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Review

Analysis of Heat and Mass Transfer in Compost-Bedded Pack Barns for Dairy Cows Using Computational Fluid Dynamics: A Review

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Abstract: To ensure a supply of dairy products, modern dairy farming has assumed an intensive nature, characterized by production in collective facilities with the presence of thermal conditioning, some automation level, and high-use inputs. Among the systems used for dairy cattle confinement, Compost-Bedded Pack Barns (CBPs) have been gaining importance and increasingly have been used in recent decades. CBPs must be designed and managed to ensure the best thermal comfort conditions throughout the year and, consequently, improve productivity, milk quality, and the health of the dairy herd. In this context, modeling via Computational Fluid Dynamics (CFD) emerges as a tool with huge potential for studying the thermal environmental conditions in the beds of CBPs, making it possible to improve projects and/or management practices in this kind of facility. This document is organized as a review, and its objective is to present the state of the art of the applicability of the CFD technique in the study of heat and mass transfer in CBP systems. So far, only four studies have used CFD for modeling CBP systems and have shown that the use of this tool helps to better understand the phenomena of heat and mass transfer in this kind of facility. Therefore, it is important that more studies using this technique in CBP systems be conducted, including additional considerations on constructive elements, animals, and the presence of beds in composting.

Keywords: dairy cattle; production environment; confinement systems; CFD modeling

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1. Introduction

The world's population could increase by up to two billion people between 2022 and 2050 according to the United Nations [1]. At the end of this period, it is estimated that it will be necessary to increase food production by up to 100%, a challenging task due to climate change, hunger, and the demand for land, facts that may increase the pressure on the use of natural resources [2]. In this scenario, it is crucial that the livestock sector continues to provide a safe supply of animal products, contributing to food security, job creation, and people's revenue [3,4].

To ensure the supply of animal products, current livestock farming has become intensive, being characterized by small-area farms, high-use inputs, and production in collective facilities, with the presence of thermal conditioning systems and some level of automation, enabling an increase in the number of animals and production rates [4–6]. Through the use of confinement facilities, it is possible to produce food of animal origin throughout the year and even in places where the production of pasture is not feasible, as production is less dependent on external environmental conditions and forager seasonality [7]. However, to achieve good performance indexes, it is necessary to maintain the thermal–environmental conditions within determined limits, in a way that the productive and reproductive performance of the animals do not be affected [8,9].

In dairy cattle production, the Compost-Bedded Pack Barn (CBP) system, characterized by collective facilities with organic material compost bedding, has been gaining prominence and use worldwide [10,11]. In this type of system, it is important to maintain thermal comfort and bedding moisture, essential conditions that can ensure that good production rates are going to be achieved [11,12]. Therefore, knowing the internal distribution of the thermal environmental conditions and bedding moisture in the animal-occupied zone (AOZ), as well as establishing relationships between ventilation conditions and bedding management, is highly relevant [13,14]. However, for CBP systems with open sides, understanding the thermal and bedding environments is still a great challenge, especially due to the complexity and variability of environmental conditions [15,16], making studies in this area essential.

By conducting evaluation studies of the thermal and bedding environments in CBP systems with open sides, it is expected that it will be possible to obtain detailed information about their operation, identify design and management failures, and propose and make available innovative solutions to producers [17,18]. Preferably, the studies should be carried out at the field level in typical facilities and with the presence of animals, but, taking into consideration that these are large-scale facilities, it is important to remember that conducting experiments is expensive and difficult [19,20].

Alternative and complementary to field studies, the assessment of thermal environmental and bedding conditions can be performed using numerical methods, including the Computational Fluid Dynamics technique—CFD [21,22]. CFD is one of the main techniques that uses numerical methods to characterize, interpret, and quantify heat and mass transfer phenomena using the numerical solution of conservation equations via computation [7,23]. In practice, the application of the CFD technique allows engineering professionals to represent complex regions of physical systems, such as animal facilities, using computational models, considering the most diverse internal and surrounding conditions [23–26].

Due to its versatility, the CFD technique has been increasingly applied for modeling airflow and moisture conditions in agricultural facilities, being considered an ideal complement for field measurements [27]. In dairy cattle facilities, particularly the use of CFD for heat and mass transfer modeling has been widely used to evaluate and understand the behavior of thermal environmental conditions [14–16,19,20,26,28–31]. The expressive majority of CFD modeling studies in dairy cattle facilities were carried out on typical conditions of collective housing systems in individual stalls (Free Stall). Therefore, the conditions are considered different in many aspects from those found in CBP systems, in which collective facilities do not have individual stalls and composting bedding.

Despite the numerous possibilities of using the CFD technique for analysis and understanding heat and mass transfer phenomena in animal facilities, few experimental studies have used this tool for modeling CBP systems. There are no known studies that have addressed the current state of the art on the application of this technique in CBP systems for dairy cattle, considering their various specificities and the advances achieved from the computational viewpoint and numerical description of heat transfer and mass phenomena. In this context, this review study aimed to address these issues, highlighting the main aspects that guide the use of the Computational Fluid Dynamics technique to study heat and mass transfer in Compost-Bedded Pack Barn systems for dairy cattle, as well as the advances and limitations of the technique.

2. Computational Fluid Dynamics

The first use of the Computational Fluid Dynamics technique was carried out in 1970 by Peter V. Nielsen for modeling air movement in a ventilated room [32]. Since then, with the increase in computational processing power, the development of efficient numerical discretization methods, and the implementation of these methods in computational systems, the use of this modeling type has grown and is being applied in the most diverse areas of knowledge [33,34].

According to Norton et al. [23], the acronym CFD, which originated from Computational Fluid Dynamics, is a sophisticated tool for simulating several phenomena, such as heat and mass transfer, phase changes, chemical reactions, etc., which makes it possible to study the computational models of physical systems under the most diverse conditions of interest. In CFD, numerical methods are used to simulate the behavior of the fluid via the resolution of nonlinear partial differential equations using the finite volume method [25,35].

2.1. Governing Equations and Turbulence Models

According to Rong et al. [33], the fundamental equations of fluid dynamics are the basis of CFD modeling. These equations govern the phenomena of continuity, momentum, and heat transfer and are the mathematical formulations of the physical laws that govern all fluid flow, heat transfer, and related phenomena. Through these equations, it is possible to describe the change rate of the interest fluid properties as a function of external forces [23,24]. The governing equations are as follows:

- Conservation of Mass (Continuity Equation) establishes that the rate of mass accumulation must balance with the mass flows into and out (Equation (1)).

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{1}$$

- Conservation of Momentum (Newton's Second Law or Navier–Stokes Equations) establishes that the sum of external forces acting on a fluid particle is equal to its rate of linear momentum change (Equation (2)).

$$\frac{\partial (\rho U)}{\partial t} + \nabla \cdot (\rho U U) = \nabla p + \left[\mu_\tau \left(\nabla U + \nabla U^T \right) \right] \tag{2}$$

- Conservation of Energy (First Law of Thermodynamics) establishes that the change in internal energy of a fluid particle is equal to the sum of the heat exchanged and the work carried out on the particle (Equation (3)).

$$\frac{\partial (C_p T)}{\partial t} + \nabla \cdot \left(-k \nabla T + \rho C_p T U \right) = 0 \tag{3}$$

where C_p is the specific heat, in $J \cdot kg^{-1} \cdot K^{-1}$; k is the thermal conductivity, in $W \cdot m^{-1} \cdot K^{-1}$; p is the pressure, in $N \cdot m^{-2}$; U is the velocity vector; T is the temperature, in K; t is the time, in s; ^{T} is the transposition operator; ρ is the density, in $kg \cdot m^{-3}$; and μ_τ is the dynamic viscosity of the fluid, in $kg \cdot m^{-1} \cdot s^{-1}$.

In addition to the Navier–Stokes and Energy Conservation Equations, additional phenomena and models should be considered, such as the phenomenon of the transfer of chemical species (humidity, gas concentration, etc.) and the physical models of turbulence, porous media, the production of heat by animals, etc. The inclusion of additional equations and models makes it possible to represent the real situation more faithfully [23,36].

The Chemical Species Conservation Equation is like the energy conservation equation and represents the spatial and temporal evolution of the transport of chemical species present in the physical system in question, such as water vapors, and gases such as ammonia (NH_3) and carbon dioxide (CO_2). The conservation equation of a generic chemical species A can be written according to Equation (4):

$$\frac{\partial C_A}{\partial t} + U \cdot \nabla C_A = \nabla \cdot (D \nabla C_A) \tag{4}$$

where C_A is the concentration of chemical species A, in $g \cdot m^{-3}$; and D is the diffusion coefficient, in $m^2 \cdot s^{-1}$.

Due to its nature, several studies have considered the fluid flow in animal facilities as turbulent, seeking to obtain better results via CFD modeling [37]. In these cases, the flows must be modeled using appropriate turbulence models to ensure that the achieved results agree with the real systems. Four different approaches have been developed to describe turbulent flows: Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), Reynolds-Averaged Navier–Stokes (RANS), and Scale Resolution Simulation (SRS) [33,38].

In the DNS approach, the Navier–Stokes equations are solved directly on the smallest length and time scales without the need to implement assumptions and/or sub-models. The application of the DNS approach is limited to relatively low Reynolds numbers, and it can be extremely time consuming, greatly limiting its use. In LES modeling, a filter is used, in which vortices larger than a certain size are directly resolved, and the effect of smaller vortices is modeled using sub-models. LES modeling is still too expensive to use in routine simulations and is currently restricted to use in industry and engineering projects. In the RANS approach, turbulent flows are averaged out, and isotropic turbulence is generally assumed (Bousinessq assumption). In SRS models, certain flow classes are resolved in the numerical domain, while others are averaged, as in the RANS approach [23,33,38,39].

2.2. Software Used

Several CFD codes and/or software are available to meet the need for fluid dynamics modeling and can be applied to different fields of study. According to the use, these codes must meet different requirements, and for modeling animal facilities in particular, they must make it possible to model flow-dependent properties (including flow through porous media) that the user implements functions of interest, which can generate different meshes, etc. [23].

Usually, the software used for CFD simulations is commercial. Among these, for modeling animal facilities can be highlighted the Ansys® CFX [28,29,36,40–43], Ansys® Fluent [15,16,19,20,31,35,39,44–46], and the Simcenter STAR-CCM+ [13,47].

Among the CFD software in the public domain, it can be highlighted using the OpenFOAM software distributed by the OpenFOAM Foundation. In addition to being free, one of its advantages is that it is open source, allowing users to access previously implemented models and make the necessary adjustments to their reality [48–50].

3. CFD Applied to Compost-Bedded Pack Barn Systems

Compost-Bedded Pack Barn (CBP) systems emerged as an alternative to Free Stall (FS) and Tie Stall (TS), models traditionally used for dairy cattle confinement worldwide [11]. The use of this confinement model began in 2001 in the United States of America [51] and, since then, has spread to the most diverse world regions, with reports of its use also in countries in South America [52–56], Asia [57–60], Europe [61–64], among other regions.

In the CBPs, the animals remain housed in collective facilities with soft and comfortable organic material bedding, which, together with the waste deposited and under certain conditions, are decomposed over time of use [10]. As bedding composting is a biological process, it is influenced by parameters such as temperature, humidity, hydrogen potential (pH), and nutrient concentrations in the bedding material, as well as oxygen availability (Figure 1) [65,66].

In these systems, as in other intensive animal production models, the control of thermal and air comfort conditions is paramount; additionally, the bedding material must be kept dry [66,67]. In this sense, it can be said that proper management (of the thermal environment and the bedding), considering the reality of each facility, is the key to achieving satisfactory performance with its use [11,12]. Therefore, the ventilation use, natural or mechanical, can be considered a primordial factor in this type of system, being related to the typology of the facilities [23,67–69] and, consequently, with the considerations to be carried out regarding the modeling of this type of system. Through the CFD technique use, it is possible to understand the different interactions that occur between the thermal environmental variables and the animals housed in this type of facility [23].

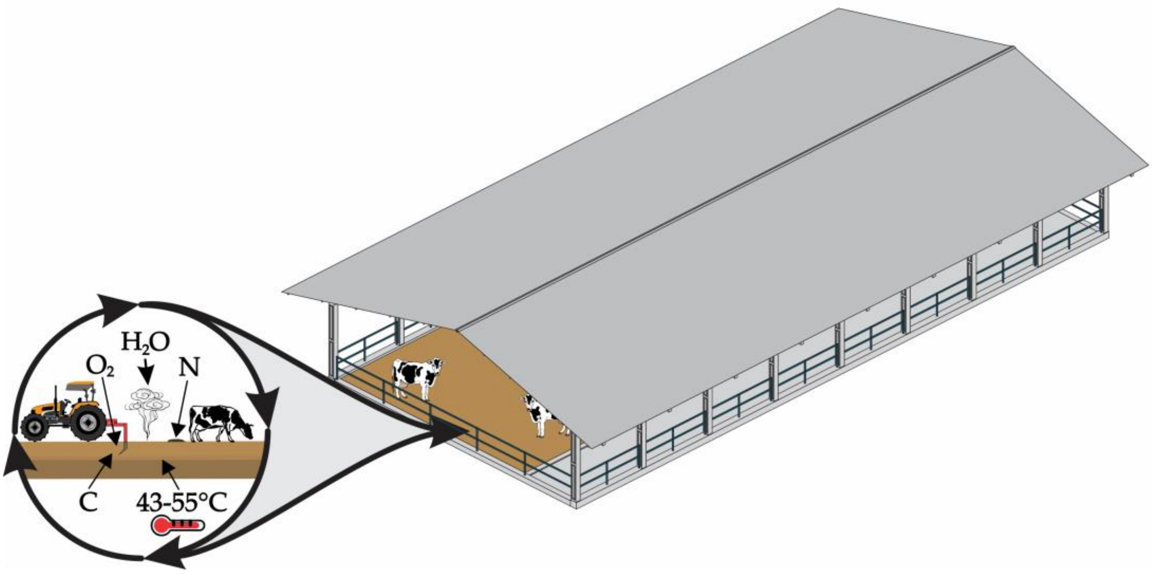

Figure 1. Schematic representation of a Compost-Bedded Pack Barn system (emphasis on the bedding). C—carbon; H_2O—water; N—nitrogen; and O_2—oxygen. Source: Adapted from Damasceno [66].

3.1. CBPs Typology and Computational Domain

Ventilation is the main strategy used to control the thermal environmental conditions inside CBP systems. Through its use, it is possible to control, within certain limits, the air temperature levels, relative humidity of the air, and bedding moisture, as well as to maintain adequate oxygen concentrations and remove gases, dust, odors, and pathogens [70]. Given the ventilation importance, the architectural design of CBP systems varies according to the type of ventilation system and can be didactically classified into two types: CBPs with open sides, positive pressure ventilation, with the use of natural air flows and supplementation via mechanical ventilation (Figure 2a); closed CBPs, with negative pressure mechanical ventilation, usually associated with evaporative cooling (Figure 2b).

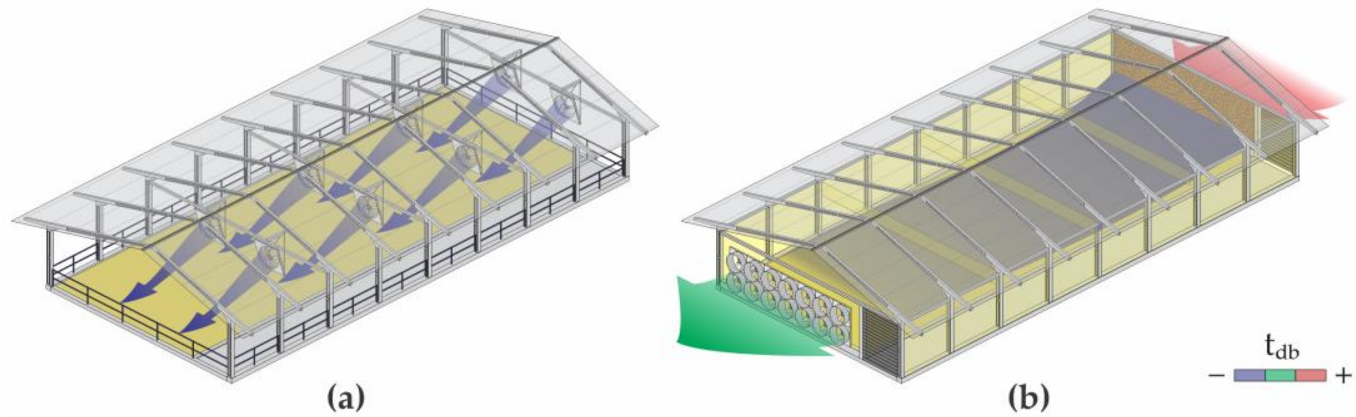

Figure 2. Representation of open Compost-Bedded Pack Barns systems with positive pressure mechanical ventilation (**a**) and closed with negative pressure mechanical ventilation and evaporative cooling (**b**). t_{db}—dry air bulb temperature. Source: The authors.

Based on the typology, the computational domain to be used in the modeling of this type of facility is defined. According to Norton et al. [23], three approaches can be used to represent the model of an animal facility in a computational domain of a CFD study:

(1) indoor and outdoor environments of the facility represented in a single computational domain; (2) internal and external environments divided into two computational subdomains, with independent resolution in each one and interpolation of interface results; and (3) only the facility's internal environment represented in the computational domain.

Approach (1) is considered more advantageous in terms of approximation with a real situation of animal facilities with open sides or with a large opening's presence, as it performs the direct coupling of the internal and external environments. However, it demands higher computational cost since the necessary mesh must satisfactorily represent the environments of the internal (must be more refined) and external (may be less refined but is large scale) facilities. From the technological development that occurred in recent decades, the computational cost is no longer a problem in CFD since the advance in computational power has made the solution of complex flow problems more accessible [71]. This type of approach has been used for modeling facilities for dairy cattle with open sides [15,16,31,47,49,72], including CBP facilities.

In approach (1), the size of the computational domain is a function of the building dimensions, always being necessary to include a sufficient surrounding volume for the flow to be fully developed windward and leeward [22,48]. Whenever this type of approach is used to represent the model of an animal facility in the computational domain, the computational volume of a height $\geq 5 \times$ H (H = highest height of the facility within the computational domain), as well as the distance to the ends $\geq 10 \times$ H (upstream and downstream of the interesting facility), as shown in Figure 3 [22,73]. Another form to define the required computational domain is via the blockage rate, obtained from the ratio between the projected frontal area (windward) of the obstacles and the cross-section of the computational domain [74]. It is recommended that the blockage rate be less than 3% to avoid artificial flow acceleration [16]. It is important to highlight those surrounding facilities and/or other types of physical obstructions to air flow, which must always be included in the computational domain, as well as considered for the calculation of minimum distances to the extremities and/or the blockage rate. If this is not carried out, the artificial acceleration of the air flow may occur. Therefore, the results obtained may not represent the real situation.

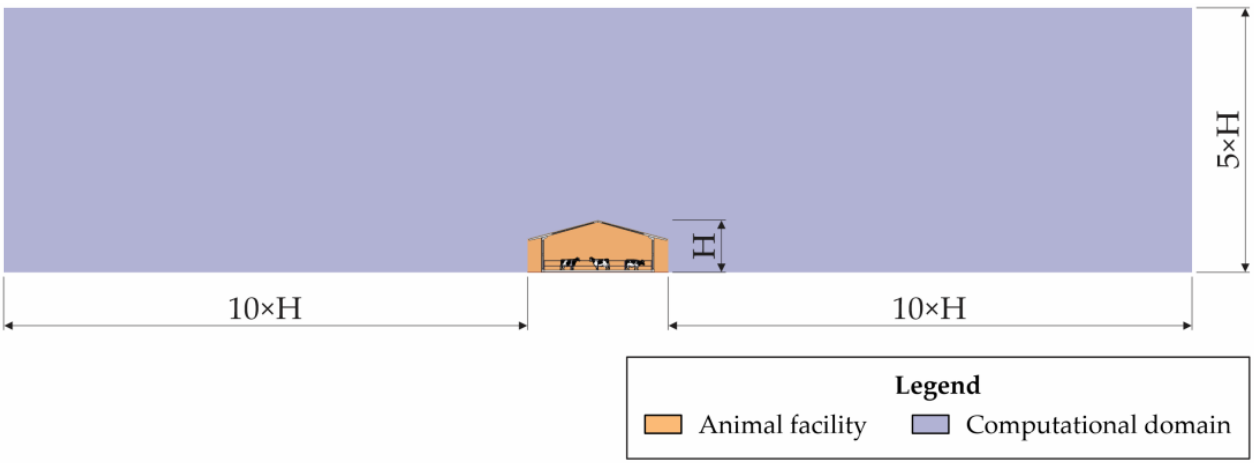

Figure 3. Schematic representation of the computational model needed in facilities with open sides (internal and external environments of the facility represented in a single computational domain). H—highest facility height within the computational domain. Source: Adapted from Lv et al. [22].

Approach (2) is not commonly applied in animal facilities, its use has been reported only in a few investigations of natural ventilation, where direct coupling between indoor and outdoor environments was not computationally achievable [23,75].

In turn, approach (3) is remarkably applicable to the case of fully closed CBP systems with negative pressure ventilation. In this case, it is assumed that the facility is perfectly sealed, with air entering and exiting only through specific openings, such as evaporative pad cooling and exhaust fans. However, as in physical (real) facilities, air leaks may occur due to failures in the curtain sealing, access gates, lining, etc., some discrepancies may be found between experimental measurements and simulated results, and, whenever possible, leaks must be quantified and considered in the computational model [39,44,76].

According to Damasceno et al. [37], CFD modeling studies comparing open and naturally ventilated animal facilities or with the presence of mechanical ventilation are rarely performed, as there is relative difficulty in establishing boundary conditions in relation to natural ventilation due to the variability and non-uniformity of direction and wind speed. Together, animal facilities usually have a large scale, but the microenvironments that compose them must be represented in detail, also contributing to their modeling being quite challenging [14]. In this sense, depending on the constructive characteristics and the type of facility, some of the following strategies can be used to reduce the computational model complexity, which may be cited:

- For facilities of big length, where there are flow conditions repeatability, it is possible to model and collect data for validation only in a smaller facility region, if it is representative. This strategy has already been used by some authors for modeling animal facilities using CFD, such as Saraz et al. [41].
- In facilities with symmetry, the computational domain can be simplified to half of the constructive unit, as discussed in some CFD studies [77,78]. This type of simplification can be interesting for modeling fully enclosed CBP facilities with a central alley, where there is normally symmetry.
- Facilities for cattle usually have a high height (>3.0 m). Therefore, the internal computational domain can be divided into two subdomains: animal-occupied zone (AOZ, height $\leq$ 1.5 m) comprising the region occupied by animals, in which there is greater interest in this study, and there is a need for refinement and structuring to ensure consistent and regular sampling; and headspace (HS, height > 1.5 m), a region of free air movement of less interest in research, may be less refined (mesh with fewer divisions) and unstructured, with refinement only at ends and openings. In this case, the plane between the subdomains must be configured as an interface to ensure the continuity of the flow in this region (between both meshes) [14,77].
- When choosing to model the animals distributed along the AOZ, they can be represented by ellipsoids with body length and diameter obtained from animals' linear measurements of the same size and age. Simply put, laying down animals can be represented by half an ellipsoid and those standing up by a whole ellipsoid, as already applied satisfactorily in some studies [47,76]. The animals can also be represented by a set of cylinders (representing the trunk, paws, and head), ensuring adequate results, as observed in some studies [43,79].
- AOZ can be assumed to be a porous medium with resistance to air flow rather than simulating animals, flooring, and small partition structures in detail, which would require complex meshes, a lot of time to calculate, and might not achieve convergence. This strategy has been adopted by several researchers in studies of animal facilities, such as Wu et al. [31], Mondaca et al. [14], and Wang et al. [77].
- If the facility has a lining under the roof, the computational model can be generated without the roof presence [41], simplifying the computational domain. However, when the facility has pillars and/or walls inside, whenever possible, these constructive components should also be included in the computational model, and their effects should be considered in the heat and mass transfer processes [36].
- Due to the high computational cost, the fan's complete geometry can be suppressed, which are represented only by circles/ellipses of the same diameter, only informing the speed and/or air flow values [42,80]. Whenever possible, performance data (air speed and flow, pressure, etc.) of the fans should be obtained using field tests [14].

In addition to the above simplifications, others can be performed, depending on the conditions observed in the field of the modeled animal facility and/or based on other studies with similar conditions. However, in all cases, these considerations must be made with caution, so that the results obtained via modeling do not present divergences in relation to the real situation [7,37]. For this reason, CFD modeling studies in CBP systems should preferably be conducted by multidisciplinary teams, including agricultural, environmental, civil and chemical engineers, biologists, physicists, and other professionals necessary for understanding the important phenomena that occur in this type of system. These multidisciplinary teams must have recognized knowledge of the transport phenomena (transfer of heat, mass, and chemical species such as moisture and gases), as well as a good understanding of the environmental dynamics (animals occupied zone) and the composting process. Thus, it is expected that the results obtained from the CFD model generated for the CBP system(s) reproduce scientifically sound results that are representative of real conditions.

3.2. Mesh Generation and Independence Testing

In order to obtain accurate and reliable results in the simulations, it is essential that adequate meshes are generated [31]. For dairy cattle facilities, hybrid meshes (structured and unstructured) with interfaces are usually used, which fulfill the role of uniting the two types of meshes and ensuring flow continuity. Typically, unstructured meshes are applied to represent complex regions, such as around animals and/or places with curvature, and structured meshes are applied to more regular regions, such as headspace [19,29].

The element size that makes up the mesh also influences the results achieved: the smaller these elements are, the greater the precision of numerical values and the better the modeling quality. However, meshes with too small elements demand more computational time, making the simulation process time consuming and costly [19,28,77,81]. Failure to properly refine the mesh can lead to increased discretization errors and hinder the convergence of the iterative process with second-order discretization schemes [74].

Seeking to minimize uncertainty in relation to mesh refinements, it is recommended to conduct mesh independence tests. To carry out such tests, meshes with distinct refinement levels in the interest regions must be generated, and adequate shapes must be used to evaluate the refinement effects in relation to temporal and spatial concentration gradients [41]. In CFD, several evaluation forms and/or metrics are used to analyze the mesh refinement effect on the results achieved, such as equiangular asymmetry [39,44,82], coefficient of determination (R^2) [81], relative difference [15], relative error [77], root mean square deviation (RMSD) [14,31,81], unidirectional nonparametric variance analysis (Kruskal–Wallis test) [41], among others. Failure to carry out mesh independence tests may compromise the results obtained, as there will be no guarantee that the refinements performed were sufficient to reduce the discretization errors to acceptable levels and that the results are mesh independent.

3.3. Boundary Conditions and Simulation Schemes

Common considerations normally assumed in CFD modeling studies of animal facilities are incompressible, turbulent, and steady flow [28,42]. Based on studies available in the literature, some distinctions regarding the boundary conditions in the CFD modeling of CBP systems with open and fully closed sides can be made (Table 1). It is important to note that Table 1 lists only general distinctions about boundary conditions that can be applied to modeling open and closed CBP systems. Therefore, for each case, procedures must be carried out to verify the applicable boundary conditions to adequately represent the heat and mass transfer processes that occur in the physical facility. Notably, the boundary and initial conditions for steady-state simulations must be defined based on the atmospheric boundary layer and experimental data [7,83].

Table 1. Boundary conditions applicable to Computational Fluid Dynamics modeling in Compost-Bedded Pack Barns systems with open and fully enclosed sides.

No.	Location	Type	Specifications	References
Compost-Bedded Pack Barn Systems with Open Sides				
1	Fans	Inlet	Establish air velocity and turbulent intensity in air flow directions	Das et al. [84]
2	Roof, pillars, floors of food and service alleys, walls, etc.	Wall	Non-slip condition, isothermal, with temperatures specified per experimental conditions	Mondaca et al. [14] Vega et al. [29] Cao et al. [15]
3	Bedding surface	Wall	Non-slip condition, with variable temperature according to experimental measurements	Vega et al. [29]
4	Inlet region of natural air currents	Inlet	Air speed established according to experimental measurements	Pakari and Ghani [16]
5	Region opposite to the entry of natural air currents	Outlet	Static pressure set to zero	Pakari and Ghani [16] Cao et al. [15]
6	Side openings	Opening	Entrainment, with relative pressure established according to experimental conditions	Pakari and Ghani [16]
Closed Compost-Bedded Pack Barns systems				
1	Evaporative pad cooling inlet	Opening	Entrainment, with relative pressure established according to experimental conditions	Wang et al. [77] Vega et al. [29]
2	Evaporative pad cooling output	Outlet	Air speed established according to experimental measurements	Vega et al. [29]
3	Roof, side curtains, deflectors, pillars, doors, floors of food and service alleys, walls, etc.	Wall	Non-slip condition, isothermal, with temperatures specified per experimental conditions	Mondaca et al. [14] Wang et al. [77] Vega et al. [29] Cao et al. [15]
4	Bedding surface	Wall	Non-slip condition, with variable temperature depending on the distance from the pad cooling	Vega et al. [29]
5	Side curtains	Symmetry		Vega et al. [29]
6	Exhaust fans	Outlet	Establish air velocity and turbulent intensity in air flow directions	Mondaca et al. [14] Das et al. [84] Vega et al. [29]

Regarding the boundary condition applied to the bedding surface, some distinctions need to be made. The modeling studies of CBP systems considered non-slip conditions and heat generation due to bedding composting activity, indicating constant [28] or variable temperature throughout the facility [29]. In future studies, it is also important to include the transfer of chemical species, such as moisture and water vapor generated via the accumulation of animal feces/urine and bedding composting, respectively. The inclusion of considerations related to the bedding composting process in CBP systems, including the generation of heat, water vapor, gases, and their inter-relationships with thermal environmental conditions is a field that still needs to be explored and improved in future CFD modeling studies.

In animal facility modeling studies, the pressure–velocity coupling is usually calculated using the Semi-Implicit Method for Pressure-Linked Equations scheme (SIMPLE), and the spatial discretization is performed using the second-order upwind scheme [14,15,19,29,31,44,47,77].

In the agricultural engineering field, specifically for modeling facilities for animal and vegetable production, the most commonly used approach to describe turbulent flows is the RANS via the standard k-ε, k-ε RNG, k- ε realizable, and Reynolds Stress Model—RSM [16,39]. In facilities for poultry, cattle, and swine, the use of the standard k-ε turbulence model is considered reliable for modeling turbulent flows due to achieving favorable convergence, reasonable accuracy, and lower computational cost compared to the others [13,15,16,31,37,42,47,77,80]. This model adds extra stress (Reynolds stress) to the viscosity (μ_T), relating the turbulent kinetic energy (k) to its dissipation (ε) [28,36,72]. In modeling animal facilities, the standard k-ε model is usually used in conjunction with an improved treatment (refinement) near the walls [19,20,29,45].

In some studies, the k-ε RNG (Renormalization Group) model has been used to model the airflow in the internal and external environments of the facilities and, according to the authors, this model can improve the results achieved due to the inclusion of the additional terms for dissipation rates modeling [37,45,78]. This turbulence model differs from standard k-ε in that it considers the small scales of fluid motion that contribute to turbulent diffusion [84].

When modeling animal facilities, it is important to also consider buoyancy forces, especially when working with natural and/or natural ventilation systems combined with mechanics [38]. In this case, the thermal buoyancy caused by the heating and/or air cooling must also be modeled, and, therefore, the state equation must relate the air density with its thermodynamic state (temperature and pressure). Methods that can be used to describe changes in air density due to thermal buoyancy are the Boussinesq approximation and treating air as an ideal gas [23,37].

The Boussinesq approximation considers only dry air as the fluid medium and is not commonly used in CFD studies in animal facilities, as most flows in these facilities have a mixture of dry air and moisture. Considering air as an ideal gas allows for expressing the difference in air density via the Ideal Gas Equation, but its use does not consider pressure, and, despite ensuring an accurate description of air density variations, it has an impact on the convergence of CFD solutions [23,37,38]. Despite their importance, buoyancy forces are not considered in most works, and their introduction is only carried out when the modeled results do not show a good fit in relation to the experimental ones [38]. For CBP systems with open sides, which normally have openings in the ridge (side opening, skylight, etc.), to take advantage of natural ventilation, whenever possible, buoyancy forces should be considered, using one of the mentioned approaches.

Several criteria for the convergence of the results can be adopted in the modeling studies of animal facilities. The most common is to consider that there a convergence of the results when the absolute residuals were less than 10^{-4} [15,19,28,29,42]. However, in some cases, other criteria may be adopted, more or less rigid, as necessary.

3.4. Post-Processing and Model Validation

In the post-processing stage, the user can visualize and analyze the simulation results using contour graphs, vectors, lines, etc. [23]. One of the most common visualizations that yields the results in studies of animal facilities using CFD is the contour planes (horizontal and/or vertical), which is applied in several studies [20,36,42,46]. In this case, the horizontal and/or longitudinal profiles of the interest variable (temperature, humidity, air velocity, thermal comfort indexes, gas concentrations, etc.) are described, making it possible to reach good detail levels in the variable distribution. Another visualization form is via the isosurface and isovolume maps, which make it possible to proportionally quantify the area/volume with values above or below the variable/index of interest, in addition to its distribution [14,45].

For air speed, in particular, in many studies, the results are visualized using air speed vectors [13,15,28,36,46,49] and air current lines [13,42], allowing us to understand in more detail how the air flow occurs. Typically, mass-weighted averages are used to sample the air velocity magnitude and calculate its average value over the interest sections [14].

From the scalar fields of the modeled variables (air temperature, relative humidity, air velocity, etc.), it is possible to proceed with the calculation of thermal comfort indexes applicable to the evaluation of the thermal environmental conditions to which the animals are submitted. Among the indexes that can be used, the Temperature and Humidity Index (THI) can be highlighted, which relates the temperature to the relative humidity of the air [85,86], and the Equivalent Temperature Index for Dairy Cattle (ETIC), which includes the effects of air velocity and solar radiation, in addition to temperature and relative humidity [19,29,87].

If is desired to calculate the achieved ventilation rate, the reduction method can be used. One of the ways to apply this method is to use a tracer gas with known concentration and with the same properties as the ventilation air. This gas can be treated as a passive scalar and solved after obtaining the flow field solution, that is, decoupling the momentum equations. Initially, all the internal cells that make up the facility mesh have a fixed unit concentration (C_0), and the external cells have zero concentration. The gas concentration inside the facility reduces at a rate that depends on local air velocity values, and, when all the gas has been removed to the outside of the facility, the volumetric gas concentration (C) can be tabulated in a time-dependent exponential function t ($C = C_0 \cdot e^{-nt}$), where the scalar n describes the ventilation rate of studied control volume [13].

The validation of the CFD modeling using experimental data is also particularly important, as it will make it possible to understand whether the simulated results adequately represent the real facility environment. When it comes to modeling animal facilities, whenever possible, experimental data for validation should be collected at different heights and facility sections to represent the animals' occupied zones and headspace in regions of inlet, central, and air outlets [44]. In relation to air velocity, in particular, its magnitude is usually measured in experimental data collections, and in some cases, its direction is also recorded [28].

To assess the agreement between simulated results and experimental data collected in animal facilities, several metrics are applicable, such as normalized mean square error —NMSE [41,42,45], root mean square error—RMSE [29], relative error [44,80], among others.

3.5. CFD Studies Performed on CBPs

The CFD technique has been widely used to study heat and mass transfer in facilities for the following production animals: cattle, poultry, and swine [10–12,15,16,20–25,27,29,30,32–44,65,67–76]. This can be evidenced by the increase in the number of peer-reviewed experimental articles that use this technique for modeling animal facilities (Figure 4).

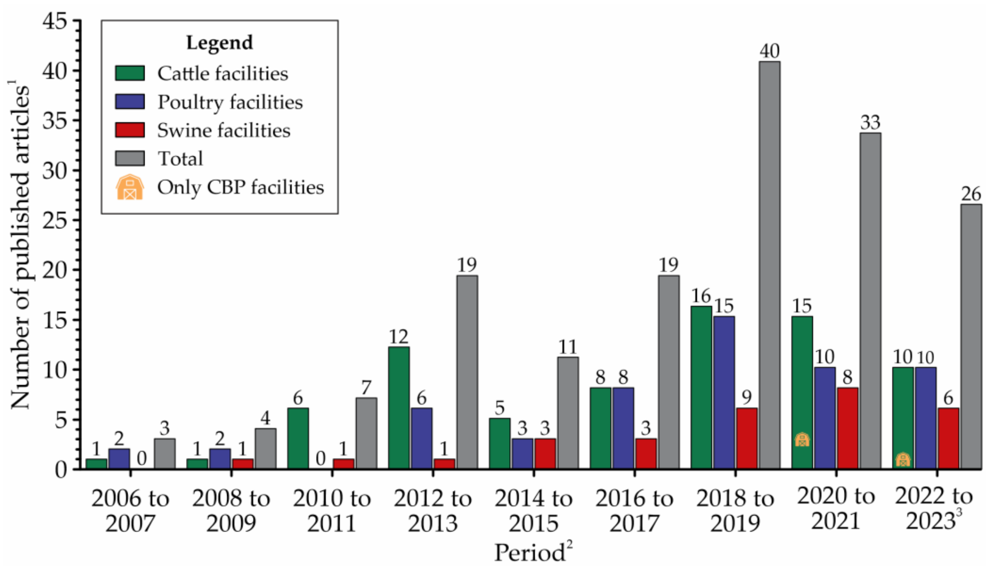

Figure 4. Number of peer-reviewed experimental articles published since 2006 on CFD applied to cattle, poultry, and swine facilities. [1] Only peer-reviewed experimental articles in English were considered (further details in Appendix A); [2] Assessment carried out from 2006 to 2023, coinciding with the period in which studies on CBP systems were published, according to reported by Silva et al. [88]; [3] Considered publications made in the first half of 2023 (until June 30). Source: The authors (Appendix A).

Regarding the modeling of cattle facilities, more than 70 studies with CFD applications were published in the period considered. However, specifically regarding CBP systems, only four peer-reviewed studies have been published, all from 2020. According to the bibliometric analysis conducted in the Scopus database (Appendix A), the four studies of CFD application in CBP systems were carried out by Fagundes et al. [42], Vega et al. [45], Damasceno et al. [28], and Vega et al. [29]. Table 2 lists some detailed information on these studies. Additional information, including specifications on the considered initial and boundary conditions, can be obtained directly from the manuscripts.

Table 2. Details on the studies that used the Computational Fluid Dynamics technique to evaluate Compost-Bedded Pack Barns (CBP) systems, according to the bibliometric research conducted in Scopus (Appendix A).

Reference	FCT	Dim.	Code	Grid	SD	Turb.	EV	Comments
Fagundes et al. [42]	CBP with open sides	3D	Ansys® CFX	GCSP	2nd order upwind	Std. k–e	Yes	Bedding surface temperature is considered constant and equal to 25 °C
Vega et al. [45]	CBP with open sides	3D	Ansys® Fluent	NGCS	NS	RNG k-ε	Yes	Only the validation of the developed propeller anemometers was carried out in CBP systems
Damasceno et al. [28]	CBP with open sides	3D	Ansys® CFX	GCSP	NS	Std. k–e	Yes	Validation carried out in a wind tunnel, using reduced models of naturally ventilated CBP systems
Vega et al. [29]	CBP fully closed	3D	Ansys® CFX	GCSP	2nd order upwind	k-ε with SWF	Yes	Modeling performed considering the animal's presence, represented by spheres

3D—three-dimensional; Dim.—dimensionality; EV—experimental validation; FCT—facility constructive typology; GCSP—grid convergence study performed; NGCS—no grid convergence stud; NS—not specified. PVC—pressure–velocity coupling; RNG—Renormalization Group; SD—spatial discretization; Std.—standard; and SWF—scalable wall function.

Fagundes et al. [42] carried out a study that aimed to validate a CFD model to determine the homogeneity of airflows generated via different mechanical ventilation systems [high-volume and low-speed fans (HVLS), and low-volume and high-speed fans (LVHS)] on CBP systems. Based on the results achieved, the authors concluded that the proposed model was satisfactory in representing the air flows promoted via both ventilation systems, and the system with HVLS fans returned a more uniform flow when compared to that equipped with LVHS fans.

Vega et al. [45] conducted a study with the objective of developing and testing a network of low-cost 3D-printed propeller anemometers, as well as simulating and validating their performance in CBP systems using CFD. Based on the results achieved, the authors concluded that the developed anemometers can be used to determine the airflow profile in CBP facilities with a predominance of air velocity values greater than 0.7 $m \cdot s^{-1}$. Additionally, they concluded that the CFD model developed was satisfactory in representing the air flow in the modeled facilities, making it possible to identify facility regions with ventilation problems.

Damasceno et al. [28] developed a 3D CFD model for evaluating naturally ventilated CBP systems with different wind direction conditions and roof ridge opening configurations, and their influence on the bedding surface. Based on the results achieved, the authors concluded that the CFD model developed showed good agreement with the experimental results, being able to adequately represent the air flow through CBP systems. For wind conditions from west to east (predominant wind direction during this study), the best roof configuration was the one with the presence of a chimney-type central opening.

Vega et al. [29] carried out a study in which a CBP system was modeled with tunnel ventilation associated with adiabatic evaporative cooling via CFD and studied the distribution of dry air bulb temperature (t_{db}), relative humidity (RH), and air velocity (v_{air}) inside the system. The CFD model was validated using experimental data, and the authors observed the conditions of high relative humidity and low air velocity, causing a moderate stress condition for the cattle housed in the facility. To improve the thermal comfort and bedding drying conditions, the authors recommended increasing the v_{air} (>3 $m \cdot s^{-1}$) for the conditions of t_{db} > 30 °C and RH > 55%, as well as installing deflectors after the evaporative pad cooling to direct the air flow to the bedding.

CFD modeling studies carried out on CBP systems indicated that it is necessary to conduct further research in facilities with similar configurations and improve on the considerations made to obtain more accurate results. Even though many studies have not yet been carried out with the application of the CFD technique for modeling the internal conditions in CBP systems, it is understood that the various studies carried out in intensive dairy cattle production systems, mainly Free Stall systems, can be used as a basis for modeling CBP systems, provided pertinent considerations are made.

3.6. Considerations for Future Studies

Potentially, some simplifications conducted to reduce the complexity of the computational domain and of the collections for CFD models validation of animal facilities can cause divergences between modeled and experimental results. In this context, based on the literature, some important considerations that can be applied to CFD modeling of CBP systems in future studies were addressed as follows:

- If the facility has pillars and/or walls inside, these constructive elements must be considered in the computational domain. Normally, there is a reduction in air velocity in the regions where these elements are located, and, consequently, there is a tendency for the concentration of temperature, humidity, and gases, which is not going to be predicted in the CFD model if they are not considered in the computational domain [36].
- In the case of CBP systems with open sides, if there are other buildings nearby, these must be included in the computational model since they can influence the air flow and the environmental conditions inside the facility [31]. The same is valid for variations in topography in the external region of the facility, which can influence the air flow when they are large scale [48]. If there is variation in the speed and direction of natural air flow through the inlet side of the facility due to variations in terrain and other obstacles, whenever possible, these variations should be included in the computational model, using relevant approaches, so that divergences do not occur in relation to the real situation [36].
- Whenever possible, it is recommended that housed animals be included in the computational domain with uneven distribution according to the places where there is a tendency for their concentration [29]. In this way, the simulation can return results closer to those of the physical (real) system, unlike the cases in which the AOZ is assumed to be a uniform porous medium [14,31], which disregards the fact that the animals tend to concentrate in certain facility regions, such as near feeders, drinkers, salt troughs, sprinkler lines, etc. Additionally, it is important to highlight that when the animal's presence is not represented in the computational domain, as observed in some CFD studies carried out in animal facilities [16,30,44], the results achieved will not represent a typical production situation.
- It is important to include momentum source terms due to the animal's presence and building elements, as well as heat source terms due to animal metabolism and the bedding composting process. These terms must be calculated considering adequate approaches, according to the pressure, energy, and metabolic loss mechanisms that occur in each case and included together with the momentum and energy conservation equations [36,48].
- As there is variation in the spatial distribution of bedding temperature, as reported in some studies [17,18], due to ventilation conditions and bedding management, it is of interest to establish distribution models of the bedding surface temperature, as performed by Vega et al. [29]. If the bedding surface temperature is considered constant throughout the area, deviations from real situations may occur.

- As there is the transfer of chemical species, such as moisture and water vapor due to the accumulation of animal feces/urine and bedding composting, it is also important to include transport models for these and other chemical species present in CBP systems. If this is not considered in the CFD modeling, the results achieved may differ from the physical systems, given that the mass balance will not faithfully represent the real situation.

Above, only the main considerations for the proper application of the CFD technique to the CBP systems modeling were highlighted. However, it is important to emphasize again that this type of study should preferably be conducted by multidisciplinary teams composed of professionals with recognized knowledge in the field of transport phenomena and a good understanding of the animal-occupied zone and the bedding composting process.

4. Conclusions

The Computational Fluid Dynamics (CFD) technique is a sophisticated tool for simulating heat and mass transfer phenomena and has immense potential for use in modeling Compost-Bedded Pack Barns (CBPs) systems. Regarding the application of the CFD technique to study CBP systems, the following can be highlighted:

- The computational domain must be defined considering the constructive typology of the facility and other aspects that influence the phenomena of heat, mass, and energy transfer. For open facilities, the indoor and outdoor environments are usually represented in a single computational domain, while for closed facilities, only the indoor environment is represented. In both cases, refinements must be performed in the interest regions, as well as mesh independence tests.
- Numerical schemes and turbulence models, specifically Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) and second-order upwind schemes, are usually used for pressure-velocity coupling and for spatial discretization, respectively. The commonly used turbulence models are the standard k-ε and k-ε RNG, selected based on the desired accuracy and computational cost.
- Post-processing and validation: The results obtained are usually visualized using contour planes, vector graphics, and air current lines. To verify that the CFD model is satisfactory in adequately representing the real facility environment, it is important that validation studies are conducted using experimental data.

So far, few studies using CFD to model the internal conditions in CBP systems have been conducted, but these have shown that the use of this tool makes it possible to better understand the phenomena of heat and mass transfer in this type of facility. In this sense, it is important that more studies are carried out using this technique in CBP systems, including additional considerations such as the presence of constructive elements and animals inside the facility, other buildings, and/or other physical barriers to air circulation in the external region of the facility, source term of heat due to the animal's metabolism, and bedding composting, among others. These future studies can potentially improve the understanding of the thermal environmental dynamics and, consequently, enable the improvement of projects and/or management in this type of facility.

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Appendix A

To survey the peer-reviewed articles published in recent years on the application of the CFD technique to study heat and mass transfer in animal facilities, a brief bibliometric analysis was performed, following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta- Analyzes (PRISMA) [89]. This analysis was performed on Scopus, which is considered a comprehensive platform because it accommodates studies published in different databases [90].

Since the objective was to return studies on specific topics (facilities for animals), several search terms were used (Table A1) to return the largest possible number of publications on the subject. To group the different words and/or expressions forms that could return studies on the interesting topics, the systematic search was carried out with the integration of Boolean operators (AND, OR, and NOT), together with wildcard truncations (" ").

In the bibliometric search carried out in Scopus, only experimental articles written in English were considered, excluding review articles, dissertations, theses, and studies in which peer review was uncertain (conference proceedings and book chapters). The period from 2006 to 2023 was considered, as it coincides with the period in which studies on CBP systems were published, according to reports by Silva et al. [88]. Inclusion and exclusion criteria for articles were defined a priori, and no additional restrictions, such as sample size or journal quality, were imposed to enable the identification of a comprehensive set of available studies.

Finally, Microsoft Excel® was used to extract and organize information about the selected studies. In the mentioned software, a graph was created containing the number of CFD application publications in the study of cattle, poultry, and swine facilities at each 2-year period (from 2006), as well as in CBP-type facilities. The graph obtained is illustrated in Figure 3 (Section 3.5. CFD studies performed on CBPs).

Table A1. Search terms used when searching for peer-reviewed experimental articles in bibliometric analysis on Computational Fluid Dynamics applied to heat and mass transfer in animal facilities.

Acronym	Search String
CFD	CFD OR "Computational Fluid Dynamics" OR "Computational Fluid Dynamic"
Cattle facilities	"dairy cattle houses" OR "dairy cattle house" OR "dairy cattle housings" OR "dairy cattle housing" OR "dairy cattle buildings" OR "dairy cattle building" OR "dairy cattle facilities" OR "dairy cattle facility" OR "dairy cattle barns" OR "dairy cattle barn" OR "dairy cows houses" OR "dairy cows house" OR "dairy cows housings" OR "dairy cows housing" OR "dairy cows buildings" OR "dairy cows building" OR "dairy cows facilities" OR "dairy cows facility" OR "dairy cows barns" OR "dairy cows barn" OR "dairy houses" OR "dairy house" OR "dairy housings" OR "dairy housing" OR "dairy buildings" OR "dairy building" OR "dairy facilities" OR "dairy facility" OR "dairy barns" OR "dairy barn" OR "cattle houses" OR "cattle house" OR "cattle housings" OR "cattle housing" OR "cattle buildings" OR "cattle building" OR "cattle facilities" OR "cattle facility" OR "cattle barns" OR "cattle barn" OR "livestock houses" OR "livestock house" OR "livestock housings" OR "livestock housing" OR "livestock buildings" OR "livestock building" OR "livestock facilities" OR "livestock facility" OR "livestock barns" OR "livestock barn" OR "compost barn" OR "compost bedded" OR "compost-bedded pack" OR "compost-bedded barn" OR "compost-bedded pack barn" OR "compost-bedded pack barn system" OR "free-stall" OR "free stall" OR "freestall" OR "free-stall barns" OR "freestall facilities" OR "freestall facility" OR "tie-stall" OR "tie stall" OR "tiestall" OR "tie-stall barns" OR "tiestall facilities" OR "tiestall facility"

Table A1. *Cont.*

Acronym	Search String
Poultry facilities	"broiler houses" OR "broiler house" OR "broiler housings" OR "broiler housing" OR "broiler buildings" OR "broiler building" OR "broiler facilities" OR "broiler facility" OR "broiler barns" OR "broiler barn" OR "poultry houses" OR "poultry house" OR "poultry housings" OR "poultry housing" OR "poultry buildings" OR "poultry building" OR "poultry facilities" OR "poultry facility" OR "poultry barns" OR "poultry barn" OR "broiler chickens houses" OR "broiler chickens house" OR "broiler chickens housings" OR "broiler chickens housing" OR "broiler chickens buildings" OR "broiler chickens building" OR "broiler chickens facilities" OR "broiler chickens facility" OR "broiler chickens barns" OR "broiler chickens barn" OR "chickens houses" OR "chickens house" OR "chickens housings" OR "chickens housing" OR "chickens buildings" OR "chickens building" OR "chickens facilities" OR "chickens facility" OR "chickens barns" OR "chickens barn" OR "hen houses" OR "hen house" OR "hen housings" OR "hen housing" OR "hen buildings" OR "hen building" OR "hen facilities" OR "hen facility" OR "hen barns" OR "hen barn" OR "layer hen houses" OR "layer hen house" OR "layer hen housings" OR "layer hen housing" OR "layer hen buildings" OR "layer hen building" OR "layer hen facilities" OR "layer hen facility" OR "layer hen barns" OR "layer hen barn"
Swine facilities	"piglet houses" OR "piglet house" OR "piglet housings" OR "piglet housing" OR "piglet buildings" OR "piglet building" OR "piglet facilities" OR "piglet facility" OR "piglet barns" OR "piglet barn" OR "pig houses" OR "pig house" OR "pig housings" OR "pig housing" OR "pig buildings" OR "pig building" OR "pig facilities" OR "pig facility" OR "pig barns" OR "pig barn" OR "swine houses" OR "swine house" OR "swine housings" OR "swine housing" OR "swine buildings" OR "swine building" OR "swine facilities" OR "swine facility" OR "swine barns" OR "swine barn" OR "swine nursery houses" OR "swine nursery house" OR "swine nursery housings" OR "swine nursery housing" OR "swine nursery buildings" OR "swine nursery building" OR "swine nursery facilities" OR "swine nursery facility" OR "swine nursery barns" OR "swine nursery barn" OR "farrowing houses" OR "farrowing house" OR "farrowing housings" OR "farrowing housing" OR "farrowing buildings" OR "farrowing building" OR "farrowing facilities" OR "farrowing facility" OR "farrowing barns" OR "farrowing barn"
Only CBP facilities	"compost barn" OR "compost bedded" OR "compost-bedded pack" OR "compost-bedded barn" OR "compost-bedded pack barn" OR "compost-bedded pack barn system"

CBP—Compost-Bedded Pack Barns; and CFD—Computational Fluid Dynamics.

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