], an air velocity close to the surface of the bedding of approximately 1.8 $m \cdot s^{-1}$ provides a higher rate of bedding drying. In addition, maintaining adequate wind velocity in the cow's resting area is important to reduce the physiological responses associated with heat stress, such as increased respiration rate [44].

According to Damasceno et al. [48], ventilation must be homogeneous so that animals are not crowded in a specific area of the facility. The lack of fans can cause the animals to crowd in areas where the natural air flow is higher during heat stress conditions, which leads to the accumulation of manure and urine. In this situation, composting is inefficient due to the increase in moisture content.

 doi:10.20944/preprints202404.1841.v1

The adequate dimensioning of the ventilation system depends on the types and models of fans available and should be based on their rotation, power, flow, and performance, in addition to the air speed required in the environment and supported by the animals without stress (which depends on the quantity and size of the animals). This adequate dimensioning also depends on the placement and size of the air inlets and outlets. The automation involved in controlling the activation of specific components, using automated handling of fans, must be considered (Figure 3). Fans that operate at variable speeds, normally controlled by thermo-hygrometers, should be chosen, as they can work in places where the temperature and relative humidity of the external air widely vary during the day [8,10,13]. The operating speed of these fan models can be changed as a function of thermal comfort indices, such as the temperature–humidity index (THI) and enthalpy (H).

Figure 3. Compost-bedded pack barn system with open sides with automated fans: (**a**) distribution of fans and (**b**) detail of the equipment. Source: The authors.

A combination of fans to increase convection heat loss and sprinklers/nebulizers to promote adiabatic evaporative air cooling is effective in cooling dairy farming environments [29]. Sprinkler systems can be installed either in the waiting room or in the feeding corridor of a CBP system, being one of the most efficient methods of reducing the thermal stress of animals [40].

In Brazil, installing the necessary number of fans in facilities is difficult due to the lack of electricity that can occur in some regions in the countryside. In addition, in some areas, if producers have a generator with insufficient demand or due to constant power outages, they chose to use solar energy or a biodigester (Figure 4).

Figure 4. Open Compost-Bedded Pack Barn systems with low-volume and high-speed (LVHS) fans and: (**a**) solar panels and (**b**) biodigesters. Source: The authors.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 28 April 2024 doi:10.20944/preprints202404.1841.v1

3.5.2. Negative Pressure Ventilation Systems

Since the early 2010s, new confinement systems are gaining popularity in dairy farming worldwide. The use of a closed system, associated with evaporative cooling, has been adopted in free stall facilities with tunnels or cross-ventilation [49].

The adoption of this type of climate control has produced substantial advantages for dairy production by drastically reducing exposure to heat stress and improving animal comfort compared with open confinement or pasture systems [20,54].

Fully enclosed facilities require mechanical ventilation and evaporative cooling systems to allow the reduction in air temperature during the hottest months of the year and the hottest hours of the day [8,13,57]. A climatized system is based on the control, direction, and cooling of the air inside the facility used for animal production.

As reported by Fournel et al. [29] and Mondaca et al. [44], a system with negative pressure ventilation is usually automated. In a tunnel-type system, the air is sucked through exhaust fans along the length of the installation (Figure 5a); in a system with cross-ventilation, the air is sucked perpendicular to the length of the building (Figure 5b). In both cases, the herd is exposed to winds practically constant speeds. Ventilation design typically follows some assumptions regarding unit of flow per animal, air exchange for a specified period, and air velocity in the cross-sectional area [44]. A properly designed negative pressure ventilation system can provide uniform air movement throughout a facility.

In this system, in hot weather conditions during the driest periods, the hot and unsaturated air that is external to the facility is forced (by the exhaust fans positioned at the opposite end) to cross the moistened porous plate, resulting in a simultaneous exchange of heat and mass. This leads to a change in state of part of the water from the liquid phase to the vapor phase and an increase in the relative humidity of the inlet air, with a consequent reduction in temperature. That is, the temperature of the indoor air decreases, however, with an increase in its relative humidity [51]. For regions with hotter and drier climates, the use of this system can allow the adiabatic cooling of the air by up to 11.0 °C [45,58].

Vega et al. [59] reported a first approach to modeling and simulating the thermal distribution inside a tunnel-ventilated CBP facility with an evaporative cooling system located in a tropical environment, using computational fluid dynamics (CFD). They observed that the average difference in dry-bulb temperature between the external and internal conditions was 2.1 to 5.8 °C. They recommended increasing the airflow velocity to above 3 $m \cdot s^{-1}$ when the external dry-bulb temperature and the relative humidity simultaneously exceed 30 °C and 55%, respectively.

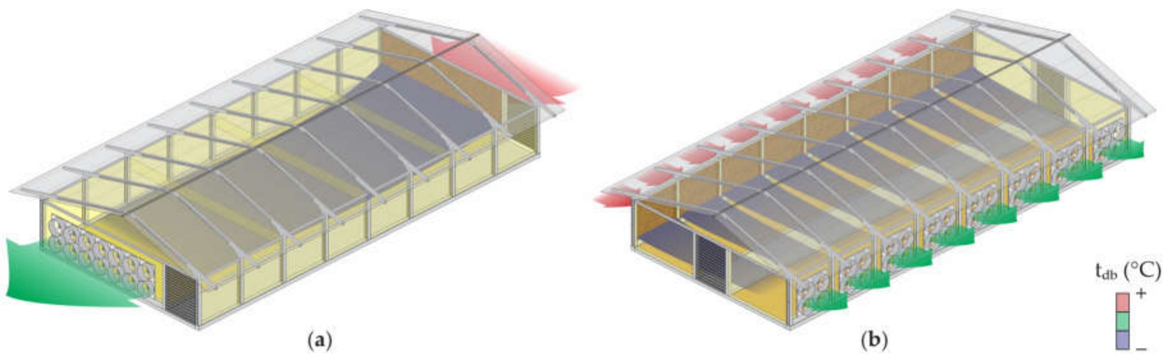

Figure 5. Mechanical exhaust ventilation system (negative pressure) in a Compost-Bedded Pack Barn system with (**a**) tunnel mode ventilation and (**b**) cross-ventilation. t_{db}—dry-bulb temperature. Source: The authors.

Air tends to move through aisles, ceilings, or feed aisle where interference with cows is minimal, i.e., the path of least resistance [60]. The set of exhausters must be dimensioned to provide a minimum air speed ranging between 2.0 and 4.0 m·s^{-1}. For systems with tunnel ventilation, a ventilation rate of 1700 m^{3}·h^{-1} per cow should be adopted and an inlet air velocity of at least 2.5 m·s^{-1} [45].

The capacity of the hoods must be adequate to guarantee the necessary air renewal rates in the summer. The time required for all the hoods to completely renew the indoor air of the facility must be calculate, a complete air change in one minute or less is desirable [45]. An air change is the equivalent of replacing all the air inside the building with fresh air, i.e., if the air change rate is one minute, every minute, the exhaust fans move enough air to completely change the air inside of the facility with outside air [8,13,61]. However, as the ventilation rate increases, the operational energy costs for running the hoods also increase.

The negative pressure system, associated with adiabatic evaporative cooling, operates through an automatically controlled panel that activates the exhaust fans and the wetting of the porous plates. In this system, sensors that monitor the environmental conditions are positioned inside the buildings, which allow the cooling system to be activated; normally, when the air temperature is equal to or greater than 21 °C and the relative humidity of the air reaches values close to 80%, the cooling system is turned off [45,58].

Controllers can be used to adjust the inlet opening, fan rotation, and porous material wetting trigger based on indoor air temperature and relative humidity. These must be installed close to the centers of the ventilated areas and at three points, at least, along the length of the facility [50,51].

Maintaining a well-programmed handling routine is important for the proper functioning of the system, because whenever the gates are opened, hot air enters the building, causing peaks in internal air temperature. Peripheral air entry should also be avoided, for example, due to sealing failures, which can cause a reduction in system efficiency. Advanced planning, careful observation, and corrections after the negative pressure system is installed can minimize performance issues. The most common problem is dead air spaces that do not have sufficient air velocity or fresh air [44,62].

However, the structural components of the facilities can affect the performance of the ventilation system, which can considerably reduce its efficiency and cost-effectiveness [44]. Moreover, the failure to appropriately dimension the air inlet dimensions can interfere with the pressure of the system, leading to pressure drops, overloading the exhaust fans and, consequently, increasing electrical energy consumption. Some dairy farmers who have adopted this type of system have chosen to place the milking parlor inside the closed CBP facility, so that the animals are exposed to a climatized environment throughout the period.

This type of climatized system also requires continuous mechanical ventilation and the use of a quality generator that is properly designed to maintain operation in the event of a power failure [45,49,57]. Dairy producers should consider incorporating generators into their projects. The system is highly dependent on electrical energy; even with the opening of curtains, if the electrical energy is not quickly restored, the internal air temperature can remarkably rises causing heat stress in the animals [24]. This also increase the concentration of ammonia and other pollutants in the air, creating an unhealthy environment unhealthy for animals and workers.

The longitudinal or transversal air flow provided by this type of climatized environment carries the metabolic heat produced by the confined animals, the composting of the bedding, the thermal load generated by the equipment used, and the solar radiation emitted through the roof and side enclosures. It also promotes the transport of air pollutants (high concentration of heat, humidity, ammonia, dust, etc.). This results in an increase in the air temperature as well as a worsening of the air quality near the hoods.

Narrower installations provide more uniform air, and buildings with a width of more than 20.0 m require additional air inlets that must be inserted close to the food aisle. According to the same author, no common consensus has been reached on the ideal length for a closed CBP system. However, in practice, buildings up to 180.0 m in length have been constructed, requiring further studies to determine the ideal length [8,10,24]. Andrade et al. [13] observed that even in installations with a length of 55.0 m, excessive bedding moisture was a problem, probably related to the high animal density, excessive relative humidity, inefficiency of the ventilation system, and the need for more frequent turning of the bedding. In this type of closed facility, the addition of a ceiling lining is recommended to reduce the cross-sectional area and the volume of internal air, increasing the system efficiency and lowering the cost implementation, as the ceiling height usually varies between 2.5 and 4.0 m [10,50,51]. Attention must also be paid to the height of the lining so that it does not interfere with the entry of tractors and trucks into the facility. The ceiling acts as a second physical barrier that allows the formation of a mobile air layer next to the roof, which contributes to the reduction in heat transfer to the interior of the building. A wider shed or one with a higher roof will require larger fan capacity to maintain air velocity over the cows [13].

Deflectors made of metal or canvas are also commonly used. The deflectors have the main function of redirecting the airflow and increasing the air velocity to the location of the cows, thus minimizing heat stress [60]. Additionally, deflectors can be located to divert airflow through dead air spaces.

Harner et al. [61] recommended that the bottom of the baffles should be high enough (3.6 to 4.0 m) to avoid interference with normal equipment operation. In the specific case of closed CBP systems, the deflectors must be installed at a height that does not interfere with the turning, replacement, and removal of the entire bed. In the closed CBP system with tunnel ventilation, the deflectors are being installed in the transverse direction of the installation. In addition, placing a transverse deflector over the feeding aisle (arranged in the continuation of the deflectors that are located above the bed) and located longitudinally in the line of the feeders is common.

Deflectors must be strategically located to direct air into cow locations [61]. The design and proper location of the deflectors are essential to minimize the static pressure encountered by the exhaust fans because as the static pressure increases, the performance of the exhaust fans decreases [57]. Figure 6 illustrates a schematic model of a closed CBP system with tunnel ventilation, associated with evaporative cooling.

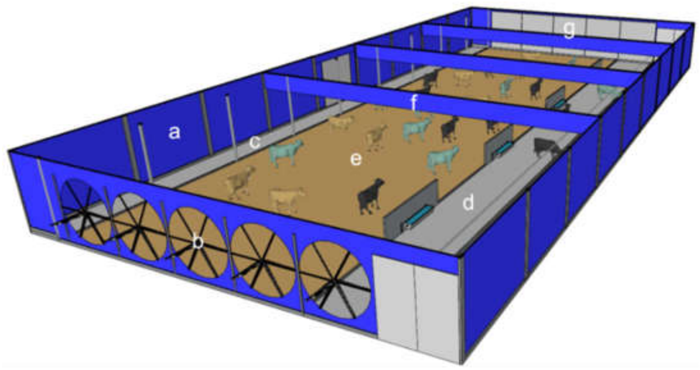

Figure 6. Schematic representation of an existing closed Compost-Bedded Pack Barn system with negative pressure ventilation, associated with evaporative cooling. a—side closing of curtains; b—high volume exhaust fans; c—service corridor; d—food corridor; e—rest area (bed area); f—deflectors; and g—evaporative cooling pads. Source: The authors.

Several negative pressure facilities have been incorrectly dimensioned when considering the exhaust fans working at nominal flow; the load losses associated with animals, deflectors, and characteristics of the evaporative plate in the calculations have often been ignored [10,24,50]. According to Tyson et al. [63], critical steps in the development of a negative pressure ventilation system include: a) determining the capacity of the exhaust fans; b) selecting exhaust fans; c) determining the size of the input; d) installing fans and controls; e) selecting locations of fans and inlet.

3.5.3. Evaporative Adiabatic Cooling Process

Evaporative cooling pads are usually composed of fibrous material and are commonly added to the air inlets of tunnel-ventilated facilities [29]. The materials most used in the filling of evaporative coolers are fiberglass, cellulose, polypropylene, and wood fiber [51]. Cellulose has been preferentially used in the manufacture of evaporative cooling pads, being predominant in animal production facilities in Brazil.

To prevent reductions in the cooling efficiency, the system must be serviced after a certain period of use. Evaporative plates may show signs of deterioration and obstruction due to exposure to too much dust. Plate clogging is also common, which can be seen as flaws in the water path. Board materials deteriorate over time and must be replaced after a certain use period [64].

The operation of this system is based on vertically or horizontally wetting plates of a porous material, so that the air is forced through the exhausters to pass perpendicularly through this material. The porous material can be wetted by dripping water on the upper edge of the vertically arranged plate or by spraying water on the surface [65].

The working principle of evaporative cooling is that the system can only remove sensible heat from the environment; therefore, it works best in hot and dry climates, where it produces maximum evaporative cooling [65,66]. In this climate-controlled animal husbandry system, the prior cooling of the air by forcing the passage of external air through plates with moistened porous material must be performed with caution. Although the system allows for a substantial reduction in air temperature, the relative humidity consequently increases, which may reduce the amount of heat dissipated by the animal in evaporative form, creating moderate heat stress in the animals in this internal environmental condition [8,13].

The increase in the relative humidity of the air can hinder the drying of bedding, becoming a limiting factor that creates challenges for handling; negatively influences animal hygiene, milk quality, and the bedding composting process; increases the emission of harmful gases, such as ammonia; and accelerates the oxidation of metallic parts, among others. Harner et al. [61] observed that the gases emitted by free-stall facilities with negative pressure ventilation were predominantly nitrogen-based (ammonia, nitrogen dioxide, and nitric oxide) during the study period in the spring and summer seasons. In addition, an excessive amount of humidity inside a closed CBP system can cause early equipment wear (corrosion).

The capacity to lower the air temperature through an evaporative cooling system depends on the ambient temperature and the relative humidity of the air to be cooled. As the relative humidity increases, the air temperature reduction capacity decreases [57]. Systems that cool the air through evaporative cooling are most effective in hot climates with low relative humidity; however, they can also be used in regions with high humidity during the hottest hours of the day, when relative humidity tends to naturally decrease. However, the effectiveness of these evaporative cooling systems is questionable in environments with a permanently humid climate [66].

As Brazil is a large country, the microclimate of each region must be carefully assessed to assist in decision making regarding the best facility project to be adopted [40]. The closed CBP system has potential for use in some regions in Brazilian and can be used with higher efficiency depending on climatic conditions. The northeast, midwest and southeast regions have the potential to adopt this type of system; however, for the north and south regions, mainly coastal regions, increased caution is needed due to the high relative humidity [8,13,24].

Currently, few guidelines exist for the proper operation of closed CBP systems. However, the adoption of this type of system has markedly increased in recent years. Systems with evaporative pad cooling and nebulizers should be used with caution in CBP systems, especially over the bedding area, because they can generate an increase in relative humidity, causing a decrease in bedding evaporation rates [1].

4. Conclusions and Future Perspectives

CPBs systems are applicable in Brazil, however, adaptations were made to the facilities in relation to the North American model to better adapt to the climate. The great challenge remains in keeping the litter at adequate temperature and humidity levels. The installation model with closed sides and negative pressure ventilation has been a major challenge for Brazilian producers. Replacement of bedding material has been performed more frequently when compared to bed management in CBP systems with open sides and positive pressure ventilation.

In the decision-making process regarding which type of CBP system to adopt, the producer must consider several aspects that guide the planning of the production process, especially animal welfare, sustainability, and cost-effectiveness.

The research on the closed CBP system so far provides preliminary impressions, be-cause only small amounts of data have been collected. As closed CBP systems are already a commercial reality in Brazil, research aimed at improving the aspects of the construction of the building, the ventilation system used, as well as the handling of the bed is required.

The dairy industry would also considerably benefit from further research into CBP systems, as this information will refine circular economy approaches to further improve efficiency while reducing their climate and environmental impacts. Sustainable alternative systems for dairy cattle production tend to be increasingly accepted by key categories such as producers, specialists and consumers.

Author Contributions: Conceptualization, R.R.A., I.F.F.T., F.A.D., C.E.A.O and M.B.; investigation, R.R.A., I.F.F.T., F.A.D., C.E.A.O. and M.B.; writing—original draft preparation, R.R.A.; writing—review and editing, R.R.A. I.F.F.T., F.A.D., C.E.A.O., M.S.C, O.F.Z., G.B. and M.B.; supervision, I.F.F.T., F.A.D. and M.B.; project administration, I.F.F.T.; funding acquisition, R.R.A and I.F.F.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CNPq, National Council for Scientific and Technological Development – Brazil (n. 150217/2021-8).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data set available on request to corresponding author.

Acknowledgments: The authors would like to thank the Federal University of Goiás (UFG), Federal University of Viçosa (UFV), Federal University of Lavras (UFLA), and University of Firenze (UniFl), whose support is appreciated. This work was conducted with the support of the National Council for Scientific and Technological Development, Brazil (CNPq) and Coordination of Superior Level Staff Improvement, Brazil (CAPES).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Leso, L.; Barbari, M.; Lopes, M.A.; Damasceno, F.A.; Galama, P.; Taraba, J.L.; Kuipers, A. Invited Review: Compost-Bedded Pack Barns for Dairy Cows. *J. Dairy Sci.* **2020**, *103*, 1072–1099. https://doi.org/10.3168/jds.2019-16864.
2. Kuipers, A.; Galama, P.; Leso, L.; Bruegemann, K.; Klopčič, M. A Composting Bedding System for Animals as a Contribution to the Circular Economy. *Processes* **2022**, *10*, 518. https://doi.org/10.3390/PR10030518.
3. Galama, P.J.; Ouweltjes, W.; Endres, M.I.; Sprecher, J.R.; Leso, L.; Kuipers, A.; Klopčič, M. Symposium Review: Future of Housing for Dairy Cattle. *J. Dairy Sci.* **2020**, *103*, 5759–5772. https://doi.org/10.3168/JDS.2019-17214.
4. Lassen, J.; Sandøe, P.; Forkman, B. Happy Pigs Are Dirty! – Conflicting Perspectives on Animal Welfare. *Livest. Sci.* **2006**, *103*, 221–230. https://doi.org/10.1016/J.LIVSCI.2006.05.008.
5. Barberg, A.E.; Endres, M.I.; Janni, K.A. Compost Dairy Barns in Minnesota: A Descriptive Study. *Appl. Eng. Agric.* **2007**, *23*, 231–238.
6. Bewley, J.M.; Robertson, L.M.; Eckelkamp, E.A. A 100-Year Review: Lactating Dairy Cattle Housing Management. *J. Dairy Sci.* **2017**, *100*, 10418–10431. https://doi.org/10.3168/JDS.2017-13251.
7. Pilatti, J.A.; Vieira, F.M.C.; Rankrape, F.; Vismara, E.S. Diurnal Behaviors and Herd Characteristics of Dairy Cows Housed in a Compost-Bedded Pack Barn System under Hot and Humid Conditions. *Animal* **2019**, *13*, 399–406. https://doi.org/10.1017/S1751731118001088.
8. Oliveira, C.E.A.; Damasceno, F.A.; Ferraz, G.A.S.; Nascimento, J.A.C.; Vega, F.A.O.; Titôco, I.F.F.; Andrade, R.R. Assessment of Spatial Variability of Bedding Variables in Compost Bedded Pack Barns with Climate Control System. *An. Acad. Bras. Cienc.* **2021**, *93*, 20200384. https://doi.org/10.1590/0001-3765202120200384.
9. Emanuelson, U.; Brügemann, K.; Klopčič, M.; Leso, L.; Ouweltjes, W.; Zentner, A.; Blanco-Penedo, I. Animal Health in Compost-Bedded Pack and Cubicle Dairy Barns in Six European Countries. *Animals* **2022**, *12*, 396. https://doi.org/10.3390/ANI12030396/S1.

10. Yameogo, B.; Andrade, R.R.; Teles Júnior, C.G.S.; Laud, G.S.; Becciolini, V.; Leso, L.; Rossi, G.; Barbari, M. Analysis of Environmental Conditions and Management in a Compost-Bedded Pack Barn with Tunnel Ventilation. *Agron. Res.* **2021**, *19*, 1195–1204. https://doi.org/10.15159/AR.21.035.
11. Shane, E.M.; Endres, M.I.; Janni, K.A. Alternative Bedding Materials for Compost Bedded Pack Barns in Minnesota: A Descriptive Study. *Appl. Eng. Agric.* **2010**, *26*, 465–473.
12. Valente, B.S.; Xavier, E.G.; Morselli, T.B.. G.A.; Jahnke, D.S.; Brum Jr., B.; Cabrera, B.R.; Moraes, P.; Lopes, D.C.N. Fatores Que Afetam o Desenvolvimento Da Compostagem de Resíduos Orgânicos. *Arch. Zootec.* **2009**, *58*, 59–85. https://doi.org/10.21071/az.v58i224.5074.
13. Andrade, R.R.; Tinôco, I.F.F.; Damasceno, F.A.; Ferraz, G.A.S.; Freitas, L.C.S.R.; Ferreira, C.F.S.; Barbari, M.; Baptista, F.J.F.; Coelho, D.J.R. Spatial Distribution of Bed Variables, Animal Welfare Indicators, and Milk Production in a Closed Compost-Bedded Pack Barn with a Negative Tunnel Ventilation System. *J. Therm. Biol.* **2022**, *105*, 103111. https://doi.org/10.1016/j.jtherbio.2021.103111.
14. Klaas, I.C.; Bjerg, B.S.; Friedmann, S.; Bar, D. Cultivated Barns for Dairy Cows - An Option to Promote Cattle Welfare and Environmental Protection in Denmark? *Dansk Veterinaertidsskrift* **2010**, *93*, 20–29.
15. Balcells, J.; Fuertes, E.; Seradj, A.R.; Maynegre, J.; Villalba, D.; de la Fuente, G. Study of Nitrogen Fluxes across Conventional Solid Floor Cubicle and Compost-Bedded Pack Housing Systems in Dairy Cattle Barns Located in the Mediterranean Area: Effects of Seasonal Variation. *J. Dairy Sci.* **2020**, *103*. https://doi.org/10.3168/jds.2019-17555.
16. Black, R.A.; Taraba, J.L.; Day, G.B.; Damasceno, F.A.; Bewley, J.M. Compost Bedded Pack Dairy Barn Management, Performance, and Producer Satisfaction. *J. Dairy Sci.* **2013**, *96*, 8060–8074. https://doi.org/10.3168/jds.2013-6778.
17. Leso, L.; Uberti, M.; Morshed, W.; Barbari, M. A Survey of Italian Compost Dairy Barns. *J. Agric. Eng.* **2013**, *44*, 17. https://doi.org/10.4081/jae.2013.e17.
18. Fávero, S.; Portilho, F.V.R.; Oliveira, A.C.R.; Langoni, H.; Pantoja, J.C.F. Factors Associated with Mastitis Epidemiologic Indexes, Animal Hygiene, and Bulk Milk Bacterial Concentrations in Dairy Herds Housed on Compost Bedding. *Livest. Sci.* **2015**, *181*, 220–230. https://doi.org/10.1016/j.livsci.2015.09.002.
19. Lazzarini, B.; Baudracco, J.; Tuñon, G.; Gastaldi, L.; Lyons, N.; Quattrochi, H.; Lopez-Villalobos, N. Review: Milk Production from Dairy Cows in Argentina: Current State and Perspectives for the Future. *Appl. Anim. Sci.* **2019**, *35*, 426–432. https://doi.org/10.15232/aas.2019-01842.
20. Bran, J.A.; Costa, J.H.C.; von-Keyserlingk, M.A.G.; Hötzel, M.J. Factors Associated with Lameness Prevalence in Lactating Cows Housed in Freestall and Compost-Bedded Pack Dairy Farms in Southern Brazil. *Prev. Vet. Med.* **2019**, *172*, 104773. https://doi.org/10.1016/J.PREVETMED.2019.104773.
21. Vieira, F.M.C.; Soares, A.A.; Herbut, P.; Vismara, E.S.; Godyń, D.; dos Santos, A.C.Z.; Lambertes, T.S.; Caetano, W.F. Spatio-Thermal Variability and Behaviour as Bio-Thermal Indicators of Heat Stress in Dairy Cows in a Compost Barn: A Case Study. *Animals* **2021**, *11*, 1197. https://doi.org/10.3390/ani11051197.
22. Méndez, M.N.; Grille, L.; Mendina, G.R.; Robinson, P.H.; Adrien, M. de L.; Meikle, A.; Chilibroste, P. Performance of Autumn and Spring Calving Holstein Dairy Cows with Different Levels of Environmental Exposure and Feeding Strategies. *Animals* **2023**, *13*, 1211. https://doi.org/10.3390/ANI13071211.
23. Silveira, R.M.F.; Ferreira, J.; Busanello, M.; Vasconcelos, A.M.; Valente, F.L.J.; Façanha, D.A.E. Relationship between Thermal Environment and Morphophysiological, Performance and Carcass Traits of Brahman Bulls Raised on Tropical Pasture: A Canonical Approach to a Set of Indicators. *J. Therm. Biol.* **2021**, *96*, 102814. https://doi.org/10.1016/J.JTHERBIO.2020.102814.
24. Andrade, R.R.; Tinôco, I.F.F.; Damasceno, F.A.; Ferraz, G.A.S.; Freitas, L.C.S.R.; Ferreira, C.F.S.; Barbari, M.; Teles Junior, C.G.S. Spatial Analysis of Microclimatic Variables in Compost-Bedded Pack Barn with Evaporative Tunnel Cooling. *An. Acad. Bras. Cienc.* **2022**, *94*, e20210226. https://doi.org/10.1590/0001-3765202220210226.
25. Ferraz, P.F.P.; Ferraz, G.A.S.; Leso, L.; Klopčič, M.; Barbari, M.; Rossi, G. Properties of Conventional and Alternative Bedding Materials for Dairy Cattle. *J. Dairy Sci.* **2020**, *103*, 8661–8674. https://doi.org/10.3168/JDS.2020-18318.
26. Oliveira, V.C.; Damasceno, F.A.; Oliveira, C.E.A.; Ferraz, P.F.P.; Ferraz, G.A.S.; Saraz, J.A.O. Compost-Bedded Pack Barns in the State of Minas Gerais: Architectural and Technological Characterization. *Agron. Res.* **2019**, *17*, 2016–2028. https://doi.org/10.15159/AR.19.179.
27. Oliveira, C.E.A.; Tinôco, I.F.F.; Oliveira, V.C.; Rodrigues, P.H.M.; Silva, L.F.; Damasceno, F.A.; Andrade, R.R.; Sousa, F.C.; Barbari, M.; Bambi, G. Spatial Distribution of Bedding Attributes in an Open Compost-Bedded Pack Barn System with Positive Pressure Ventilation in Brazilian Winter Conditions. *Animals* **2023**, *13*, 786. https://doi.org/10.3390/ANI13050786.
28. Radavelli, W.M.; Danieli, B.; Zotti, M.L.A.N.; Gomes, F.J.; Endres, M.I.; Schogor, A.L.B. Compost Barns in Brazilian Subtropical Region (Part 1): Facility, Barn Management and Herd Characteristics. *Res. Soc. Dev.* **2020**, *9*, e445985198. https://doi.org/10.33448/rsd-v9i8.5198.
29. Fournel, S.; Ouellet, V.; Charbonneau, É. Practices for Alleviating Heat Stress of Dairy Cows in Humid Continental Climates: A Literature Review. *Animals* **2017**, *7*, 37. https://doi.org/10.3390/ANI7050037.

30. Barberg, A.E.; Endres, M.I.; Salfer, J.A.; Reneau, J.K. Performance and Welfare of Dairy Cows in an Alternative Housing System in Minnesota. *J. Dairy Sci.* **2007**, *90*, 1575–1583. https://doi.org/10.3168/jds.S0022-0302(07)71643-0.
31. Eckelkamp, E.A.; Taraba, J.L.; Akers, K.A.; Harmon, R.J.; Bewley, J.M. Understanding Compost Bedded Pack Barns: Interactions among Environmental Factors, Bedding Characteristics, and Udder Health. *Livest. Sci.* **2016**, *190*, 35–42. https://doi.org/10.1016/j.livsci.2016.05.017.
32. Oliveira, C.E.A.; Tinôco, I.F.F.; Souza, C.F.; Baêta, F.C.; Andrade, R.R.; Vieira, F.M.C.; Barbari, M.; Bambi, G. Physicochemical Bedding Quality in Compost-Bedded Pack Barn Systems for Dairy Cows: A Systematic Review. *Appl. Sci.* **2023**, *13*, 9832. https://doi.org/10.3390/APP13179832.
33. Black, R.A.; Taraba, J.L.; Day, G.B.; Damasceno, F.A.; Newman, M.C.; Akers, K.A.; Wood, C.L.; McQuerry, K.J.; Bewley, J.M. The Relationship between Compost Bedded Pack Performance, Management, and Bacterial Counts. *J. Dairy Sci.* **2014**, *97*, 2669–2679. https://doi.org/10.3168/JDS.2013-6779.
34. Silva, K.H.; Teixeira, M.C.; Stracke, M.P.; Girardello, V.C.; Knob, D.; Lenz, R.L.S.; Huber, E.; Backes, T.R. Evaluation of the Compost Barn System of Milk Producers from Cooperatives in the Mission Region. *Brazilian J. Dev.* **2021**, *7*, 27227–27241. https://doi.org/10.34117/BJDV7N3-434.
35. Janni, K.A.; Endres, M.I.; Reneau, J.K.; Schoper, W.W. Compost Dairy Barn Layout and Management Recommendations. *Appl. Eng. Agric.* **2007**, *23*, 97–102. https://doi.org/10.13031/2013.22333.
36. Llonch, L.; Gordo, C.; López, M.; Castillejos, L.; Ferret, A.; Balanyà, T. Agronomic Characteristics of the Compost-Bedded Pack Made with Forest Biomass or Sawdust. *Processes* **2021**, *9*, 546. https://doi.org/10.3390/PR9030546.
37. Llonch, L.; Castillejos, L.; Mainau, E.; Manteca, X.; Ferret, A. Effect of Forest Biomass as Bedding Material on Compost-Bedded Pack Performance, Microbial Content, and Behavior of Nonlactating Dairy Cows. *J. Dairy Sci.* **2020**, *0*. https://doi.org/10.3168/jds.2020-18496.
38. De-Boer, H.C.; Wiersma, M. Thermophilic Composting of the Pack Can Reduce Nitrogen Loss from Compost-Bedded Dairy Barns. *Biosyst. Eng.* **2021**, *210*, 20–32. https://doi.org/10.1016/J.BIOSYSTEMSENG.2021.07.015.
39. Mota, V.C.; Campos, A.T.; Damasceno, F.A.; Resende, E.A.M.; Rezende, C.P.A.; Abreu, L.R.; Vareiro, T. Confinamento Para Bovinos Leiteiros: Histórico e Características. *Pubvet* **2017**, *11*, 433–442. https://doi.org/10.22256/pubvet.v11n5.433-442.
40. Leso, L.; Conti, L.; Rossi, G.; Barbari, M. Criteria of Design for Deconstruction Applied to Dairy Cows Housing: A Case Study in Italy. *Agron. Res.* **2018**, *16*, 794–805. https://doi.org/10.15159/AR.18.085.
41. Biasato, I.; D'Angelo, A.; Bertone, I.; Odore, R.; Bellino, C. Compost Bedded-Pack Barn as an Alternative Housing System for Dairy Cattle in Italy: Effects on Animal Health and Welfare and Milk and Milk Product Quality. *Ital. J. Anim. Sci.* **2019**, *18*, 1142–1153. https://doi.org/10.1080/1828051X.2019.1623095.
42. Silva, M.V.; Pandorfi, H.; Almeida, G.L.P.; Jardim, A.M.R.F.; Batista, P.H.D.; Silva, R.A.B.; Lopes, I.; Oliveira, M.E.G.; Silva, J.L.B.; Moraes, A.S. Spatial Variability and Exploratory Inference of Abiotic Factors in Barn Compost Confinement for Cattle in the Semiarid. *J. Therm. Biol.* **2020**, *94*, 102782. https://doi.org/10.1016/j.jtherbio.2020.102782.
43. Kogima, P.A.; Diesel, T.A.; Vieira, F.M.C.; Schogor, A.L.B.; Volpini, A.A.; Veloso, G.J.; Ferraz, P.F.P.; Zotti, M.L.A.N. The Welfare of Dairy Cows in Pasture, Free Stall, and Compost Barn Management Systems in a Brazilian Subtropical Region. *Animals* **2022**, *12*, 2215. https://doi.org/10.3390/ANI12172215.
44. Mondaca, M.R.; Choi, C.Y.; Cook, N.B. Understanding Microenvironments within Tunnel-Ventilated Dairy Cow Freestall Facilities: Examination Using Computational Fluid Dynamics and Experimental Validation. *Biosyst. Eng.* **2019**, *183*, 70–84. https://doi.org/10.1016/j.biosystemseng.2019.04.014.
45. Mrema, G.C.; Gumbe, L.O.; Chapete, H.J.; Agullo, J.O. *Rural Structures in the Tropics: Design and Development*; 1st ed.; FAO: Roma, 2011; ISBN 9789251070475.
46. Menconi, M.E.; Grohmann, D. Model Integrated of Life-Cycle Costing and Dynamic Thermal Simulation (MILD) to Evaluate Roof Insulation Materials for Existing Livestock Buildings. *Energy Build.* **2014**, *81*, 48–58. https://doi.org/10.1016/j.enbuild.2014.06.005.
47. Smith, T.R.; Chapa, A.; Willard, S.; Herndon, C.; Williams, R.J.; Crouch, J.; Riley, T.; Pogue, D. Evaporative Tunnel Cooling of Dairy Cows in the Southeast. II: Impact on Lactation Performance. *J. Dairy Sci.* **2006**, *89*, 3915–3923. https://doi.org/10.3168/JDS.S0022-0302(06)72434-1.
48. Damasceno, F.A.; Day, G.B.; Taraba, J.L.; Oliveira, C.E.A.; Andrade, R.R.; Frigeri, K.D.-M.; Vieira, F.M.C.; Barbari, M.; Bambi, G. Compost Dairy Barn Layout and Management Recommendations in Kentucky: A Descriptive Study. *Anim. 2022, Vol. 12, Page 3324* **2022**, *12*, 3324. https://doi.org/10.3390/ANI12233324.
49. Lobeck, K.M.; Endres, M.I.; Shane, E.M.; Godden, S.M.; Fetrow, J. Animal Welfare in Cross-Ventilated, Compost-Bedded Pack, and Naturally Ventilated Dairy Barns in the Upper Midwest. *J. Dairy Sci.* **2011**, *94*, 5469–5479. https://doi.org/10.3168/JDS.2011-4363.
50. Yameogo, B.; Andrade, R.R.; Teles-Júnior, C.G.S.; Laud, G.S.; Becciolini, V.; Leso, L.; Rossi, G.; Barbari, M. Behavioural Patterns of Cows Housed in Two Different Typologies of Compost-Bedded Pack Barns. *Agron. Res.* **2021**, *19*, 1205–1215. https://doi.org/10.15159/AR.21.013.

51. Andrade, R.R.; Tinôco, I.F.F.; Damasceno, F.A.; Barbari, M.; Valente, D.A.; Vilela, M.O.; Souza, C.F.; Conti, L.; Rossi, G. Lighting and Noise Levels in Compost Dairy Barns with Natural and Forced Ventilation. *Agron. Res.* **2020**, *18*, 689–698. https://doi.org/10.15159/AR.20.104.
52. Blanco-Penedo, I.; Ouweltjes, W.; Ofner-Schröck, E.; Brügemann, K.; Emanuelson, U. Symposium Review: Animal Welfare in Free-Walk Systems in Europe. *J. Dairy Sci.* **2020**, *103*, 5773–5782. https://doi.org/10.3168/JDS.2019-17315.
53. Marcondes, M.I.; Mariano, W.H.; De Vries, A. Production, Economic Viability and Risks Associated with Switching Dairy Cows from Drylots to Compost Bedded Pack Systems. *Animal* **2020**, *14*, 399–408. https://doi.org/10.1017/S1751731119001848.
54. Burgstaller, J.; Raith, J.; Kuchling, S.; Mandl, V.; Hund, A.; Kofler, J. Claw Health and Prevalence of Lameness in Cows from Compost Bedded and Cubicle Freestall Dairy Barns in Austria. *Vet. J.* **2016**, *216*, 81–86. https://doi.org/10.1016/j.tvjl.2016.07.006.
55. Vilela, M.O.; Gates, R.S.; Martins, M.A.; Barbari, M.; Conti, L.; Rossi, G.; Zolnier, S.; Teles, C.G.S.; Zanetoni, H.H.R.; Andrade, R.R.; et al. Computational Fluids Dynamics (CFD) in the Spatial Distribution of Air Velocity in Prototype Designed for Animal Experimentation in Controlled Environments. *Agron. Res.* **2019**, *17*, 890–899. https://doi.org/10.15159/AR.19.108.
56. Pilatti, J.A.; Vieira, F.M.C. Environment, Behavior and Welfare Aspects of Dairy Cows Reared in Compost Bedded Pack Barns System. *J. Anim. Behav. Biometeorol.* **2017**, *5*, 97–105.
57. Smith, J.F.; Harner, J.; Zulovich, J.; Pohl, S.; Fulhage, C.; Nicoli, D.; Hetchler, B.; Jacobson, L.; Brouk, M. Comprehensive Evaluation of a Low-Profile Cross-Ventilated Freestall Barn. In Proceedings of the Proceedings of the 8th Western Dairy Management Conference; Reno, 2007; pp. 127–147.
58. Arcidiacono, C. Engineered Solutions for Animal Heat Stress Abatement in Livestock Buildings. *Agric. Eng. Int. CIGR J.* **2018**, 1–22.
59. Vega, F.A.O.; Ríos, A.P.M.; Saraz, J.A.O.; Andrade, R.R.; Damasceno, F.A.; Barbari, M. CFD Study of a Tunnel-Ventilated Compost-Bedded Pack Barn Integrating an Evaporative Pad Cooling System. *Animals* **2022**, *12*, 1776. https://doi.org/10.3390/ANI12141776.
60. Lobeck, K.M.; Endres, M.I.; Janni, K.A.; Godden, S.M.; Fetrow, J. Environmental Characteristics and Bacterial Counts in Bedding and Milk Bulk Tank of Low Profile Cross-Ventilated, Naturally Ventilated, and Compost Bedded Pack Dairy Barns. *Appl. Eng. Agric.* **2012**, *28*, 117–128. https://doi.org/10.13031/2013.41280.
61. Harner, J.P.; Smith, J.F.; Marti, M.H.; Sheffield, R.E.; Zulovich, J.M.; Pohl, S.H.; Pasikanti, S.; Fulhage, C.D.; Nicoli, R.E.; Hetchler, B.; et al. Characteristics of Low-Profile Cross-Ventilated Freestalls. In Proceedings of the 6th International Dairy Housing Conference Proceeding; American Society of Agricultural and Biological Engineers: Minneapolis, 2007; pp. 1–9.
62. Oliveira, C.E.A.; Tinôco, I.F.F.; Sousa, F.C.; Damasceno, F.A.; Andrade, R.R.; Maciel, F.F.; Barbari, M.; Martins, M.A. Analysis of Heat and Mass Transfer in Compost-Bedded Pack Barns for Dairy Cows Using Computational Fluid Dynamics: A Review. *Appl. Sci. 2023, Vol. 13, Page 9331* **2023**, *13*, 9331. https://doi.org/10.3390/APP13169331.
63. Tyson, T.; McFarland, D.F.; Graves, R.E. *Tunnel Ventilation for Tie Stall Dairy Barns*; Penn State Extension: State College, PA, USA, 2014;
64. Melo Júnior, J.C.M.; Bamberg, J.V.M.; Machado, N.S.; Caldas, E.N.G.; Rodrigues, M.S. Evaporative Cooling Efficiency of Pads Consisting of Vegetable Loofah. *Comun. Sci.* **2019**, *10*, 38–44. https://doi.org/10.14295/CS.v10i1.2930.
65. Liao, C.M.; Chiu, K.H. Wind Tunnel Modeling the System Performance of Alternative Evaporative Cooling Pads in Taiwan Region. *Build. Environ.* **2002**, *37*, 177–187. https://doi.org/10.1016/S0360-1323(00)00098-6.
66. Smith, J.F.; Bradford, B.J.; Harner, J.P.; Potts, J.C.; Allen, J.D.; Overton, M.W.; Ortiz, X.A.; Collier, R.J. Effect of Cross Ventilation with or without Evaporative Pads on Core Body Temperature and Resting Time of Lactating Cows. *J. Dairy Sci.* **2016**, *99*, 1495–1500. https://doi.org/10.3168/JDS.2015-9624.