CARLOS EDUARDO ALVES OLIVEIRA

PRODUCTION SYSTEMS OF DAIRY CATTLE IN COMPOST-BEDDED PACK BARNS DURING WINTER AND SUMMER IN BRAZIL

Thesis submitted to the Agricultural Engineering Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Doctor Scientiae*.

Adviser: Ilda de Fátima Ferreira Tinôco

Co-advisers: Fernanda Campos de Sousa
Márcio Arêdes Martins
Matteo Barbari
Rafaella Resende Andrade
Richard Stephen Gates

VIÇOSA - MINAS GERAIS
2024

Ficha catalográfica elaborada pela Biblioteca Central da Universidade Federal de Viçosa - Campus Viçosa

T

O48c
2024

Oliveira, Carlos Eduardo Alves, 1995-
Production systems of dairy cattle in Compost-Bedded Pack Barns during winter and summer in Brazil / Carlos Eduardo Alves Oliveira. – Viçosa, MG, 2024.
1 tese eletrônica (169 f.): il. (algumas color.).

Texto em inglês.
Inclui anexo.
Inclui apêndice.
Orientador: Ilda de Fátima Ferreira Tinôco.
Tese (doutorado) - Universidade Federal de Viçosa, Departamento de Engenharia Agrícola, 2024.
Inclui bibliografia.
DOI: https://doi.org/10.47328/ufvbbt.2024.270
Modo de acesso: World Wide Web.

1. Construções rurais - Aquecimento e ventilação. 2. Bovinos de leite - Instalações. 3. Saúde animal. 4. Compostagem. I. Tinôco, Ilda de Fátima Ferreira, 1957-. II. Universidade Federal de Viçosa. Departamento de Engenharia Agrícola. Programa de Pós-Graduação em Engenharia Agrícola. III. Título.

CDD 22. ed. 631.22

Bibliotecário(a) responsável: Bruna Silva CRB-6/2552

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APPROVED: July 22, 2024.

Assent:

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Data: 05/08/2024 08:16:26-0300
Verifique em https://validar.iti.gov.br

Ilda de Fátima Ferreira Tinôco
Adviser

To the men and women who live in the countryside,

Who dedicate themselves daily to the fundamental and important mission of producing food for the human population.

I OFFER!

To God,

To my beloved parents, Verbene and Lisboa,
To my greatest role example, my grandfather Eduardo,
To my beloved, Ana Isabel.

I DEDICATE!

ACKNOWLEDGEMENTS

To God, my guide and protector always, for all the blessings bestowed, for being my light in life and throughout my PhD journey, and for helping me overcome all obstacles. You are my refuge, God!

To my beloved wife, Ana Isabel, for the love, understanding, companionship, patience, trust, and unconditional support. Thank you so much for taking such loving care of me and walking by my side at all times. With you by my side, this journey has become lighter and happier!

To my beloved parents, Verbene and Lisboa, to my dear sisters, Carla and Débora, and to my beloved nephews, Davi and Júlia, for the unconditional love, encouragement, and affection, even despite all the absences. I am incredibly grateful to you all for supporting me in the pursuit of this dream!

To my dear maternal grandparents, Maria and Eduardo, my examples of honesty, simplicity, character, and dedication to the family. You are the strong foundation of our family!

To my dear paternal grandparents, Ana Rosa (in memoriam) and Manoel (in memoriam), my examples of simplicity and love. Even though you are no longer present in this realm, I am sure you are watching over and caring for our entire family!

To my uncles, aunts, cousins, and other family members, for your prayers, support, and constant encouragement. This achievement is also yours!

To the Universidade Federal de Viçosa (UFV), especially the Department of Agricultural Engineering (DEA) and the Graduate Program in Agricultural Engineering (PPGEA), for the opportunity to pursue my PhD in this environment of rich learning.

To the Research Centre on Ambience and Engineering of Agro-industrial Systems (AMBIAGRO), my second home and workplace sanctuary in Viçosa.

Special thanks to my dear supervisor, Professor Ilda de Fátima Ferreira Tinôco, for the opportunity, encouragement, wise guidance and teachings, trust, professional and personal example, and the valuable friendship we have built. You have my eternal gratitude!

To Professor Fernanda Campos de Sousa, for the co-supervision, recommendations, timely suggestions, and friendship built during both the master's and doctoral periods.

To the distinguished Professor Matteo Barbari, for the wise co-supervision, timely suggestions, numerous opportunities, and friendship built throughout my academic journey.

To Professors Márcio Arêdes Martins, Rafaella Resende Andrade, and Richard Stephen Gates (in memoriam), for the co-supervision, helpfulness, suggestions, and friendship.

To the esteemed Professors Cecília de Fátima Souza Ferreira and Fernando da Costa Baêta, for the knowledge imparted, words of support, countless teachings and contributions, and friendship built throughout the master's and doctoral journeys. To Professor Valmir Sartor, for the knowledge exchanges, words of encouragement, and friendship built.

To the professors and staff of DEA/UFV, for their countless contributions to my professional development and readiness to help whenever needed.

To Professor Flávio Alves Damasceno, my esteemed undergraduate advisor, for the friendship, incentive, teachings, and unique contributions to my professional development.

To my dear colleagues from AMBIAGRO, Charles Paranhos, Erika Cruz, Fabiane Maciel, Fellype Franco, Harold Torres, Hiago Zanetoni, Jhoan Ramos, Leonardo França, Mariana Ribeiro, Maria Angela, Sarah Martins, and Victor Crespo, for the moments of professionalism and relaxation, and for the partnership built.

Special thanks to the scholarship holders and/or interns Ana Carolina Sabino, Dezirrê Costa, Jocássia Reis, Marcos Castro, Thais Mello, Thalya Avelar, Thauane Soares, Thiago Braga, and Túlio Mariano, for their availability and commitment during the setup and execution of field experiments. Thank you very much!

To the dear friends that PPGEA/UFV has given me, especially Beatriz Vargas, Poliana Bandeira, and Pedro Rodrigues, for the friendship forged, partnership, and assistance during classes, experiment management, and student representation.

To the dear friends that Viçosa has given me, especially Khalil Lacerda, Raissa Nascimento, Joslanny Higino, and Laylton de Albuquerque, for the friendship and countless special moments shared.

To Farm Nô da Silva, its owners, family members, administrators, and staff, for their availability for conducting experiments and the friendship built.

To the members of the thesis defense committee, for the time spent reading and valuable contributions to the improvement of this work.

To the Coordination of Superior Level Staff Improvement – Brazil (CAPES), who financed in part the execution of this study (Finance Code 001).

To the National Council for Scientific and Technological Development – Brazil (CNPq), who financed in part the execution of this study (Process 422912/2018-2). To the Minas Gerais Research Support Foundation – Brazil (FAPEMIG), who financed in part the execution of this study (Finance Code 001).

Finally, to all those who directly or indirectly contributed to my achieving this long-awaited milestone in my life, thank you very much!

"The achievements depend 50% on inspiration, creativity, and dreams, and 50% on discipline, hard work, and determination. They are two legs that must walk together".

(Augusto Cury)

BIOGRAPHY

CARLOS EDUARDO ALVES OLIVEIRA, son of Antônio Lisboa Oliveira and Antônia Verbene Alves Bezerra, was born on 12th May 1995, in Quiterianópolis, Ceará, Brazil.

In August 2013, he began his undergraduate studies in Agricultural and Environmental Engineering at the Federal University of Mato Grosso (UFMT), Rondonópolis Campus, where he was a Scientific Initiation (PIBIC/UFMT) and Teaching Assistant scholarship holder.

In August 2015, he transferred to the Agricultural Engineering program at the Federal University of Lavras (UFLA), where he was a Scientific Initiation (PIBIC/UFLA and PIBIC/CNPq) and Program for Tutorial Education scholarship holder (PET/MEC).

In December 2018, he underwent the defense of his undergraduate thesis titled "**Spatial distribution of thermal environment, noise, illuminance, and bedding variables in Compost Barn facilities**", under the adviser of the Professor Flávio Alves Damasceno.

In August 2019, he graduated with a Bachelor's degree in Agricultural Engineering from UFLA. In the same year, he started his professional career as Agricultural Mechanization Trainee at SLC Agrícola S/A, where he completed an internship in the first semester of 2019.

In March 2020, he started his Master's degree in the Agricultural Engineering Graduate Program at the Federal University of Viçosa (PPGEA/UFV), focusing on Rural Constructions and Ambience (research line Ambience, Engineering, and Architecture of Agricultural and Agro-industrial Systems in Animal and Plant Production).

In February 2022, he underwent the defense of his Master's dissertation titled "**Spatial and temporal distribution of environmental and bedding variables in open Compost Barn in winter conditions in Brazil**", under the adviser of the Professor Ilda de Fátima Ferreira Tinôco.

In March 2022, he started his PhD in the Agricultural Engineering Graduate Program at UFV, focusing on Rural Constructions and Ambience (research line Ambience, Engineering, and Architecture of Agricultural and Agro-industrial Systems in Animal and Plant Production).

In July 2024, he underwent the defense of his PhD thesis titled "**Production systems of dairy cattle in Compost-Bedded Pack Barns during winter and summer in Brazil**", under the adviser of the Professor Ilda de Fátima Ferreira Tinôco.

ABSTRACT

OLIVEIRA, Carlos Eduardo Alves, D.Sc., Universidade Federal de Viçosa, July, 2024. **Production systems of dairy cattle in Compost-Bedded Pack Barns during winter and summer in Brazil**. Adviser: Ilda de Fátima Ferreira Tinôco, Co-advisers: Fernanda Campos de Sousa, Marcio Arêdes Martins, Matteo Barbari, Rafaella Resende Andrade e Richard Stephen Gates.

Given the growing interest among Brazilian dairy producers in adopting Compost-Bedded Pack Barns (CBP) systems, this research was developed to contribute to a greater elucidation of aspects of environmental aspects in terms of thermal comfort, animal health, and the physicochemical bedding quality in these systems, particularly for the typical climatic conditions of Brazil. This research started with a comprehensive review of the state of the art in the mentioned areas of interest, based on studies conducted worldwide. This was followed by experimental phases in the field, conducted in a typical CBP system located in a major dairy region in Minas Gerais (the largest milk-producing state in the country), under winter and summer climatic conditions (considered the most challenging). In the first article, health and thermal comfort indicators for dairy cattle housed in CBP, Free Stall (FS), Loose Housing (LH), and/or Tie-Stall (TS) systems were described and discussed through a systematic literature review. It was found that the incidence of certain health issues, such as lameness, limb injuries, and reproductive disorders, is lower in animals housed in CBP systems. However, if bedding management in this system is not effective in providing dry, comfortable, and hygienic surfaces for the housed animals, there may be an increase in somatic cell count and the prevalence of mastitis. For thermal comfort, within CBP systems with open sides and positive-pressure mechanical ventilation, higher temperatures were observed in summer and lower temperatures in winter, compared to those recorded in FS-CV systems (negative-pressure ventilation combined with evaporative padding cooling). Secondly, in the next systematic literature review article, it was found that environmental conditions affect the physicochemical indicators of bedding quality in CBP systems, with the composting process being less intense during winter when bedding management was considered more challenging. To keep the composting process active, it was found necessary to adopt more efficient and intensive management practices during winter, such as more frequent replacement of bedding with dry material, increased bedding turning, use of aeration systems under the bedding, installation of side closures in the facilities, among other measures. The third article addressed the current state of the art regarding the use of Computational Fluid Dynamics (CFD) techniques for analyzing heat and mass transfer in CBP systems. It was found that relatively few studies have been conducted using CFD to model the internal conditions of CBP systems. However, these studies demonstrated that using this tool allows for a better understanding of heat and mass transfer phenomena in such systems. Therefore, new evaluations of CBP systems must be conducted using this technique, which has great potential and can contribute to elucidating the thermal environment and the composting process in these systems. In the fourth article, the temporal and spatial behavior of dry-bulb air temperature (t_{db}, in °C), relative humidity (RH, in %), and the Temperature-Humidity Index (THI) was characterized in a typical CBP system (with open sides and positive-pressure ventilation) used for housing lactating Holstein dairy cows during winter and summer in a subtropical mesothermal climate region in Brazil. It was found that, during winter, the average thermal conditions were maintained within the comfort range for lactating Holstein dairy cows ($t_{db} \leq 24.00$ °C and THI ≤ 74.00), despite the prevalence of high RH values. However, during summer, the average values of t_{db} and THI remained above 24.00 °C and 74.00, respectively, between 09:10 a.m. and 6:30 p.m. During this period of time, it was observed that there was potential for more efficient use of evaporative cooling systems, as the RH values were below 80.00 %. Using geostatistical techniques, it was found that there was strong spatial dependence, and maps were created from which it was observed that spatial variability was greater in the morning, afternoon, and during the times of absolute minimum and maximum values for t_{db}, RH, and THI. Based on these results, it can be concluded that the thermal environment improvement methods used in the CBP system under study were insufficient to maintain uniform and thermally comfortable conditions for the Holstein dairy cows housed, particularly during the hot summer afternoons. Consequently, it can be inferred that these systems were either not properly sized or not adequately managed. It will be necessary to redefine them and/or employ other methods, whether natural or artificial, during the warmer periods of the day throughout the year.

Keywords: Animal health; Composting bedding; Dairy cows housing; Modelling; Physicochemical parameters; Thermal comfort.

RESUMO

OLIVEIRA, Carlos Eduardo Alves, D.Sc., Universidade Federal de Viçosa, julho de 2024. **Sistemas *Compost-Bedded Pack Barns* na produção de bovinos leiteiros durante inverno e verão no Brasil**. Orientadora: Ilda de Fátima Ferreira Tinôco. Coorientadores: Fernanda Campos de Sousa, Marcio Arêdes Martins, Matteo Barbari, Rafaella Resende Andrade e Richard Stephen Gates.

Considerando o crescente interesse dos produtores de leite brasileiros na adoção dos sistemas de confinamento de bovinos leiteiros denominados *Compost-Bedded Pack Barns* (*CBP*), desenvolveu-se essa pesquisa, objetivando contribuir para maior elucidação de aspectos do ambiente sob o prisma de conforto térmico, saúde animal e qualidade físico-química da cama nesses sistemas, para condições climáticas típicas do Brasil. Partiu-se de amplo levantamento do estado da arte nos mencionados aspectos de interesse, com base em estudos realizados em todo o mundo, seguido de fases experimentais, em campo, conduzidas em sistema *CBP* típico situado em bacia leiteira importante em Minas Gerais (Estado maior produtor de leite do país), em condições climáticas de inverno e de verão (consideradas mais desafiadoras). No primeiro artigo, indicadores de saúde e conforto térmico de bovinos leiteiros alojados em sistemas *CBP*, *Free Stall* (*FS*), *Loose Housing* (*LH*) e/ou *Tie-Stall* (*TS*), foram descritos e discutidos por meio de revisão sistemática de literatura. Verificou-se que a incidência de alguns problemas de saúde, tais como claudicação, lesões nos membros e distúrbios reprodutivos, é menor nos animais alojados no sistema *CBP*. Todavia, se o manejo da cama nesse sistema não for eficiente em assegurar o fornecimento de superfícies secas, confortáveis e saudáveis para os animais alojados, pode ocorrer aumento na contagem de células somáticas e na prevalência da incidência de mastite. Para conforto térmico, no interior dos sistemas *CBP* abertos com ventilação mecânica por pressão positiva, foram retratadas temperaturas mais altas no verão e mais baixas no inverno, em relação ao que foi registrado em sistemas *FS-CVe* (ventilação por pressão negativa associada ao resfriamento evaporativo, via placas de celulose umedecidas). No segundo artigo de revisão sistemática de literatura, verificou-se que as condições ambientais afetam indicadores de qualidade físico-química da cama nos sistemas *CBP*, sendo que o processo de compostagem é menos intenso durante o inverno, quando o manejo da cama foi considerado mais desafiador. Para manter o processo de compostagem ativo, verificou-se que é necessário adotar práticas de manejo mais eficientes e intensivas durante o inverno, como maior periodicidade de reposição da cama com material seco, maior frequência de revolvimento, uso de sistemas de aeração sob a cama, implantação de fechamentos laterais nas instalações,

entre outras medidas. No terceiro artigo, foi abordado o estado atual da arte sobre o uso da técnica de Fluidodinâmica Computacional (*CFD*) para análises de transferência de calor e massa em sistemas *CBP*. Verificou-se que ainda foram conduzidos poucos estudos utilizando *CFD* para modelar as condições internas de sistemas *CBP*. Contudo, tais estudos evidenciaram que o uso dessa ferramenta possibilita entender melhor os fenômenos de transferência de calor e massa nesse tipo de sistema. Portanto, é importante que novas avaliações de sistemas *CBP* sejam realizadas aplicando essa técnica, que tem grande potencial de uso e pode contribuir para elucidação do ambiente térmico e do processo de compostagem nesse sistema. No quarto artigo, caracterizou-se o comportamento temporal e espacial de temperatura de bulbo seco do ar (t_{bs}, em °C), umidade relativa do ar (UR, em %), e Índice de Temperatura e Umidade (ITU), em sistema *CBP* típico (laterais abertas e ventilação por pressão positiva), utilizado para alojamento de vacas leiteiras holandesas em lactação, durante inverno e verão, em uma região de clima mesotérmico subtropical no Brasil. Verificou-se que, durante o inverno, as condições térmicas médias foram mantidas dentro da faixa de conforto térmico para vacas leiteiras holandesas em lactação ($t_{bs} \leq 24,00$ °C; e ITU $\leq 74,00$), apesar da prevalência de altos valores de UR. Porém, durante o verão os valores médios de t_{bs} e ITU mantiveram-se acima de 24,00 °C e 74,00, respectivamente, no intervalo entre às 09:10 e às 18:30. Nesse intervalo de tempo, se verificou que havia potencial para uso mais eficiente de sistemas de resfriamento evaporativo do ar, uma vez que os valores de UR eram inferiores a 80,00 %. Utilizando a técnica de geoestatística, verificou-se que houve ocorrência de forte dependência espacial e foram gerados mapas, a partir dos quais observou-se que a variabilidade espacial era maior pela manhã, à tarde, e nos horários de valores mínimos e máximos absolutos de t_{bs}, UR e ITU. Com base nesses resultados, conclui-se que os métodos de melhoria do ambiente térmico utilizados no sistema *CBP* em estudo não foram suficientes para manter condições homogêneas e termicamente confortáveis às vacas leiteiras holandesas alojadas, notadamente durante as tardes quentes de verão. Por conseguinte, pode-se inferir que esses sistemas não estavam bem dimensionados e/ou não foram manejados adequadamente, sendo necessário redimensioná-los e/ou fazer uso de outros métodos, naturais e/ou artificiais, durante os períodos mais quentes do dia, ao longo do ano.

Palavras-chave: Alojamento de vacas leiteiras; Cama em compostagem; Conforto térmico; Modelagem; Parâmetros físico-químicos; Saúde animal.

LIST OF ILLUSTRATIONS

Health and Thermal Comfort of Dairy Cattle in Compost-Bedded Pack Barns and Other Types of Housing: A Comparative Systematic Review

Physicochemical Bedding Quality in Compost-Bedded Pack Barn Systems for Dairy Cows: A Systematic Review

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

Temporal and spatial behavior of thermal microenvironment variables in a Compost-Bedded Pack Barn system with positive-pressure ventilation during winter and summer in Brazil

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LIST OF ACRONYMS AND ABBREVIATIONS

1^{st}	First.
2^{nd}	Second.
3D	Three-dimensional.
3^{rd}	Third.
4^{th}	Fourth.
A	Area
AFD	Airflow direction.
AMBIAGRO	Research Centre on Ambience and Engineering of Agro-industrial Systems.
AOZ	Animal-occupied zone.
AT	Austria.
BAA	Bedding area per animal.
BCS	Body condition score.
BM	Bedding material.
BR	Brazil.
BTO	Bedding turning operations.
C	Carbon.
C.d.F.S.	Cecília de Fátima Souza.
C.E.A.O.	Carlos Eduardo Alves Oliveira.
C:N	Carbon:Nitrogen ratio.
C_A	Concentration of chemical species A.
CAPES	Coordination of Superior Level Staff Improvement.
CBP	Compost-Bedded Pack Barn.
CFD	Computational Fluid Dynamics.
CFD	Fluidodinâmica Computacional.
CH	Coffee husk.
CNPq	National Council for Scientific and Technological Development.
CO_2	Carbon dioxide.
C_p	Specific heat.
CS	Corn straw.
CV	Coefficient of variation.
CVe	Systems with negative-pressure mechanical ventilation.
D	Diffusion coefficient.

DE	Germany.
DEA	Department of Agricultural Engineering.
Dep.	Depth.
Dim.	Dimensionality.
DNS	Direct Numerical Simulation.
ETIC	Equivalent Temperature Index for Dairy Cattle.
EU	Experimental unit.
EV	Experimental validation.
F.C.d.S.	Fernanda Campos de Sousa.
F.d.C.B.	Fernando da Costa Baêta.
F.d.F.M.	Fabiane de Fátima Maciel.
F.M.C.V.	Frederico Márcio Côrrea Vieira.
FAPEMIG	Minas Gerais Research Support Foundation, Brazil.
FaS	Faecal score.
FB	Forest biomass.
FCT	Facility constructive typology.
FS	Free Stall.
FS-B	Free Stall systems that used straw bedding.
FS-CVe	Free Stall systems with negative-pressure mechanical ventilation.
FS-CVe	Sistemas Free Stall com ventilação mecânica por pressão negativa.
FS-M	Free Stall systems that used rubber mattresses.
FS-NV	Free Stall systems with natural and/or positive-pressure mechanical ventilation.
FS-SC	Free Stall systems with a self-cleaning floor.
FS-SR	Free Stall systems barn with a slatted floor scraped by robots.
FSt.	Flax straw.
G.B.	Gianluca Bambi.
GCSP	Grid convergence study performed.
GO	Goiás.
H	Highest height of the facility.
h	Distance.
H_2O	Water.
HS	Hygiene score.
HVLS	High-volume, low-speed mechanical ventilation.
HW	Household waste.

i	Roof inclination.
I.d.F.F.T.	Ilda de Fátima Ferreira Tinôco.
IT	Italy.
ITU	Índice de Temperatura e Umidade.
k	Thermal conductivity.
K	Potassium.
LES	Large Eddy Simulation.
LH	Loose Housing.
LL	Length of life.
LS	Locomotion score.
LVHS	Low-volume, high-speed mechanical ventilation.
M.A.M.	Márcio Arêdes Martins.
M.B.	Matteo Barbari.
M_B	Bedding moisture.
$M_{B\text{-Dep.}}$	Moisture in the aerobically active layer.
ME	Mean error.
MG	Minas Gerais.
ML	Maximum Likelihood.
MVT-EC	Negative-pressure mechanical ventilation associated with evaporative cooling.
N	Nitrogen.
N(h)	Number of experimental pairs.
NGCS	No grid convergence stud.
NH_3	Ammonia.
NL	Netherlands.
NMSE	Normalized mean square error.
NS	Not specified.
NV	Systems with natural and/or positive-pressure mechanical ventilation.
O_2	Oxygen available.
OH	Oat husk.
OLS	Ordinary Least Squares.
OM	Other materials.
p	Pressure.
P	Phosphorus.
P_C	Prevalence of coughing.

P_{CE}	Prevalence of cytological endometritis.
P_{CL}	Prevalence of chronic laminitis.
P_{CM}	Prevalence of calf mortality.
$P_{Conj.}$	Prevalence of conjunctivitis.
P_{DA}	Prevalence of displaced abomasum.
P_{DC}	Prevalence of downer cows.
$P_{Diar.}$	Prevalence of diarrhea.
$P_{Dys.}$	Prevalence of dystocia.
PEFH	Parity at exit from the herd, parity number.
P_{FCR}	Prevalence of first calving risk.
$P_{Footrot}$	Prevalence of footrot.
pH	Hydrogen potential.
pH_{B}	Bedding hydrogen potential.
P_{HHE}	Prevalence of heel horn erosion.
P_{HL}	Prevalence of hock lesion.
P_{HL-Sev}	Prevalence of severe hock lesion.
P_{Hoof-L}	Prevalence of hoof lesions.
P_{HR}	Prevalence of hampered respiration.
P_{ICB}	Prevalence of inflamed coronary bands.
PICO	Population, Intervention, Comparison, and Outcome.
P_{IH}	Prevalence of interdigital hyperplasia.
P_{KL}	Prevalence of knee lesion.
P_{KR}	Prevalence of ketosis risk.
PL	Poland.
PL	Productive lifespan.
$PL_{Clin.}$	Prevalence of clinical lameness.
P_{Limb-C}	Prevalence of limb contusion.
PL_{Mildly}	Prevalence of mildly lameness.
$PL_{Sev.}$	Prevalence of severe lameness.
$P_{M-Clin.}$	Prevalence of clinical mastitis.
P_{MI}	Prevalence of mastitis infection.
$P_{Misc.}$	Prevalence of miscarriage.
P_{Mo}	Prevalence of mortality.
P_{ND}	Prevalence of nasal discharge.

$P_{NH\text{-}SCC}$	Prevalence of new high SCC.
P_{OD}	Prevalence of ocular discharge.
P_{PCI}	Prevalence of prolonged calving intervals.
$P_{Pneu.}$	Prevalence of pneumonia.
P_{PP}	Prevalence of parturient paresis.
P_{PVD}	Prevalence of purulent vaginal discharge.
PR	Paraná
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses.
P_{RP}	Prevalence of retained placenta.
P_{SA}	Prevalence of skin alopecia.
P_{SL}	Prevalence of sprained limb.
$P_{Still.}$	Prevalence of stillbirth.
P_{SU}	Prevalence of sole ulcers.
P_{TI}	Prevalence of teat infection.
PVC	Pressure–velocity coupling.
P_{WLD}	Prevalence of white line disease.
R^2	Coefficient of determination.
RANS	Reynolds-Averaged Navier–Stokes.
REML	Restricted Maximum Likelihood.
RH_{Adj}	Relative humidity adjusted value.
RH_R	Relative humidity value read by the DHT22 sensor.
RMSD	Root mean square deviation.
RMSE	Root mean square error.
RNG	Renormalization Group.
ROBIS	Risk of Bias in Systematic Reviews.
RR	Respiration Rate.
RSM	Reynolds Stress Model.
Sa.	Sawdust.
$Sa._G$	Green sawdust.
SCC	Somatic Cell Count.
ScP	Scopus.
SDI	Spatial Dependence Index.
SD_{ME}	Mean-error standard deviation.
SD_{SEr}	Standardized-error standard deviation.

SE	Sweden.
SEr	Standardized-error.
SH	Soy husk.
SI	Slovenia.
SIMPLE	Semi-Implicit Method for Pressure-Linked Equations.
SP	Spain.
SRS	Scale Resolution Simulation.
SS	Soybean straw.
Std.	Standard.
Sur.	Surface.
SWF	Scalable wall function.
T	Temperature.
t	Time.
TAS	Thermophilic aerobic spores.
t_{B}	Bedding temperature.
$t_{B\text{-}Dep.}$	Bedding temperature in the aerobically active layer.
t_{bs}	Temperatura de bulbo seco do ar.
$t_{B\text{-}Sur.}$	Bedding surface temperature.
t_{db}	Dry-bulb air temperature.
$t_{db\text{-}Adj}$	Dry-bulb air temperature adjusted value.
$t_{db\text{-}Fall}$	Dry-bulb air temperature in Fall.
$t_{db\text{-}R}$	Dry-bulb air temperature value read by the DHT22 sensor.
$t_{db\text{-}Spring}$	Dry-bulb air temperature in Spring.
$t_{db\text{-}Summer}$	Dry-bulb air temperature in Summer.
$t_{db\text{-}Winter}$	Dry-bulb air temperature in Winter.
THI	Temperature and Humidity Index.
THI_{Summer}	Temperature and Humidity Index in Summer.
TS	Tie-Stall.
UFLA	Federal University of Lavras.
UFV	Federal University of Viçosa.
UniFI	University of Firenze.
UR	Umidade relativa do ar.
USA	United States of America.
UTCL	Upper thermal comfort limit.

UTFPR	Federal University of Technology—Paraná.
v_{air}	Air velocity.
VM	Various materials.
VST	Ventilation system type.
VW	Vegetable waste.
WC	Wood chips.
WLS	Weighted Least Squares.
WoS	Web of Science.
WS	Wheat straw.

LIST OF SYMBOLS

%	Percentage.
*	Asterisk.
$\hat{\gamma}(h)$	Estimated semivariance.
$\wedge$	Minimum.
$\vee$	Maximum.
®	Trademark.
°C	Celsius Degree.
a	Range.
a’	Practical range.
$C_0 + C_1$	Sill.
C_0	Nugget effect.
C_1	Contribution.
n	Number of observations.
s	Standard deviation.
^{T}	Transposition operator.
U	Velocity vector.
$\overline{x}$	Mean.
X_i	Value of t_{db} or RH recorded by the DHT22 sensor module.
Y_i	Adjusted t_{db} or RH value.
$Z(X_i)$	Value at a sampled point.
β_0	Intercept coefficient.
β_1	Slope coefficient.
ΔRH	Amplitude of variation of relative humidity.
Δt_{db}	Amplitude of variation of dry-bulb air temperature.
ΔTHI	Amplitude of variation of Temperature and Humidity Index.
ε	Dissipation.
μ_τ	Dynamic viscosity of the fluid.
ρ	Density.

SUMMARY

GENERAL INTRODUCTION

Bovine milk production plays a vital role in human food and nutritional security, significantly contributing to job and income generation worldwide. Over the next decade, global milk production is estimated to grow by approximately 1.60% per year, according to the OECD-FAO Agricultural Outlook 2024-2033 (OECD/FAO, 2024). However, in most regions of the world, this growth will only be achieved if significant improvements in housing, nutrition, genetics, and animal health are ensured (OECD/FAO, 2023).

Despite the growth expectation in global milk production, the productive sector faces several challenges, such as climate change, which affects the availability of food and water, causes heat stress, and consequently leads to a decline in dairy cow's productivity (Becker et al., 2020; Ji et al., 2020; Britt et al., 2021; Herron et al., 2022; Neethirajan, 2023; Schrobback et al., 2023). In addition, increasing changes in consumer expectations also pose a significant challenge, as they demand alterations in housing methods and animal management practices to improve their welfare during production (Blanco-Penedo et al., 2020; Galama et al., 2020; Beaver et al., 2021; Klopčič et al., 2021; Poulopoulou et al., 2023).

The use of adequate confinement systems is one of the main strategies employed to minimize the impacts of climatic fluctuations and/or changes on milk productivity and consistency throughout the year (Saitone & Sexton, 2017; Bleizgys et al., 2022). Among dairy cattle confinement systems, the Free Stall (FS) system is predominantly adopted, not only in Brazil but also in other countries with high milk production volumes. This model of confinement allows animals to roam freely within facilities that include common areas for movement, exercise, and feeding, as well as individual resting areas composed of parallel stalls with bedding made from various materials (Bewley et al., 2017; Beaver et al., 2021; Mõtus et al., 2024). However, in recent decades, there has been a significant increase in the use of the Compost-Bedded Pack Barns (CBP) system, recognized as an alternative model for intensive dairy farming worldwide. This system is particularly favored due to its reduced water requirement (a rare and scarce resource) for the removal of animal waste (a costly and more complex process) and the utilization of it. When mixed with the organic bedding material and decomposed, it becomes an excellent material for agricultural (Biasato et al., 2019; Blanco-Penedo et al., 2020; Galama et al., 2020; Leso et al., 2020; Fuertes et al., 2023; Guesine et al., 2023; Andrade et al., 2024).

In the CBP system, dairy cows are housed in a collective area made up of vegetable bedding (usually sawdust or wood shavings) and without individual stalls (Eckelkamp et al., 2016; Leso et al., 2020; Llonch et al., 2020; Freu et al., 2023; Pons et al., 2023). This organic material present in the collective resting area (vegetable bedding + animal waste) is degraded over time through composting processes, which is the main difference compared to other models of dairy cattle confinement in facilities with bedding (Biasato et al., 2019; Damasceno, 2020; Andrade et al., 2024). According to studies available in the scientific literature, the use of CBP can improve the productivity, health, and longevity of lactating dairy cows, reduce milk production costs, and enhance the management of the waste produced by the animals (Bewley et al., 2017; Silva et al., 2019; Blanco-Penedo et al., 2020; Fernández et al., 2020; Leso et al., 2020; Emanuelson et al., 2022).

Typically, CBP systems feature facilities with open sides and utilize active devices such as fans, sometimes combined with evaporative cooling of the air through water misting in the feeding alley (activated during the hottest times of the day), to reduce the effects of animal's heat stress, control humidity, renew the air, and maintain the composting process of the bedding (Mondaca & Cook, 2019; Leso et al., 2020; Oliveira et al., 2023). When operated with open sides, these systems are more susceptible to external environmental fluctuations, due to the specific climatic and geographic characteristics of each location (Damasceno, 2020; De Masi et al., 2021; Pons et al., 2023).

Depending on the nature of climatic fluctuations and the thermal conditioning systems used in CBP systems with open sides, dairy cows housed in these facilities may experience heat stress. This condition is particularly severe when high temperatures and relative humidity are recorded simultaneously (Collier et al., 2019; Cheng et al., 2024; Chopra et al., 2024). Such exposure can lead to a reduction in dry matter intake and milk production, impair reproductive rates, and increase the incidence of various diseases, such as mastitis and lameness (Sammad et al., 2020; Tao et al., 2020; Wang et al., 2020; Dahl & McFadden, 2022). In addition, climatic fluctuations can also affect the physicochemical quality of the resulting compost, as composting is a biological process influenced by environmental variables (primarily dry-bulb air temperature, relative humidity, and air speed) and the characteristics of the bedding being composted (mainly temperature, humidity, pH, and carbon and nitrogen concentrations in the bedding material) (Epstein, 2011; Damasceno, 2020; Oliveira et al., 2023b).

Since thermal comfort indicators, animal health, and the physicochemical bedding quality in CBP systems are influenced by climatic conditions, the type of facilities, the methods of environmental cooling used, and bedding management practices, it is essential to increasingly conduct studies to characterize these production systems. For tropical and subtropical climates, such as in Brazil, where the introduction of the CBP system is still relatively recent and less studied.

Studies characterizing CBP systems for dairy cattle production should be conducted in the field whenever possible. This allows for the monitoring and assessment of thermal comfort, animal health, and the physicochemical bedding quality over time, across the entire animals occupied zone (AOZ), and under extreme climatic conditions, especially in winter and summer, when potential issues may be more challenging (Freitas et al., 2019; Arulmozhi et al., 2021; Leliveld et al., 2024). In this case, innovative tools for data collection should be used, such as embedded systems with microprocessors and low-cost sensors (Djajadi & Wijanarko, 2016; Arulmozhi et al., 2021). At the same time, suitable methods for assessing field-recorded conditions should be employed, such as exploratory and geostatistical analysis, which are widely used tools in the field of animal ambiance (Ferraz et al., 2019; Silva et al., 2020; Oliveira et al., 2021; Peixoto et al., 2021; Vieira et al., 2021; Andrade et al., 2022; Guesine et al., 2023; Silva et al., 2023).

Alternatively, and/or complementarily to field studies, modeling tools such as Computational Fluid Dynamics (CFD) can be employed (Ding et al., 2016; Lv et al., 2022). The use of this tool emerges as a highly promising alternative for modeling heat and mass transfer in CBP systems, given that field studies can be costly and relatively difficult to conduct due to the large scale of the facilities (Drewry et al., 2018; Mondaca et al., 2019; Zhou et al., 2019; Bournet & Rojano, 2022; Jung et al., 2023).

A third approach that can be explored is the use of classic and/or systematic literature review tools. By employing search and selection methodologies and using appropriate data analysis packages, these tools enable a reliable and unbiased scientific mapping of studies conducted on topics of interest (Pollock et al., 2016; Mazov et al., 2020; Silva et al., 2022; Sharma & Bansal, 2023). Therefore, like CFD, the use of review tools can be considered an interesting alternative for searching, selecting, organizing, and interpreting results available in the literature on thermal comfort, animal health, and the physicochemical bedding quality in CBPs under different housing, climatic, and management conditions.

This study is justified by increasing interest among Brazilian producers in implementing CBPs for housing dairy cattle. It aims to elucidate aspects of the environment from the perspectives of thermal comfort, animal health, and physicochemical bedding quality. This thesis comprises four articles. The first three articles cover the state of the art concerning the following topics: 1) Health and thermal comfort of dairy cattle housed in CBP systems compared to other housing systems; 2) Physicochemical bedding quality in CBP systems; and 3) Application of CFD techniques to study heat and mass transfer in CBP systems for dairy cattle. The fourth article, in turn, is an experimental study conducted in a CBP system with open sides, a model typically used for housing lactating dairy cattle.

The first article, entitled **“Health and Thermal Comfort of Dairy Cattle in Compost-Bedded Pack Barns and Other Types of Housing: A Comparative Systematic Review”**, presents a systematic literature review. It aimed to describe and discuss the key findings available on health and thermal comfort indicators for dairy cattle housed in CBP systems, compared to Free Stall (FS), Loose Housing (LH), and/or Tie Stall (TS) systems.

The second study, entitled **“Physicochemical Bedding Quality in Compost-Bedded Pack Barn Systems for Dairy Cows: A Systematic Review”**, is also a systematic literature review. This study aimed to organize, describe, and discuss the key findings available in the literature on physicochemical indicators of bedding quality in CBP systems, across different types of facilities, climatic conditions, and seasons.

The third article, titled **"Analysis of Heat and Mass Transfer in Compost-Bedded Pack Barns for Dairy Cows Using Computational Fluid Dynamics: A Review"**, presents the current state of the art regarding the application of CFD techniques for studying heat and mass transfer in CBP systems for dairy cattle. This study discusses the advancements and limitations of using this technique, as well as detailing the key aspects that should be considered when applying it to model the environment in CBPs, which emerges as a highly promising alternative.

The fourth article is an experimental study titled **"Temporal and Spatial Behavior of Thermal Microenvironment Variables in a Compost-Bedded Pack Barn with Positive Pressure Ventilation During Winter and Summer in Brazil"**. This study characterized the temporal and spatial behavior of thermal environment variables in a CBP facility with open sides, typical of Brazil, equipped with mechanical positive pressure ventilation and a water misting system, both were positioned to promote longitudinal airflow within the housing. The evaluated CBP system is in a major dairy region in Minas Gerais (the largest milk-producing state in the country), an area with a subtropical mesothermal climate in Brazil. The study was conducted under winter and summer climatic conditions, as these are considered the most challenging for managing the thermal environment and bedding in CBP systems.

It is anticipated that the results of this study could aid in identifying problems and potential needs for adjustments, as well as in defining measures and solutions for existing facilities or in designing new CBP systems for dairy cattle. It is also understood that it is always necessary to consider the specific climatic and geographical characteristics of the location where each CBP project is implemented. The primary aim should be to contribute to sustainable modern milk production, especially in balancing productivity with animal welfare.

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Systematic Review

Health and Thermal Comfort of Dairy Cattle in Compost-Bedded Pack Barns and Other Types of Housing: A Comparative Systematic Review

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Abstract: This systematic review was conducted to describe and discuss the main research findings available in the literature concerning the health and thermal comfort of dairy cattle housed in Compost-Bedded Pack Barn (CBP) systems, in comparison to Free Stall (FS), Tie-Stall (TS), and/or Loose Housing (LH) systems. Searches for peer-reviewed experimental articles in English were performed in the Scopus and Web of Science databases. Forty-three non-duplicated scientific articles were obtained and subjected to a four-stage evaluation process, according to the PRISMA methodology and predefined eligibility criteria. This process resulted in the selection of 13 articles for inclusion. Regarding animal health, the results provide evidence that the incidence of problems such as lameness, limb injuries, and reproductive disorders is lower in CBP systems. However, if bedding management is not effective in ensuring the provision of dry and comfortable surfaces, an increase in somatic cell count (SCC) and prevalence of mastitis incidence (P_{MI}) may occur. For thermal comfort, it was found that the CBP system exhibited higher temperatures during summer and lower temperatures during winter when compared to FS with cross-ventilation in association with evaporative cooling. However, no differences were observed in terms of thermal comfort in spring and autumn. As this is a recent research area, caution should be exercised when extrapolating the results, considering the specificities of each cited study.

Keywords: dairy cows; confinement systems; animal welfare; animal health

Citation: Oliveira, C.E.A.; Tinôco, I.d.F.F.; Sousa, F.C.d.; Baêta, F.d.C.; Vieira, F.M.C.; Barbari, M. Health and Thermal Comfort of Dairy Cattle in Compost-Bedded Pack Barns and Other Types of Housing: A Comparative Systematic Review. *AgriEngineering* **2024**, *6*, 1395–1416. https://doi.org/10.3390/agriengineering6020080

Academic Editor: In-Bok Lee

Received: 19 February 2024
Revised: 27 April 2024
Accepted: 16 May 2024
Published: 20 May 2024

1. Introduction

To ensure food security and the high quality of animal products, modern livestock farming has assumed a more intensive nature characterized by smaller farms, increased use of inputs, and production in collective facilities, typically equipped with artificial thermal conditioning systems and some level of automation [1,2]. Different housing systems can be employed in intensive animal production, provided that the health, proper feeding management, and thermal comfort of the animals are ensured—conditions that are necessary to achieve good productive and reproductive performance [3,4].

Especially for dairy cattle, there is a lot of variation in housing and management conditions (from the thermal environment, sanity, and nutrition) among different locations. Therefore, the animal health and thermal comfort indices achieved can be very different [5–7]. The main housing systems used in intensive dairy production are Tie-Stall (TS), Free Stall with individual stalls (FS), Loose Housing (LH), and Compost-Bedded Pack Barn (CBP). Each system has advantages and limitations related to its use and the management solutions adopted [8–10]. Drawing on the advantages and limitations of each housing system, this review aims to provide insights for stakeholders in the dairy industry. By addressing the multifaceted aspects of intensive livestock farming, including housing systems and adopted thermal conditioning solutions, this paper contributes to the ongoing discourse on balancing productivity with animal welfare in modern agriculture.

The TS system is characterized by the animals' permanence in individual stalls with dividers (side by side), where they are restrained by the neck by means of chains attached to a rail fixed in the upper region of the stall [11,12]. In this system, traditionally used worldwide for small herds and for research purposes, the feed is provided individually and the animals are typically loosed only during milking times [8,13].

The FS is another housing model that emerged in the United States of America in the 1950s and quickly became common in intensive dairy production, mainly due to the lower requirement for bedding to keep the animals clean. In the FS system, the animals remain loose in collective facilities comprising individual areas for rest (individual stalls side by side, with bedding composed of materials such as sand or shredded rubber on a rubber mattress), feeding, and exercise [8,11].

Another system that emerged in the mid-1950s is the LH system, characterized by the presence of a large covered area, in which animals have access to two distinct areas: a soft collective bedding area for resting (normally between 5.0 and 10.0 m^2 $animal^{-1}$) and an area with feeders and drinkers, offering forages and concentrates. While LH systems allow for housing breeds of different sizes and the storage of solid manure, their effectiveness requires intensive management and larger amounts of bedding compared to Tie-Stall (TS) and Free Stall (FS) systems [8,12,14].

Relatively new compared to TS, FS, and LH, the CBP system is a housing system in free-walk facilities with bedding composed of lignocellulosic material, where animals have free access to the bedding and feeding areas [15–17]. The CBP system operates on the concept of composting the bedding material together with the manure deposited by the animals in the collective resting area. This concept differentiates it from other confinement systems for dairy cattle in bedding facilities [18,19]. In the literature, improvements in animal welfare, productivity, health, and longevity, as well as reduced production costs and better disposal of manure produced, are reported as advantages of its use [8,16,20,21].

Regardless of the type of housing used, the production of dairy cattle confined in facilities aims to ensure improvements in their welfare. However, it is essential to evaluate how different housing systems and thermal-environmental management practices used can impact the health and thermal comfort conditions of dairy cattle, as some health and thermal comfort problems of these animals may be associated with the way they are housed and managed [22,23]. Therefore, establishing potential synergies between factors related to the type of housing and management with animal health and thermal comfort is crucial [13]. In this context, this systematic review was designed to describe and discuss the main results available in the literature on the health and thermal comfort of dairy cattle housed in CBP systems in comparison with FS, LH, and/or TS systems. Therefore, it seeks to provide support and contribute to evidence-based decision-making regarding the adoption or not of CBP systems, as there is a recurring question about the improvements that can be achieved in animal health and thermal comfort from the adoption of this system, also considering the different forms of thermal conditioning that can be employed.

2. Materials and Methods

2.1. Search Strategy

To identify the main comparative studies between CBP, FS, LH, and/or TS systems in terms of animal health and thermal comfort, this systematic review was conducted using a Population, Intervention, Comparison, and Outcome (PICO) search strategy [24], following the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [25]. PICO is a methodology used in practice in systematic reviews, being evidence-based [26]. Based on this methodology, the following question was defined: "Does housing in CBP systems promote positive impacts on the health and thermal comfort of dairy cattle, compared to the FS, LH, and/or TS systems?" To answer this question, search, selection, eligibility, and inclusion procedures were carried out, and information of interest from eligible studies was extracted and analyzed [27].

Searches for studies relevant to the topic of interest were conducted in the Scopus (ScP) and Web of Science (WoS) databases, widely recognized as the largest and most reliable repositories of scientific literature data worldwide [28]. The choice of these databases was made because Scopus is a comprehensive platform that accommodates studies published in different databases, and Web of Science only includes studies published in journals indexed by Clarivate Analytics, which are peer-reviewed [29].

Since this study addressed a specific topic, different search terms were used (Table 1), aiming to return a representative set of publications on the topic of interest. Using the different expressions listed in Table 1, searches were conducted in the main repositories of studies from Sc and WoS, with the integration of Boolean operators (AND and OR) to combine words or phrases, as well as wildcard truncation (" ") to denote different expressions. Additionally, the asterisk (*) was employed to include alternative spellings of the words and/or expressions of interest, such as variations between US English and British English.

Table 1. Population, intervention, comparison, and outcome (PICO) of the search term sequence used in this systematic review study.

Acronym	Search Sequence
Population	(cattle OR cow* OR calves OR heifers) AND (dairy OR lactating OR milking)
Intervention	("compost barn*" OR "compost bedded*" OR "compost-bedded pack*" OR "compost-bedded barn*" OR "compost-bedded pack barn*" OR "compost-bedding*" OR "open pack barn*" OR "free-stall*" OR "free stall*" OR freestall* OR "tie-stall*" OR "tie stall*" OR tiestall* OR "loose housing*" OR "loose-housing*")
Comparison	("compost barn*" OR "compost bedded*" OR "compost-bedded pack*" OR "compost-bedded barn*" OR "compost-bedded pack barn*" OR "compost-bedding*" OR "open pack barn*") AND (("free-stall*" OR "free stall*" OR freestall*) OR ("tie-stall*" OR "tie stall*" OR tiestall*) OR ("loose housing*" OR "loose-housing*"))
Outcome	(health OR disease* OR pathology* OR incidence* OR prevalence* OR sanity OR score* OR dirtiness) OR (comfort OR environment OR "heat stress" OR microclimate OR "thermal comfort" OR "thermal environment" OR "thermal stress" OR welfare)

2.2. Inclusion and Exclusion Criteria for Studies

Since this systematic review aimed to select only studies evaluating and/or characterizing the health and thermal comfort of dairy cattle housed in CBP systems, in comparison to FS, LH, and/or TS, only experimental articles written in

English, peer-reviewed, and published in any year up to December 2023 were considered. In collaboration with co-authors, a priori inclusion and exclusion criteria were established.

Searches in the ScP and WoS databases returned 30 and 33 studies, respectively. All results (n = 63) were included in a Mendeley® account, using a Google Chrome plugin, from which duplicates were identified and removed. The remaining studies (n = 43) underwent a 4-stage assessment process, in accordance with the PRISMA methodology—Figure 1 [25]:

- First stage: Meta-data assessment, excluding studies that were not published in English, review articles, dissertations, theses, conference proceedings, and book chapters;
- Second stage: Assessment of study titles and abstracts, identifying and excluding studies that did not evaluate CBP systems compared to other intensive housing systems for dairy cattle (FS, LH, and/or TS), or that did not evaluate and/or characterize indicators of animal health and/or thermal comfort in the aforementioned systems;
- Third stage: Qualitative assessment of the filtered studies, using the domains 1 (study eligibility criteria), 2 (study identification and selection), and 3 (data collection and assessment) of the Risk of Bias in Systematic Reviews (ROBIS) tool, in accordance with Whiting et al. [25];
- Fourth stage: Finally, the remaining studies were read in detail, with the aim of assessing whether all of them referred to experimental studies that assessed/characterized the health and/or thermal comfort of dairy cattle housed in CBP systems, compared to FS, TS, and/or LH systems.

To provide a comprehensive overview of the literature on the topic, no additional restrictions, such as sample size, facility and/or farm size, or journal quality, were imposed. However, it was not possible to determine the extent to which the systematic exclusions affected the results obtained in the study.

2.3. Data Extraction

Two investigators (C.E.A.O. and F.C.S.) independently selected the full texts of the included articles. To organize the information of interest about the studies, Microsoft Excel®, version 2404, was used to create a spreadsheet containing the following information: authorship, publication year, journal, country and/or region where the study was conducted, local climate classification, evaluated systems, characteristics of evaluation systems, number and types of facilities for each system, breed and number of animals housed in each facility, indicators of animal health and/or thermal comfort used, and main results achieved. Interobserver reliability for data extraction was tested for all categories (except authorship and publication year), with 100% agreement obtained.

For the purpose of bibliometric analysis, the R Bibliometrix package, version 4.2.1, was used [31,32]. With this package, the intellectual structure of scientific domains was determined through multiple correspondence analyses of article titles, abstracts, and keywords [26]. To assess the appropriateness of the search terms and expressions used, a word cloud was created containing the 25 most cited words in the abstracts (frequency > 10%). Additionally, the R Bibliometrix package was used to obtain the co-occurrence network and link between the most used words in the abstracts of the 14 articles [33]. In the co-occurrence network, the size of the circle and the label of the words was a function of the number of times the term was used in the abstracts of the articles (which defines its weight), and the links between circles indicated the relationship between areas of knowledge, with closer circles having a stronger relationship [26].

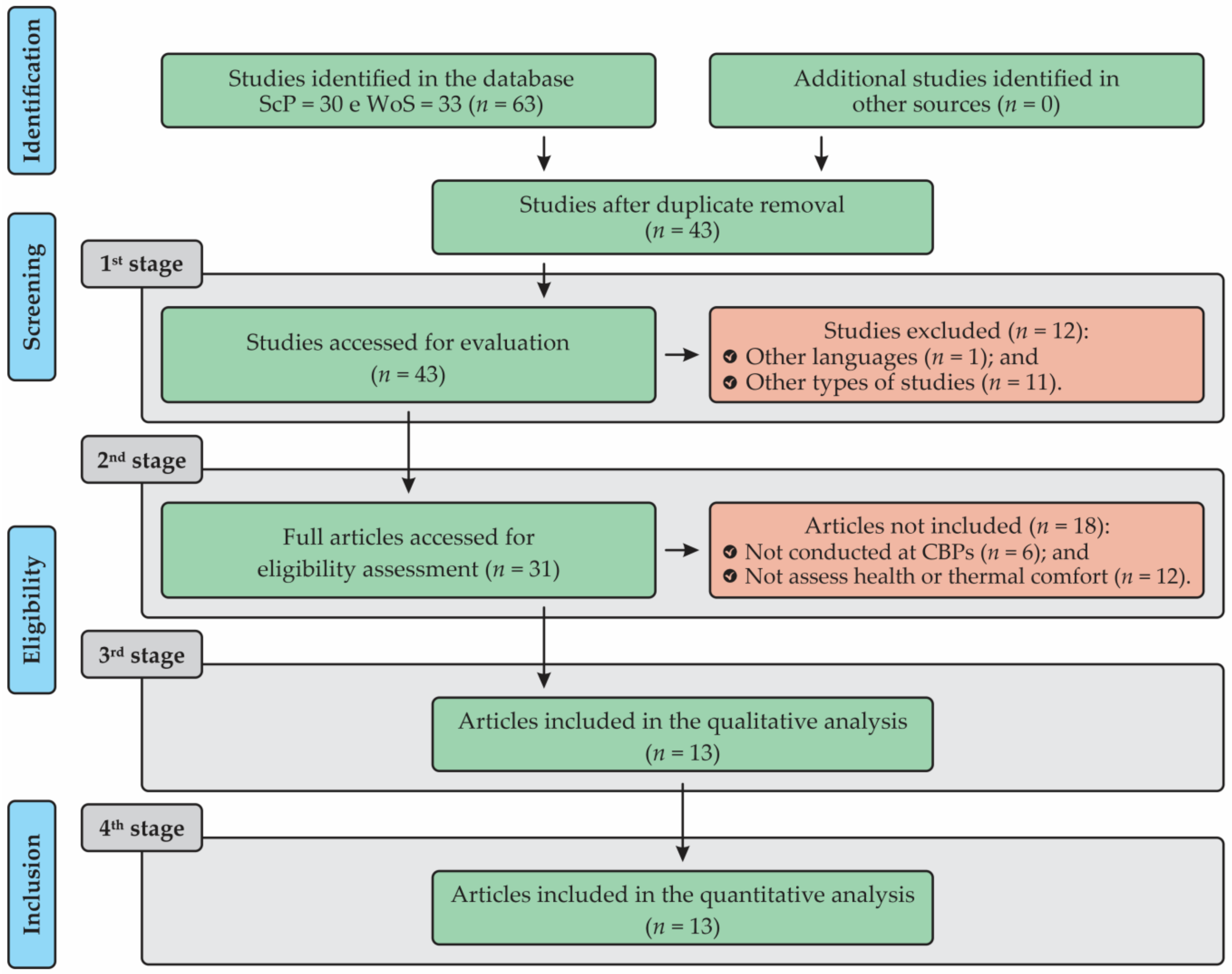

Figure 1. Flowchart of selection, indicating the total number of studies identified and filtered at each stage of the systematic review process. Source: Adapted from Moher et al. [25].

3. Results and Discussion

3.1. Overview of Included Studies

This study was designed to describe and discuss the main results available in the literature on the health and thermal comfort of dairy cattle housed in CBS systems, compared to FS, LH, and/or TS systems. Through a search of the ScP and WoS databases, 43 non-duplicated studies were found on the topic of interest (Figure 1). In 1st stage of the screening process, 12 studies were excluded from the study because they did not meet the eligibility criteria: 1 study was written in a language other than English (Portuguese); 8 studies were literature reviews; 2 studies were published in conference proceedings; and 1 study was published as a book chapter. Among the remaining 31 studies (n = 31), 18 did not meet the eligibility criteria defined in 2nd stage and were excluded: 6 were not conducted in CBP systems or, when they were, did not compare with other housing systems (FS, TS, or LH); and 12 did not evaluate indicators of health and/or thermal comfort of the housed animals. Finally, 13 articles met the eligibility criteria and, therefore, were selected to compose the results of the systematic review.

Table 2 provides detailed information on the selected studies, including the authors, region, and country where they were conducted, types of facilities used, and the main objective of the study. The selected articles were published between

2011 and 2023 and conducted in different countries: Austria (n = 1); Brazil (n = 3); Spain (n = 2); United States of America (n = 3); Italy (n = 2); and Poland (n = 1). One study was conducted in six different European countries (Austria, Germany, Italy, Netherlands, Slovenia, and Sweden). The studies did not use the same methodology; therefore, a meta-analysis was not performed.

An analysis of the word cloud generated from the article abstracts (Figure 2) revealed that six words appeared with a frequency greater than 50% in the article abstracts: systems (97%); compost barn (92%); cattle (88%); dairy (88%); barns (69%); and free stall (63%). The frequency of the remaining words included ranged from 10 to 49%, with emphasis on some words related to animal health and thermal comfort: lameness (49%); prevalence (39%); health (26%); score (24%); and thermal-comfort (17%). From the co-occurrence network (Figure 3), it was observed that the words that appeared with the highest frequency in the word cloud also had larger circles and more connections, indicating that they were explored in more articles.

Figure 2. Word cloud generated from the 25 most used words in the abstracts of the experimental articles included in the systematic review. Bigger words were used more frequently. CVe—systems with negative pressure mechanical ventilation; NV—systems with natural and/or positive pressure mechanical ventilation; SCC—somatic cell count.

Table 2. Characterization of the 13 experimental studies that evaluated animal health and thermal comfort in Compost-Bedded Pack Barn (CBP), compared to Free Stall with individual stalls (FS), Loose Housing (LH) and/or Tie Stall (TS) systems.

Study Details					
Reference	**Local**	**Facilities Type**	**Animals/EU**	**Breed**	**Objective**
Lobeck et al. [20]	Minnesota and South Dakota (USA)	6 CBP [1] 6 FS-NV [1] 6 FS-CVe [2]	78.8 ± 32.4 126.7 ± 79.6 139.6 ± 63.4	Holstein and Jersey–Holstein crossbreds	To describe animal welfare in CBP and FS-CVe facilities, compared to FS-NV facilities, using outcome-based measures (locomotion, body condition, hygiene, foot lesions, respiratory rates, slaughter, mortality, and prevalence of mastitis infection)
Lobeck et al. [34] [3]	Minnesota and South Dakota (USA)	6 CBP [1] 6 FS-NV [1] 6 FS-CVe [2]	78.8 ± 32.4 126.7 ± 79.6 139.6 ± 63.4	Holstein and Jersey–Holstein crossbreds	To describe different housing systems for dairy cattle (CBP, FS-CVe, and FS-NV), and to evaluate air temperature, relative humidity, air velocity, and air quality (ammonia and hydrogen sulfide), as well as light intensity
Astiz et al. [35]	SP [4]	1 CBP [1] 1 LH [1]	180 [5] 110 [5]	Holstein	To analyze the potential effects of using CBP systems, compared to LH systems, during the dry period on the health (udder and uterus), reproductive performance, and productive performance during the following lactation of cows with more than 2 calfs
Eckelkamp et al. [36]	Kentucky (USA)	8 CBP [1] 7 FS [1]	178 ± 108 84 ± 37	NS	To evaluate the differences between CBP and FS systems for mastitis indicators (clinical mastitis, SCC, high SCC, and SCC in bulk tanks), locomotion, hygiene, and foot scores
Burgstaller et al. [37]	AT [6]	5 CBP [1] 5 FS [1]	20–41 20–39	Fleckvieh and Holstein	To evaluate the prevalence of lameness and the prevalence and type of foot lesions in cows kept in CBP systems, and to compare these results with data from cows kept in other conventional housing systems (FS)
Costa et al. [38] [7]	Paraná (BR)	12 CBP [1] 23 FS [1]	56–173 207–376	Holstein	To compare the prevalence of lameness and lesions in the hocks and knees of confined dairy cattle in CBP, FS, or a combination of these two systems, in southern Brazil
Leso et al. [39]	Mantua and Cremona (IT)	10 CBP [1] 10 FS-M [1,8] 10 FS-S [1,9]	112.0 ± 56.6 147.0 ± 102.3 143.0 ± 83.9	Holstein	To evaluate and compare the performance of dairy cows housed in CBP and FS systems, with a primary focus on herd longevity
Bran et al. [40]	Paraná (BR)	12 CBP [1] 38 FS [1]	104.3 ± 62.9 327.7 ± 201.0	Holstein and others	To study the factors at the cow, barn, and herd levels associated with lameness in lactating dairy cows housed in CBP and FS systems in southern Brazil
Biasato et al. [41]	Cuneo (IT)	1 CBP [1] 1 FS [1]	11 11	Fleckvieh	To develop and describe a CBP system for dairy cattle housing, evaluate and compare the health and welfare of cows housed in CBP versus those kept in a conventional system (FS), and characterize the quality of milk and three local traditional products from northwestern Italy
Fernández et al. [42]	Catalonia (SP)	2 CBP [1] 2 FS [1] 2 LH [1]	73–105 [10] 95–96 [10] 88–9 [10]	Holstein	To examine the comfort and behavior of lactating dairy cows housed in three different types of housing systems on the same farm: CBP, FS, and LH
Kogima et al. [43] [11]	Santa Catarina (BR)	17 CBP [1] 17 FS [1]	52.2 ± 23.5 82.0 ± 57.0	NS	To evaluate the impact of different dairy cattle production systems (CBP, FS, and grazing) on animal welfare using the Welfare Quality® protocol

Table 2. *Cont.*

Study Details					
Reference	**Local**	**Facilities Type**	**Animals/EU**	**Breed**	**Objective**
Witkowska and Ponieważ [9]	PL [6]	1 CBP [1] 1 FS-SR [1,12] 1 FS-SC [1,13] 1 TS [1]	120 (in each system)	Polish Holstein-Friesian	To evaluate the impact of different housing systems (CBP, FS-SR, FS-SC, and TS) on the prevalence of diseases and productive life of dairy cows
Emanuelson et al. [44]	AT, DE, IT, NL, SI and SE	16 CBP [1,14] 16 FS [1,14]	14–175 [15] 28–156 [15]	Holstein and others	To evaluate the health of dairy cattle housed in CBP and FS systems based on health indicators (SCC, high SCC, elevated SCC, ketosis risk, prolonged calving intervals, dystocia, and stillbirths) and other characteristics (lifespan, productive life, parity at herd exit, first-calving risk, calf mortality)

[1] Facility provided with natural and/or mechanical ventilation with positive pressure; [2] Facility provided with mechanical ventilation with negative pressure; [3] Study conducted simultaneously with the study conducted by Lobeck et al. [20]; [4] Study conducted in the region of eastern Spain; [5] Maximum number of animals housed during the experimental period (density of 10.3 and 10.5 $m^2 \cdot cow^{-1}$ in CBP and LH systems, respectively); [6] More details about the region in which it was conducted were not specified; [7] The results from farms using a combination of CBP and FS systems were not used in this review because they were not separated by system; [8] FS systems that used rubber mattresses; [9] FS systems that used straw bedding; [10] The number of animals housed can vary between facilities; [11] Grazing systems were also evaluated, but they were not included in this systematic review because of the proposed objective; [12] Free Stall barn with a slatted floor scraped by robots; [13] Free Stall barn with a self-cleaning floor; [14] Number of systems varies by country; [15] The number of animals varies by facility and country; AT—Austria; BR—Brazil; CBP—Compost-Bedded Pack Barn; DE—Germany; SP—Spain; EU—experimental unit; FS—Free Stall; FS-CVe—Free Stall systems with negative pressure mechanical ventilation; FS-NV—Free Stall systems with natural and/or positive pressure mechanical ventilation; FS-SC—Free Stall systems with a self-cleaning floor; FS-SR—Free Stall systems barn with a slatted floor scraped by robots; IT—Italy; LH—Loose Housing; NS—not specified; NL—Netherlands; PL—Poland; SCC—somatic cell count; SE—Sweden; SI—Slovenia; TS—Tie Stall; USA—United States of America.

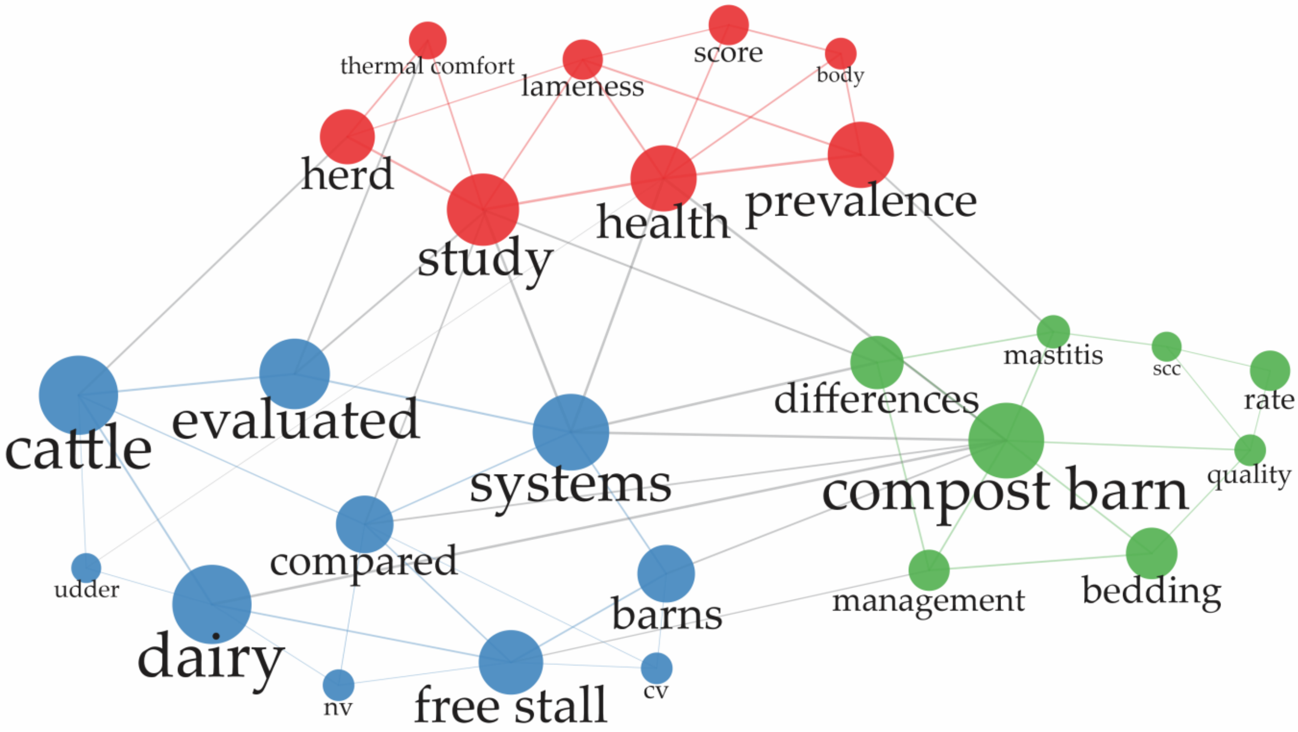

Figure 3. Word network of co-occurrences in the abstracts of the articles included in this systematic review study. The size of the labels and circles is determined by the frequency of the word, and the lines illustrate the relationship between the areas of knowledge; words that are closer have a stronger relationship.

Out of the studies selected for this systematic review, nine compared CBP systems with one of the other systems (eight studies compared with FS; and one study compared with LH), and four studies compared CBP systems with more than one of the systems (one study compared with FS and with the combination of CBP+FS systems; one study compared with FS and LH systems; one study compared with TS and FS systems; and one study compared with FS and semi-intensive grazing). Since the primary objective of this study was to analyze indicators of animal health and thermal comfort in CBPs, compared to other cattle housing models, the results obtained from the comparison with grazing systems were not considered. For the two studies in which this was performed [38,43], only the results depicting the comparisons between CBP and FS systems, individually, were considered.

Regarding the evaluations performed, 12 studies (92.3%) examined animal health indicators, while 3 studies (23.1%) evaluated thermal housing indicators. The results obtained in these studies, including the effect of housing in CBPs compared to other systems, are listed in Table 3.

3.2. Animal Health

Various animal health indicators were used to assess CBP systems compared to FS, LH, and/or TS systems, with lameness being the most reported indicator, including prevalences of clinical lameness ($PL_{Clin.}$, n = 8) and severe lameness ($PL_{Sev.}$, n = 7). Lameness is a multifactorial problem frequently used as an animal health indicator in dairy production systems. It is still a major concern for animal welfare in the global dairy industry [40,45–47].

Table 3. Characterization of animal health and thermal comfort in Compost-Bedded Pack Barn (CBP) systems, compared to Free Stall (FS), Loose Housing (LH), and/or Tie Stall (TS) systems, according to the results obtained in the studies included in this systematic review.

Reference	Indicator	Result Achieved [1]				Effect [2]		
		CBP	FS	LH	TS	CBP × FS	CBP × LH	CBP × TS
Lobeck et al. [20]	Respiration rate (RR, in breaths min^{-1}) [3]	58.4	59.3 (NV) and 57.5 (CVe)			=		
	Prevalence of clinical lameness ($PL_{Clin.}$, in %) [4,5]	4.4	15.9 (NV) and 13.1 (CVe)			+		
	Prevalence of severe lameness ($PL_{Sev.}$, in %) [4,6]	0.8	1.4 (NV) and 1.0 (CVe)			=		
	Prevalence of hock lesion (P_{HL}, in %) [7,8]	3.8	23.9 (NV) and 31.2 (CVe)			+		
	Prevalence of severe hock lesion ($P_{HL\text{-}Sev.}$, in %) [7,9]	1.0	6.3 (NV) and 6.5 (CVe)			+		
	Prevalence of mastitis infection (P_{MI}, in %) [10]	33.4	26.8 (NV) and 26.8 (CVe)			=		
	Prevalence of mortality (P_{Mo}, in %)	5.1	5.0 (NV) and 5.8 (CVe)			=		
	Hygiene score (HS, in scores from 0 to 5) [11]	3.2	2.8 (NV) and 2.8 (CVe)			–		
	Body condition score (BCS, in scores from 1 to 5) [12]	2.9	3.0 (NV) and 3.0 (CVe)			=		
Lobeck et al. [34]	Dry-bulb air temperature in winter ($t_{db\text{-}Winter}$, in °C)	–3.7	–1.4 (NV) and 3.9 (CVe)			=/–		
	Dry-bulb air temperature in spring ($t_{db\text{-}Spring}$, in °C)	11.8	12.2 (NV) and 12.2 (CVe)			=		
	Dry-bulb air temperature in summer ($t_{db\text{-}Summer}$, in °C)	20.7	20.8 (NV) and 19.6 (CVe)			=		
	Dry-bulb air temperature in fall ($t_{db\text{-}Fall}$, in °C)	5.0	6.4 (NV) and 8.2 (CVe)			=/–		
	Temperature and humidity index in summer (THI_{Summer}) [13]	68.0	68.4 (NV) and 65.9 (CVe)			=/–		
Astiz et al. [35]	Prevalence of mastitis infection (P_{MI}, in %) [10,14]	22.1		35.0			+	
	Prevalence of purulent vaginal discharge (P_{PVD}, in %)	7.2		10.0			+	
	Prevalence of cytological endometritis (P_{CE}, in %)	27.2		26.9			+	
	Prevalence of mortality (P_{Mo}, in %)	3.9		5.0			+	
	Somatic cell count (SCC, in ×1000 cells mL^{-1})	96.1		139.5			+	
Eckelkamp et al. [36]	Bedding surface temperature ($t_{B\text{-}Sur.}$, in °C)	17.8	16.1			=		
	Prevalence of hock lesion (P_{HL}, in %) [7,8]	0.0	0.0			=		
	Prevalence of mild lameness (PL_{Mildly}, in %) [4,15]	33.3	30.4			=		
	Prevalence of clinical lameness ($PL_{Clin.}$, in %) [4,5]	39.2	40.8			=		
	Prevalence of severe lameness ($PL_{Sev.}$, in %) [4,6]	10.7	13.3			=		
	Prevalence of mastitis infection (P_{MI}, in %) [10]	22.0	19.0			=		
	Prevalence of clinical mastitis ($P_{M\text{-}Clin.}$, in %) [16]	1.2	1.2			=		
	Hygiene score (HS, in scores from 0 to 5) [11]	2.2	2.3			=		
	Somatic cell count (SCC, in ×1000 cells mL^{-1})	242	229			–		
Burgstaller et al. [37]	Prevalence of mild lameness (PL_{Mildly}, in %) [4,15]	13.7	9.9			=		
	Prevalence of clinical lameness ($PL_{Clin.}$, in %) [4,5]	3.9	4.7			=		
	Prevalence of severe lameness ($PL_{Sev.}$, in %) [4,6]	1.1	0.3			=		
	Prevalence of heel horn erosion (P_{HHE}, in %)	26.9	59.5			+		
	Prevalence of white line disease (P_{WLD}, in %)	20.4	46.6			+		
	Prevalence of interdigital hyperplasia (P_{IH}, in %)	0.2	3.1			+		
	Prevalence of chronic laminitis (P_{CL}, in %) [17]	6.5	15.9			+		
Costa et al. [38]	Prevalence of clinical lameness ($PL_{Clin.}$, in %) [4,5]	31.9	43.2			+		
	Prevalence of severe lameness ($PL_{Sev.}$, in %) [4,6]	14.2	22.2			+		
	Prevalence of hock lesion (P_{HL}, in %) [7,8]	0.5	9.9			+		
	Prevalence of knee lesion (P_{KL}, in %) [18]	<1.0 [19]	7.4			+		
	Hygiene score (HS, in scores from 0 to 3) [20]	NS [21]	NS [21]			=		
	Body condition score (BCS, in scores from 1 to 5) [12]	NS [22]	NS [22]			=		

Table 3. *Cont.*

Reference	Indicator	Result Achieved [1]				Effect [2]		
		CBP	FS	LH	TS	CBP × FS	CBP × LH	CBP × TS
Leso et al. [39] [23]	Prevalence of mastitis infection (P_{MI}, in %) [10]	32.8	23.2 (M) and 29.6 (S)			–/=		
	Somatic cell count (SCC, in ×1000 cells mL^{-1})	354	259 (M) and 310 (S)			–/=		
Bran et al. [40]	Prevalence of clinical lameness ($PL_{Clin.}$, in %) [4,5]	32.2	44.0			+		
	Prevalence of severe lameness ($PL_{Sev.}$, in %) [4,6]	14.3	23.0			+		
Biasato et al. [41] [24]	Prevalence of hock lesion (P_{HL}, in %) [7,8]	0.0	25.0			+		
	Prevalence of hoof lesions ($P_{Hoof\text{-}L}$, in %)	0.0	5.0			+		
	Prevalence of nasal discharge (P_{ND}, in %)	66.0	16.0			–		
	Prevalence of ocular discharge (P_{OD}, in %)	20.0	32.0			+		
	Prevalence of skin alopecia (P_{SA}, in %)	7.0	16.0			+		
	Hygiene score (HS, in scores from 0 to 5) [11]	2.0	2.2			+		
	Body condition score (BCS, in scores from 1 to 5) [12]	3.0	3.0			=		
	Locomotion score (LS, in scores from 1 to 5) [4]	1.0	1.1			=		
	Fecal score (FaS, in scores from 1 to 5) [25]	1.4	1.4			=		
Fernández et al. [42] [26]	Prevalence of clinical lameness ($PL_{Clin.}$, in %) [27,28]	13.2	15.4	8.4		=	–	
	Prevalence of severe lameness ($PL_{Sev.}$, in %) [27,29]	4.2	0.7	3.4		–	=	
	Prevalence of inflamed coronary bands (P_{ICB}, in %)	19.1	15.2	16.0		–	=	
Kogima et al. [43]	Prevalence of clinical lameness ($PL_{Clin.}$, in %) [4,5]	3.3	8.6			+		
	Prevalence of severe lameness ($PL_{Sev.}$, in %) [4,6]	3.3	6.7			+		
	Prevalence of coughing (P_C, in %)	<0.1 [19]	<0.1 [19]			=		
	Prevalence of nasal discharge (P_{ND}, in %)	46.7	51.9			=		
	Prevalence of ocular discharge (P_{OD}, in %)	6.7	6.7			=		
	Prevalence of purulent vaginal discharge (P_{PVD}, in %)	0.0	2.7			+		
	Prevalence of hampered respiration (P_{HR}, in %)	0.0	0.0			=		
	Prevalence of diarrhea ($P_{Diar.}$, in %)	6.7	20.0			+		
	Prevalence of downer cows (P_{DC}, in %)	3.9	4.2			=		
	Prevalence of mortality (P_{Mo}, in %)	6.5	9.7			+		
	Prevalence of dystocia ($P_{Dys.}$, in %)	2.2	3.7			=		
Witkowska and Ponieważ [9]	Prevalence of clinical lameness ($PL_{Clin.}$, in %) [4,5]	32.0	41.0 (SR) and 43.0 (SC)		45.0	+		+
	Prevalence of limb contusion ($P_{Limb\text{-}C}$, in %)	29.0	42.0 (SR) and 42.0 (SC)		40.0	+		+
	Prevalence of sprained limb (P_{SL}, in %)	8.0	21.0 (SR) and 28.0 (SC)		9.3	+		=
	Prevalence of footrot ($P_{Footrot}$, in %)	30.0	32.0 (SR) and 32.0 (SC)		26.0	=		–
	Prevalence of sole ulcers (P_{SU}, in %)	29.0	28.0 (SR) and 29.0 (SC)		27.0	=		=
	Prevalence of interdigital hyperplasia (P_{IH}, in %)	1.0	2.0 (SR) and 2.0 (SC)		1.0	=		=
	Prevalence of white line disease (P_{WLD}, in %)	4.0	5.0 (SR) and 5.0 (SC)		6.0	=		+
	Prevalence of heel horn erosion (P_{HHE}, in %)	3.0	3.0 (SR) and 4.0 (SC)		3.0	=		=
	Prevalence of chronic laminitis (P_{CL}, in %)	3.0	1.0 (SR) and 2.0 (SC)		2.0	–/=		=
	Prevalence of mastitis infection (P_{MI}, in %) [10]	17.0	15.0 (SR) and 18.0 (SC)		12.0	=		–
	Prevalence of teat infection (P_{TI}, in %)	8.0	7.0 (SR) and 9.0 (SC)		9.0	=		=
	Prevalence of retained placenta (P_{RP}, in %)	32.0	36.0 (SR) and 35.0 (SC)		38.0	=		+
	Prevalence of parturient paresis (P_{PP}, in %)	13.0	15.0 (SR) and 16.0 (SC)		17.0	=		+
	Prevalence of miscarriage ($P_{Misc.}$, in %)	10.0	9.0 (SR) and 11.0 (SC)		8.0	=		–
	Prevalence of conjunctivitis ($P_{Conj.}$, in %)	3.0	2.0 (SR) and 1.0 (SC)		0.0	=/–		–
	Prevalence of pneumonia ($P_{Pneu.}$, in %)	31.0	40.0 (SR) and 34.0 (SC)		28.0	+		–
	Prevalence of displaced abomasum (P_{DA}, in %)	13.0	13.0 (SR) and 12.0 (SC)		15.0	=		=
	Productive lifespan (PL, in months)	65.2	63.5 (SR) and 56.8 (SC)		57.1	+		+

Table 3. *Cont.*

Reference	Indicator	Result Achieved [1]				Effect [2]		
		CBP	FS	LH	TS	CBP × FS	CBP × LH	CBP × TS
Emanuelson et al. [44]	Prevalence of mastitis infection (P_{MI}, in %) [30]	18.9	12.9			–		
	Prevalence of new high SCC ($P_{NH\text{-}SCC}$, in %) [31]	12.2	8.2			–		
	Prevalence of ketosis risk (P_{KR}, in %)	9.8	10.3			=		
	Prevalence of prolonged calving intervals (P_{PCI}, in %)	34.7	39.8			+		
	Prevalence of dystocia ($P_{Dys.}$, in %)	2.7	3.3			=		
	Prevalence of stillbirth ($P_{Still.}$, in %)	3.9	2.5			–		
	Prevalence of first calving risk (P_{FCR}, in %)	26.9	29.8			+		
	Prevalence of calf mortality (P_{CM}, in %)	0.1	0.1			=		
	Length of life (LL, in months)	68.4	67.8			=		
	Productive lifespan (PL, in months)	33.7	33.7			=		
	Parity at exit from the herd (PEFH, in parity number)	3.5	3.6			=		
	Somatic cell count (SCC, in ×1000 cells mL^{-1})	86.9	67.7			–		

[1] The mean value was only indicated, without standard deviation; [2] Effect of housing in CBP systems, where +, −, or = indicate a statistically significant positive, negative, or no effect on animal health or thermal comfort, as depicted in the selected studies; [3] Evaluated in association with the THI; [4] Assessment performed using the locomotion score (LS), with a score from 1 (normal locomotion) to 5 (severely lame), as described by Sprecher et al. [50] and Flower and Weary [51]; [5] Animals were considered to have clinical lameness when LS ≥ 3; [6] Animals were considered to have severe lameness when LS ≥ 4; [7] Evaluations of hock lesions (HL) were made with a score of 1 (no lesion) to 3 (swollen hock); [8] Animals were considered to have hock lesions when HL ≥ 2; [9] Animals were considered to have severe hock lesions when HL = 3; [10] Animals with CCS > 200.000 cells mL^{-1} were considered to have mastitis infection; [11] Hygiene score (HS) assessment made using a score from 1 (clean) to 5 (dirty), according to the methodology described by Reneau et al. [52]; [12] Body condition score (BCS) evaluation was performed with a score from 1 (thin) to 5 (obese), according to the methodology described by Ferguson et al. [53]; [13] THI was calculated and evaluated using the equation of West et al. [54]—analysis was performed only for the summer period; [14] Results regarding the first cases of clinical mastitis; [15] Animals were considered to have mild lameness when LS = 2; [16] They only portray cases reported by producers; [17] In this systematic review, only data on hoof lesion types where a significant difference was observed between the two systems were included; [18] Knee lesion assessments were performed with a score from 1 (no lesion) to 3 (swollen knee)—prevalence was calculated in relation to the total number of animals; [19] Exact numeric value not specified; [20] Hygiene score (HS) assessment was performed with a score from 1 (clean) to 3 (dirty), according to the methodology described by Lombard et al. [55]; [21] HS score evaluated by body region (udder, leg, and flank)—for this reason, it was not included in this table; [22] BCS score evaluated using body condition type (thin, obese, and ideal)—therefore, it was not included in this table; [23] Other parameters related to the productive performance of the herd were assessed but were not included in this study due to the specific aim of the study; [24] Other parameters related to the health of the herd were evaluated but were not included in this study due to the lack of clarity of the data in the study; [25] Faecal score (FaS) evaluation was performed with a score from 1 (firm, but not hard) to 4 (without solid matter), according to the methodology described by Larson et al. [56]; [26] Other parameters related to the health and cleanliness of the herd were evaluated but were not included in this study because they were evaluated according to body region; [27] Assessment was performed based on a score from 0 (normal gait) to 2 (severely lame); [28] Animals were considered to have clinical lameness when the score was equal to 1; [29] Animals were considered to have severe lameness when the score was equal to 2; [30] Animals with SCC > 150 and >200 × 1000 cells mL^{-1} for first and last calving, respectively, were considered to have mastitis infection; [31] Animals with a new high SCC, compared to the previous day; FS-S—Free Stall systems used straw bedding; FS-CVe—Free Stall systems with negative pressure mechanical ventilation; FS-M—Free Stall systems that used rubber mattresses; FS-NV—Free Stall systems with natural and/or positive pressure mechanical ventilation; FS-SC—Free Stall systems with a self-cleaning floor; FS-SR—Free Stall systems barn with a slatted floor scraped by robots; NS—not specified.

Of the eight studies evaluating $PL_{Clin.}$ in CBP systems, compared to FS, LH, and/or TS systems, five indicated that $PL_{Clin.}$ was statistically lower in cattle housed in CBP systems [9,20,38,40,43] (Table 3). In other studies, CBP and FS had statistically similar results, but $PL_{Clin.}$ was higher in CBP when compared to LH [36,37,42]—Table 3. Similar results were obtained for $PL_{Sev.}$, with animals housed in CBP systems showing statistically lower (n = 3) or equal (n = 4) indices than those obtained in FS, LH, or TS systems (Table 3). In studies where no statistical difference in $PL_{Clin.}$ and $PL_{Sev.}$ was observed between systems, the discrepancy may be, in part, due to the multiple factors associated with this problem and/or differences between housing systems and management practices [40].

The occurrence of lameness in dairy cows is not a single condition, as it can be indicative of a wide range of different diseases. The main causes of lameness are disruption lesions, such as sole ulcers, white line disease, and infections affecting the animal's hooves, such as interdigital dermatitis, interdigital necrobacillosis, etc. [47]. Therefore, the lower incidences of lameness in CBP systems may be attributed to a reduction in the prevalence of these types of lesions and diseases, as depicted in some studies for hoof lesions ($P_{Hoof\text{-}L}$), heel horn erosion (P_{HHE}), white line disease (P_{WLD}), interdigital hyperplasia (P_{IH}), and chronic laminitis (P_{CL}) [9,37,41]—Table 3.

In CBPs, cows spend less time standing on concrete and have no restrictions on movement, as is the case in FS and TS systems [20]. Moreover, CBPs provide a surface for lying down composed of organic bedding, which is softer than sand and other materials typically used in FS. This characteristic can help reduce friction with the animals' feet [20,36]. As a consequence, it is possible to reduce the prevalence of lameness and lesions in the hocks and knees [20,38,41] (Table 3). Therefore, the lower prevalence of hoof, hock, and knee problems in dairy cattle housed in CBP systems, compared to FS and TS systems, is a function of the organic material present in the bedding, as these lesions are closely associated with the relative hardness and abrasiveness of the floor material [48]. These results suggest that, when managed properly to avoid excessive moisture in the bedding, the use of CBP systems can be advantageous in reducing the occurrence of lameness, a condition that could compromise not only the animals' health but also their productive and reproductive performance [6,8,49].

Three studies also examined the body condition score (BCS), a visual tool used to assess the proportion of body fat in dairy cows [57]. In these studies, average BCS scores of 3.0 were obtained, and they were statistically equal for both systems evaluated (CBP and FS). According to the methodology described by Ferguson et al. [53], these results indicate that the nutritional status of the housed animals could be classified as normal.

Another indicator used to evaluate housing conditions was the hygiene score (HS), which evaluates the cleanliness of the animals and has a direct relationship with somatic cell count (SCC) [20,52]. The results obtained in the four studies that used this indicator to compare body cleanliness conditions between CBP and FS systems were divergent: one study showed higher average HS in CBP systems [20]; two studies indicated that there was no statistical difference between HS values between systems [36,38]; and one study showed lower average HS values in CBP systems [41] (Table 3). Generally, better cleanliness conditions are achieved when a larger area of bedding per animal is provided, as shown in the study conducted by Biasato et al. [41], where the area of bedding per animal was 25.0 m^2.

As mentioned earlier, HS is directly associated with somatic cell count (SCC), an indicator of the number of leukocytes present in milk that can be used as an index of mammary health, as it reflects an immune response and, therefore, the presence of infection [58]. In a study evaluating CBP and LH systems, Astiz et al.

[58] reported lower SCC values in CBP [(96 ± 135) × 1000 cells mL^{-1}, compared to (139 ± 242) × 1000 cells mL^{-1} in an LH system; Table 3]. The authors indicated that the reduction in SCC can be interpreted as an advantage of housing cows in CBPs during the dry period. Eckelkamp et al. [36] reported numerically higher SCC values in CBP systems [(242 ± 21) × 1000 cells mL^{-1}, compared to (229 ± 23) × 1000 cells mL^{-1} in FS systems; Table 3]. However, when evaluating the prevalence of high SCC (P_{MI}), they found no evidence of differences between systems, indicating that, on average, 20% of each herd had subclinical mastitis throughout the year. The results reported by Eckelkamp et al. [36] diverge from those obtained by Emanuelson et al. [44], who reported statistically higher occurrences of SCC, P_{MI}, and the prevalence of new, high SCC ($P_{NH\text{-}SCC}$, which compares SCC with the value obtained in the previous test) for milk samples obtained from confined cattle in CBP systems (Table 3). These results also diverge from those reported by Leso et al. [39], who observed higher SCC values and higher P_{MI} in CBPs (compared to rubber-bedded FS systems; Table 3). Comparing studies is challenging due to variations between housing types, but also in terms of bedding management and climate in the locations where the studies were conducted. However, the results reported are indications that udder health in CBP systems is negatively affected by the increased dirtiness normally observed in cattle housed in this type of system [42,44,59].

The discrepancies between the results obtained in some studies for HS, SCC, and P_{MI} may be attributed not only to differences between housing systems but also to bedding management practices adopted in each case [40]. If bedding management is not effective in keeping the surface dry, as shown in the study conducted by Lobeck et al. [20], the lack of manure incorporation and excess moisture cause HS scores to be higher, indicating that the animals are dirtier [36]. Consequently, animal health may have been affected, as evidenced by the values of SCC, P_{MI}, and $P_{NH\text{-}SCC}$ [15,60]. These findings underscore the fundamental importance of proper bedding management in CBP systems to provide dry, comfortable, and healthy surfaces for housed animals [44], ensuring optimal animal health.

SCC values > 200 × 1000 cells mL^{-1} are typically used to calculate the prevalence of mastitis infection (P_{MI}), which is used as an indirect measure of animal welfare [20]. Mastitis is a disease caused by bacteria and is considered endemic in the dairy industry, as it is responsible for high economic costs (prevention and treatment) and an increase in animal morbidity and culling rates [9,61]. In most studies that evaluated P_{MI}, no significant difference was found between animals housed in CBP and FS systems [9,20,36,39] (Table 3). However, CBPs presented statistically lower P_{MI} values when compared to LH [35] and higher values when compared to TS [9]. Regarding the prevalence of clinical mastitis ($P_{M\text{-}Clin.}$), statistically equal results were also obtained for CBP and FS systems. These outcomes suggest that, if well managed, CBP systems can provide environments as adequate as those obtained in FS, which are considered to have a lower risk for mastitis [9,48].

In the study conducted by Biasato et al. [41] fecal score (FaS) was also evaluated. FaS is scored on a scale from 1 (firm, but not hard) to 4 (devoid of solid matter), and is used to analyze diet digestion and the gastrointestinal health of animals [56,62]. The results indicated no significant difference between CBP and FS systems, and, therefore, gastrointestinal health was adequate in both systems. For the prevalence of ketosis risk (P_{KR}), a metabolic disease associated with fat, the study conducted by Emanuelson et al. [44] also showed equal values between these systems.

In addition to the aforementioned indicators, it is also important to evaluate reproductive disorders, which, along with lameness, mastitis, and metabolic diseases, are a major concern for the dairy cattle production sector [44]. The results of some studies have indicated lower prevalences of cytological endometritis (P_{CE}), purulent vaginal discharge (P_{PVD}), prolonged calving intervals (P_{PCI}), first calving risk (P_{FCR}), retained placenta (P_{RP}), and parturient paresis (P_{PP}) for cattle housed in CBP systems (Table 3). The lower rates observed for reproductive disorders may be associated with the reduction in the prevalence of diseases and/or lesions of hooves and limbs in CBP systems, as these problems could also compromise the reproductive performance of the housed animals [49].

No evidence of improvements in the indicators as prevalences of dystocia ($P_{Dys.}$) and of calf mortality (P_{CM}), and higher prevalences of stillbirth ($P_{Still.}$) and miscarriage ($P_{Misc.}$), were observed in CBP systems compared to FS and TS systems, respectively. This could be attributed to the greater freedom of interaction between cows in CBP systems, which, due to dominance order conflicts, can increase $P_{Still.}$. However, it is extremely difficult to provide a specific explanation, as this result may be associated with other factors not evaluated [44]. Therefore, it is important that new studies on the topic be conducted. Regarding $P_{Misc.}$, the better results achieved in TS can be justified by the lower probability of slipping, tripping, and/or pushing in this type of system, as animals do not need to compete for space in the feeding aisle, as can occur in CBP systems [9].

The prevalences of respiratory disorders such as pneumonia ($P_{Pneu.}$), coughing (P_C), and nasal discharge (P_{ND}) were not significantly different between CBP and FS systems. These respiratory disorders are caused by infectious agents (bacteria, fungi, parasites, or viruses), and their occurrence can also be related to environmental, hygiene, and ventilation conditions [9,63]. Despite the low occurrence of P_C (<1.0%), relatively high $P_{Pneu.}$ and P_{SN} (>25.0%) were observed for all confinement systems evaluated (CBP, FS, and TS). It is estimated that these results are associated with the higher housing density used in confinement systems, which can facilitate the rapid spread of diseases when animals with respiratory problems are not isolated, compared to pasture production [64]. Some studies conducted in CBP systems have associated the occurrence of respiratory disorders with excessive levels of humidity and dust, which can be observed in some situations in this system [59,65]. However, more studies are still needed on the topic to obtain more conclusive results.

The evaluation of indicators related to eye health is also important, as the presence of certain concentrations of gases and dust in the facilities can cause eye irritation in animals [66]. The frequency of occurrence of conjunctivitis ($P_{Conj.}$) was higher in CBP and FS-SC systems compared to FS-SC and TS systems [9] (Table 3). According to the study authors, these results were associated with the accumulation of manure in the bedding and under the slatted floor in these two systems, respectively, which caused higher emissions of ammonia (NH_3) and, consequently, higher P_{Conj}. However, another study found no statistical difference between CBP and FS systems in terms of the prevalence of ocular discharge (P_{OD}) [43] (Table 3).

Indicators related to herd longevity, such as length of life (LL), productive lifespan (PL), parity at exit from the herd (PEFH), and prevalence of mortality (P_{Mo}) were also evaluated in some studies [9,20,35,43,44] (Table 3). When only CBP and FS systems were compared, no significant difference was observed between LL, PL, and PEFH; however, lower P_{Mo} was reported [44] (Table 3), as when compared to LH systems [35] (Table 3). In a study that also evaluated TS systems, a longer PL time was observed for cattle housed in CBP systems [43]—Table 3. These results suggest that, when well-managed, the use of CBP systems can help to reduce the rates of morbidity and culling of cattle, which can lead to significant economic losses for the dairy industry [61].

3.3. Thermal Comfort

For thermal comfort, only experimental studies comparing CBPs with other types of intensive housing systems were also included to ensure equal conditions for obtaining the indicators. Consequently, the thermal-ambient indicators were limited to the following: respiration rate (RR) in association with the Temperature and Humidity Index (THI) [20]; dry-bulb air temperature (t_{db}) and THI [34]; and bedding surface temperature ($t_{B\text{-}Sur.}$) in the resting areas [36].

Lobeck et al. [20] used RR in conjunction with the THI to assess the thermal comfort of dairy cattle housed in CBP systems with positive-pressure mechanical ventilation, compared to FS systems with positive-pressure mechanical ventilation (FS-NV) and cross-ventilation in association with evaporative cooling (FS-CVe). In this study, 75% of the RR measurements were performed under some degree of thermal stress (THI ≥ 70, as defined by Cook et al. [67] and Vitali et al. [68]). Based on the results, the authors noted that numerically lower THI values were obtained in FS-CVe systems (2.0 and 2.1 units lower than the THI values obtained in CBP and FS-NV, respectively). However, the RR values were statistically equal between systems, suggesting that the environmental conditions in the CBP and FS-NV housing systems did not lead to as significant an increase in this animal physiological response as the FS-CVe system (58.4, 59.3, and 57.5 breaths min^{-1} for CBP, FS-NV, and FS-CVe, respectively; Table 3).

In another study conducted in the same facilities described previously, Lobeck et al. [34] assessed the thermal comfort conditions of the animals housed based on the t_{db} and the THI (only evaluated in the summer, as it is a metric used to assess heat stress). The study was conducted between January and November 2008, with one collection in each climatic season (winter, spring, summer, and fall). Based on the results obtained, the authors observed that the prevalence of t_{db} values was statistically equal between the CBP, FS-NV, and FS-CVe systems in the spring and summer periods, but different in the winter and fall periods, when the FS-CVe systems ensured the maintenance of slightly higher tbs values (Table 3). The THI, one of the main indices used to assess heat stress in dairy cattle [29,69,70], was also used to compare the thermal performance of the three housing types. During the summer, it was found that FS-CVe systems maintained statistically lower THI values (65.9, compared to 68.0 and 68.4 obtained in CBP and FS-NV systems, respectively; Table 3).

According to Lobeck et al. [34], the best results observed during extreme climatic conditions in FS-CVe systems were achieved due to the greater insulation provided by the installation during the winter and the use of evaporative cooling during the summer, respectively. The use of side closures during the winter can help to ensure that heat is retained within the facility, and, consequently, that higher air temperature levels are maintained [18]. In fully enclosed facilities with negative pressure ventilation, exhaust fans suck air out of the facility, causing the internal pressure to be lower. Due to this pressure difference between the exterior and interior of the facility, external air is forced to enter the facility through wet plates [71]. When air passes through wet plates, simultaneous heat and mass exchange occurs: part of the water is converted from liquid to vapor, increasing the relative humidity of the air; the sensible heat present in the air is converted into latent heat and used for the phase change of water, and the result of this conversion is a reduction in the temperature of the air entering the facility [71,72]. Therefore, in closed facilities with the use of evaporative cooling, it is possible to achieve more pleasant thermal conditions during the summer [34,73]. Despite the good results obtained with the use of cross ventilation associated with evaporative cooling in FS systems, the use of this type of thermal conditioning solution should be carefully evaluated before implementation in CBPs. In this type of system, in addition to meeting criteria related to animal comfort, ventilation, and cooling systems must be sized and managed to ensure the physical-chemical quality of the bedding (especially in relation to humidity). Therefore, they must also consider aspects related to the specificities of each facility, as well as the local climatic and geographic conditions.

Eckelkamp et al. [36] evaluated the bedding surface temperature ($t_{B\text{-}Sur.}$) conditions that dairy cattle had available to lie down in CBP and FS systems. The authors found that there was no difference in $t_{B\text{-}Sur.}$ between these two types of housing, and that the recorded values were close to the air temperature values. In fact, the environmental conditions, the bedding materials used in CBP systems (usually sawdust and wood shavings, which typically have thermal insulation characteristics), and the use of ventilation yield $t_{B\text{-}Sur.}$ similar to air temperature, even when temperature levels are higher throughout the depth of the bedding [18,19,74,75].

When considering thermal comfort, it is also important to describe in detail the climatic conditions and the characteristics of the housings in which the studies were conducted. Detailed characterization is crucial because the local climate, the construction characteristics, and the thermal conditioning solutions used typically have more direct implications for the thermal conditions achieved in the housings [71,72].

Two studies that evaluated thermal comfort indicators [20,34] were conducted in CBP and FS systems located in Minnesota and eastern South Dakota, United States, in a region with high annual thermal amplitude (≈36 °C). In these studies, sampling was conducted at different times of the year: winter (January to February; average external temperature ranging from −14 to −7 °C, according to the Minnesota Department of Natural Resources [76]), spring (April to May; average external temperature ranging from 2 to 8 °C, according to the Minnesota Department of Natural Resources [76]), summer (July to August; average external temperature ranging from 15 to 22 °C, according to the Minnesota Department of Natural Resources [76]), and fall (October to November; average external temperature ranging from 4 to 9 °C, according to the Minnesota Department of Natural Resources [76]). The third study [36] was also conducted in CBP and FS systems located in a region with high annual thermal amplitude (Kentucky, USA, where the temperature variation can be greater than 30 °C, according to the National Weather Service [77]).

As the regions where the studies of Lobeck et al. were conducted [20], the results obtained by Lobeck et al. [34] and Eckelkamp et al. [34] have a high annual thermal amplitude, and the use of closed facilities with negative pressure ventilation associated with evaporative cooling may be a good option for improving housing thermal conditions. This is because it ensures higher internal temperatures during the cold season and more mild temperatures during hot and dry periods (summer), as shown in the study by Lobeck et al. [34]. Notably, significant gains can be achieved during hot and dry periods (low air humidity) when evaporative cooling systems can provide air cooling of up to 11 °C, depending on local environmental conditions [71,78].

Therefore, the use of closed facilities (with mechanical ventilation associated with evaporative cooling) is recommended for areas with high annual thermal amplitude (requiring greater control), as well as for those where temperatures exceed the upper critical limit of thermal comfort for lactating dairy cows (≥24 °C, according to Baêta and Souza [72]) and relative humidity not too high (≤80%, according to Arcidiacono [78]). However, considering that housing and thermal conditioning solutions must align with the reality of each location, it is crucial to conduct more studies evaluating the thermal performance of CBP systems compared with other housing models (FS, LH, and/or TS) in locations with diverse climatic realities not covered in the described studies.

Concerning the architectural and technological characterization of the facilities used in the studies, the work conducted by Lobeck et al. [34] provided detailed and comprehensive information on the housing conditions. This includes various relevant data such as the length and width of the barns, ceiling height, width of aisles, dimensions of the bedding area (when applicable), and types of ventilation and lighting systems, among other details (for a more in-depth exploration, refer to the original study). However, only average values of thermal-environmental characterization were reported for each system type (CBP, FS-NV, and FS-CVe). Consequently, establishing correlations between the thermal results achieved and the specific housing conditions in each experimental unit became relatively difficult. In the study conducted by Eckelkamp et al. [36], the architectural and technological characteristics of the facilities were not described, possibly because the main objective was to evaluate indicators related to animal health. Again, it was not possible to establish relationships between the specific housing conditions and the achieved thermal results.

Although only three studies have been listed where thermal comfort was evaluated comparatively between CBP and FS systems, the results suggest that thermal conditions are more influenced by the level of thermal conditioning adopted in the facilities than by the presence of composting bedding. In truth, it is recognized that the use of engineering solutions can make it possible to fully control the thermal environment. However, it is essential to evaluate which forms of thermal conditioning best suit the local reality, considering technical, economic, and social factors [71]. Therefore, regardless of the construction type of the facility, the thermal conditioning techniques to be used must ensure optimal conditions for the animals, allowing them to express their maximum productive and reproductive potential [16,64,79,80].

3.4. Limitations and Future Directions

Studies examining the impact of housing systems (CBP, FS, LH, and/or TS) on the health and thermal comfort of confined dairy cattle have been conducted in diverse locations, including Austria, Germany, Brazil, Slovenia, the United States of America, Netherlands, Italy, Poland, and Sweden. However, the comparison of the results of the studies for different systems was hindered due to the variations in the construction typologies, management practices, and climatic conditions that can affect the production systems studied [44]. In addition, the housing systems included through systematic results in this study were not grouped by farm size. Therefore, some caution is needed regarding the extrapolation of the results.

The studies addressed used various indicators to assess animal health and thermal comfort. For this reason, it was not possible to analyze the quality of the studies through a meta-analysis, which could influence the results obtained. Additionally, studies published as conference proceedings, book chapters, and/or not published in English were excluded. However, it was not possible to determine to what extent the results were affected by such exclusions.

The number of studies on animal health and thermal comfort in CBP systems is still low, and it is even lower when considering only studies that compared CBPs with other housing systems (FS, LH, and/or TS). This is likely because CBP is a relatively new housing model, and more comprehensive studies are needed to expand knowledge in this area.

In terms of animal health, the limited number of studies comparing CBPs with other systems (FS, LH, and/or TS) may have made it difficult to obtain conclusive results for some indicators used, such as for example, respiratory disorders and their interrelationships with environmental and bedding management. As discussed previously, the diseases studied in these systems are caused by multiple factors, and, therefore, in-depth studies on this topic have great potential to generate knowledge about animals in different construction typologies. A similar condition was observed for thermal comfort, where, in addition to the limited number of studies, only results obtained in facilities located in the same climatic region were portrayed, making it impossible to achieve more comprehensive results. Therefore, it is crucial to conduct new experimental studies on animal health and thermal comfort in CBP systems, with comparisons to other housing systems when possible. Preferably, future studies should group the housing technologies employed according to the size of the farm and consider the effects of housing on animal health and welfare in the long term. In all cases, they should comprehensively describe the many variations that can be found in terms of facility typologies, climatic and geographical conditions, ventilation systems, materials, environmental and bedding management practices, size and breed of animals housed, etc.

Finally, regarding the assessment of animal health and thermal comfort in intensive dairy production systems, it is also important to develop and validate new precision livestock farming tools. These tools should be applicable and accessible to a wide range of producers, enabling remote and real-time assessment. This can reduce the need for labor and operational costs, as well as improve the detection of thermally stressful conditions, injuries, and diseases in the early stages, facilitating the implementation of thermal conditioning solutions and early treatment to improve the health and thermal comfort of housed animals [3,61,62,81].

4. Conclusions

In this study, the results available in the literature on the health and thermal comfort of dairy cattle housed in CBP systems, compared to FS, LH, and/or TS systems, were described and discussed. Regarding animal health, it was evidenced that the incidence of problems such as lameness, limb injuries, and reproductive disorders is significantly lower in CBP systems. However, if bedding management is not effective in ensuring the provision of dry, comfortable, and healthy surfaces for housed animals, an increase in somatic cell count (SCC) and prevalence of mastitis incidence (P_{MI}) may occur. For thermal comfort, it was found that the CBP system exhibited higher temperatures during summer and lower temperatures during winter when compared to FS with cross-ventilation in association with evaporative cooling. However, no differences were observed in terms of thermal comfort in spring and autumn. Therefore, thermal comfort indicators are more directly related to the time of year and thermal conditioning solutions than to the type of housing system. Although the results achieved in this systematic review do not fully clarify how animal health and thermal comfort can be affected by housing type, they represent the state of the art in this topic and can provide valuable insights for future research.

Author Contributions: Conceptualization, C.E.A.O., I.d.F.F.T. and F.M.C.V.; methodology, C.E.A.O., I.d.F.F.T. and F.C.d.S.; formal analysis, C.E.A.O. and F.C.d.S.; investigation, C.E.A.O.; data curation, C.E.A.O. and F.C.d.S.; writing—original draft preparation, C.E.A.O.; writing—review and editing, C.E.A.O., I.d.F.F.T., F.C.d.S., F.d.C.B., F.M.C.V. and M.B.; supervision, I.d.F.F.T., F.C.d.S. and M.B.; project administration, I.d.F.F.T.; funding acquisition, I.d.F.F.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Coordination of Superior Level Staff Improvement, Brazil (CAPES)—Finance Code 001; the National Council for Scientific and Technological Development, Brazil (CNPq)—Process 422912/2018-2; and the Minas Gerais Research Support Foundation, Brazil (FAPEMIG)—Finance Code 001.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The authors would like to thank the Federal University of Viçosa (UFV) and University of Firenze (UniFI), whose support is appreciated. This work was conducted with the support of the National Council for Scientific and Technological Development, Brazil (CNPq); Coordination of Superior Level Staff Improvement, Brazil (CAPES); and Research Supporting Foundation of Minas Gerais State, Brazil (FAPEMIG).

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

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applied sciences

MDPI

Systematic Review

Physicochemical Bedding Quality in Compost-Bedded Pack Barn Systems for Dairy Cows: A Systematic Review

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Abstract: In this study, a systematic review was performed to describe and discuss the main results available in the literature on physicochemical bedding quality in compost-bedded pack barn (CBP) systems for dairy cows. Experimental peer-reviewed articles in English were searched in the Scopus (ScP) and Web of Science (WoS) databases. The resulting articles (n = 162) underwent an evaluation process in four stages, following the PRISMA methodology and, based on a priori-defined eligibility criteria, 12 were selected. Several indicators of bedding quality were used, emphasizing bedding temperature in the aerobically active layer, evaluated in all studies. The decomposition activity was less intense in winter due to mild environmental conditions. During this period, appropriate management practices should be used (more frequent bedding replacement and turning, use of aeration systems under the bedding, lateral closures in the facilities, etc.) to maintain the fully active composting process. In conclusion, the physicochemical bedding quality in this system type is mainly affected by environmental conditions. However, some care is needed to extrapolate these results since this is a recent research area, which still requires further studies.

Keywords: dairy cattle; confinement systems; composting; bedding characterization; management

Citation: Oliveira, C.E.A.; Tinôco, I.d.F.F.; Souza, C.d.F.; Baêta, F.d.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

Academic Editor(s): Norman Q. Arancon

Received: 7 August 2023
Revised: 24 August 2023
Accepted: 29 August 2023
Published: 30 August 2023

1. Introduction

Current livestock production has assumed an intensive nature, being characterized by compact farms, high input use and production in collective facilities, with the presence of thermal conditioning systems and some level of automation. These strategies, used in intensive animal systems, make it possible to increase the number of animals housed in terms of productive indexes and therefore ensure the safe supply of animal products [1,2]. Choosing the facility type is a crucial step. It must be chosen considering aspects related to the local reality (climate conditions, techniques, materials and construction costs, labor for operation and maintenance, return on investment, etc.) and the needs of the animals to be housed (thermal comfort, health, and performance) [3–6].

For dairy cattle, in particular, the compost-bedded pack barn (CBP) system, considered an alternative to traditionally used systems (tie-stall (TS) and free-stall with cubicles (FS)), has been gaining prominence and use worldwide in the last decades [5,7–10]. In CBP, the cows are housed in collective facilities with bedding made of soft and comfortable organic materials, which, together with the excrements deposited by the animals and under certain conditions, decompose over time—Figure 1 [11,12].

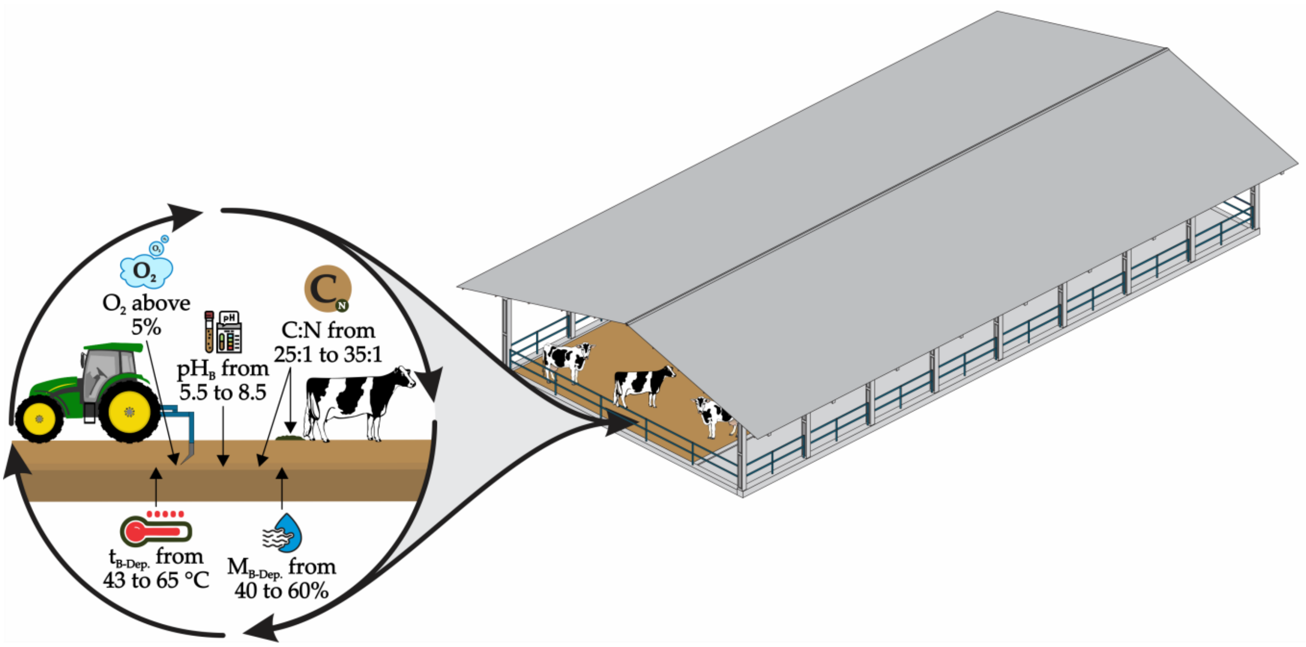

Figure 1. Schematic representation of the bedding composting process in a compost-bedded pack barn system (emphasis on the bedding turning). C:N—carbon:nitrogen ratio; $M_{B\text{-}Dep.}$—moisture in the aerobically active layer; O_2—oxygen available; pH_B—bedding hydrogen potential; and $t_{B\text{-}Dep.}$—temperature in the aerobically active layer. Source: Adapted from Damasceno [13].

Bedding composting in CBP systems is a biological process influenced mainly by factors such as temperature, moisture, hydrogen potential (pH), and concentrations of carbon and nitrogen in the bedding, as well as the oxygen availability [13–15]. Ideally, these parameters should be controlled within adequate ranges so that adequate decomposition levels of organic matter are ensured and, consequently, pathogenic microorganisms are eliminated and compost with good agronomic quality is generated [13,16,17]. The importance and general recommendations for these bedding parameters in CBP systems are:

- Bedding temperature: A parameter directly related to the decomposing microorganisms' activity, as the more intense this activity is, the greater the heat production. In the CBP's aerobically active layer (0.15 to 0.30 m) it is desirable that it be maintained between 43.0 and 65.0 °C [11,13,14,16];
- Bedding moisture: A variable associated with the metabolic activity of decomposing microorganisms, including oxygen availability in the bedding and the animals' manure. It is recommended that its levels be kept in the range of 40.0 to 60.0%, ensuring the maintenance of aerobic conditions and the survival of decomposing microorganisms [7,11,14,18,19];
- Bedding hydrogen potential (pH): A parameter associated with the enzymatic activity and development of decomposing microorganisms. It varies according to the composting process stage and the material used, but

it is recommended that it be kept in a range of between 5.5 and 8.5 [13,14,20–22];

- Bedding carbon (C) and nitrogen (N) available: Especially important for decomposition activity, it is normally evaluated through the C:N ratio, since C and N are used for energy supply and protein synthesis, respectively. It is recommended that higher C:N ratios be provided at the beginning of the composting process (25:1 to 35:1), as most of the assimilated carbon (≈66%) is eliminated in the form of carbon dioxide (CO_2) and only part of it is immobilized and incorporated into the cellular protoplasm. With the degradation of organic matter during the composting process, there is a reduction in the C:N ratio, and it is important that C source materials are provided (wood sawdust, wood shavings, etc.) so that the composting process is not diminished [7,13,16,23];
- Bedding oxygen available (O_2): A crucial factor, as it is related to the respiration of aerobic decomposing microorganisms. The required O_2 concentration is a function of the material type, environmental conditions (temperature and humidity), and the composting stage, but the recommended minimum between bedding intraparticle spaces is 5% [13,14,24,25].

In CBPs, managing the bedding properly, with basis on the environmental factors in each facility, is considered the crucial point to achieving satisfactory performance with its use [7,26]. Due to the importance of bedding management in CBP systems, conducting studies to evaluate/characterize the bedding quality and monitor the composting process's efficiency in this system type is essential [4,27]. Some studies with this objective have been conducted in different places [5,11,19,28–34] which, in addition to specific climatic conditions, have notable differences in facility types, materials, and bedding management practices. However, until now, there is no knowledge of any systematic review on the physicochemical bedding quality in CBP systems. Therefore, it is important to understand the potential synergies between the different CBP systems in terms of climatic conditions, facility types, materials and bedding management practices, and quality of the material being composted. From the understanding of the CBPs operation, it is possible to propose management adaptations in existing systems and future projects. In this context, this systematic review was conducted to describe and discuss the main results available in the literature on physicochemical bedding quality of CBP systems in different housing facilities, climatic conditions, and seasons.

2. Materials and Methods

To obtain the main results available in recent studies on bedding quality in CBP systems, a systematic literature review was carried out, conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses methodology—PRISMA [35]. To achieve the proposed objective, search, selection, eligibility, and inclusion of studies were conducted, as well as analysis and extraction of interesting information [36].

2.1. Systematic Search of Studies

To identify articles relevant to the interesting topics, systematic searches were conducted in the Scopus (ScP) and Web of Science (WoS) databases, the most significant data repositories of the world's scientific literature [37]. It was decided to carry out a systematic search in these databases because ScP is a comprehensive platform, accommodating studies published in different databases, and WoS contemplates only studies published in journals indexed by Clarivate Analytics, which are peer-reviewed [38].

As this study addressed a specific topic, several search terms were used (Table 1) to return as many publications as possible. To group the different words and expressions that could return studies on the interesting topic, the systematic search was carried out with the integration of Boolean operators (AND, OR, and NOT), together with wildcard truncations (" ").

Table 1. Search terms used during study searches in this systematic review.

Acronym	Search String
Animals	(cattle OR "dairy cattle" OR "dairy cows" OR "lactating cows")
System	("compost barn" OR "compost bedded" OR "compost-bedded pack" OR "compost-bedded barn" OR "compost-bedded pack barn" OR "compost-bedded pack barn system")
Bedding	(bedding OR "composting bed" OR "bed quality" OR "bed characterization" OR "bedding characteristics" OR "bed evaluation" OR "bed features")

2.2. Selection and Organization of Studies

In this systematic review, we sought to select only studies evaluating and/or characterizing physicochemical variables and/or bedding quality indicators in CBP systems for dairy cattle. Thus, only experimental articles in English, peer-reviewed and published until May 2023 were considered. Criteria for inclusion and exclusion of articles were defined a priori.

Searches in the WoS and ScP databases returned 93 and 65 results, respectively, and all the results were included in Mendeley® software (Mendeley Desktop, version 1.19.8, Elsevier©) from which duplicates were identified and excluded. The remaining studies were selected through a four-step screening process, following the PRISMA methodology—Figure 2 [35]:

- First stage: Metadata evaluation—excluding studies that have not been published in English, review articles, dissertations, theses, and studies where peer review is uncertain (conference proceedings and book chapters);
- Second stage: Review of titles and abstracts—identifying and excluding studies that were not conducted in dairy cattle facilities (e.g., beef cattle, horses, swine, etc.), that were not conducted in compost-bedded pack barn systems (e.g., studies carried out in free-stall systems with cubicles, tie-stall systems, etc.), which did not evaluate or only partially evaluated physicochemical bedding properties at the facility level and/or did not specify the location and period in which bedding collections were carried out (e.g., characterization studies of dry bedding materials at laboratory level and/or evaluation of only one bedding property, such as surface temperature);
- Third stage: Qualitative assessment and selection of filtered studies—using domains 1 (study eligibility criteria), 2 (study identification and selection), and 3 (data collection and evaluation) of the risk of bias in systematic reviews (ROBIS), as reported by Whiting et al. [39];
- Fourth stage: Finally, the set of selected studies was read in detail to verify that all referred to experimental works of evaluation and physicochemical characterization of bedding materials in CBP systems were conducted with lactating dairy cattle, specifying the place and year season in which they were carried out.

To carry out a more comprehensive study of the available literature about the proposed theme, no additional restrictions, such as publication period, sample size, or journal quality, were imposed.

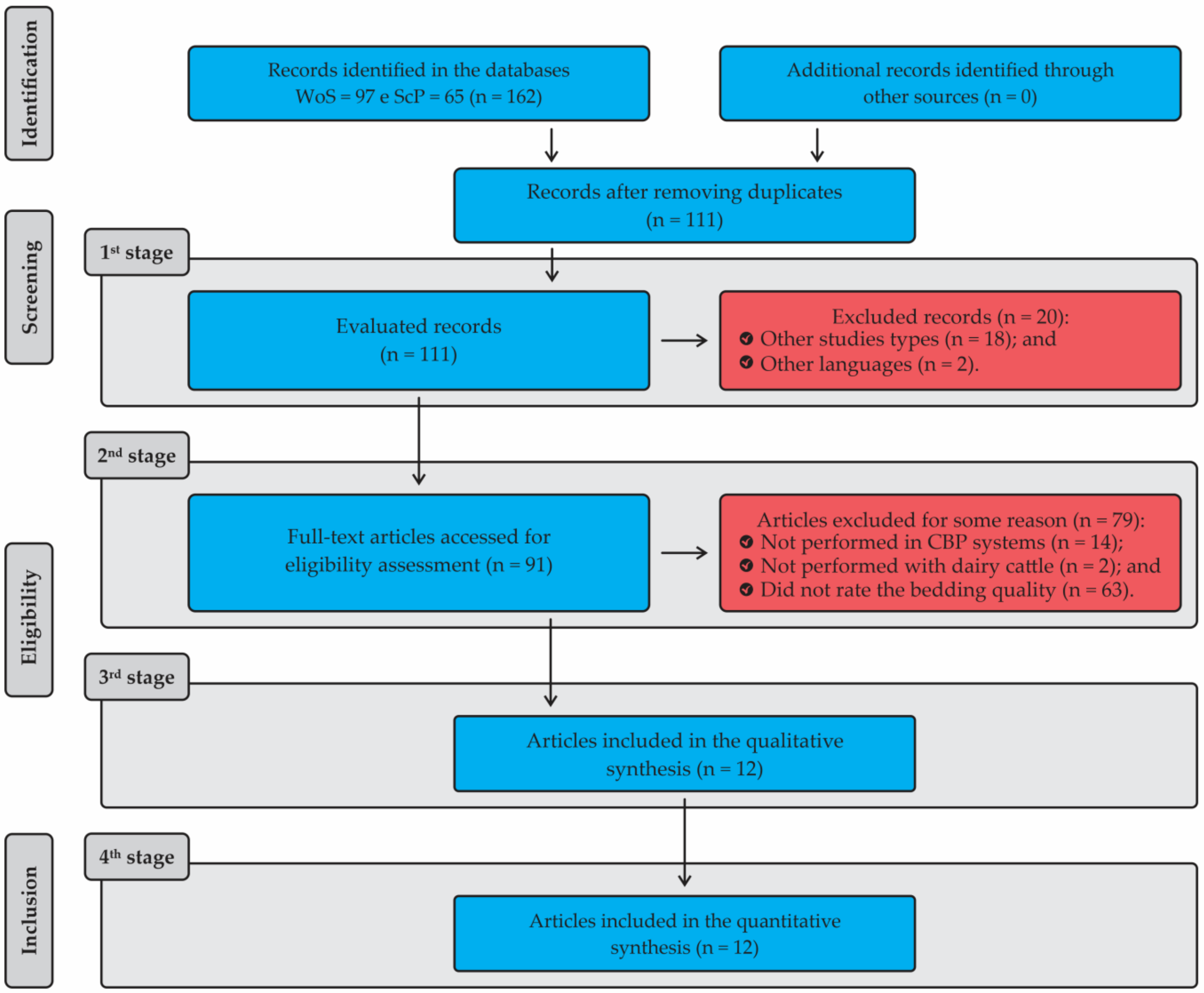

Figure 2. Information flow indicates the number of studies identified and filtered at each stage of the systematic review process. Source: Adapted from Moher et al. [35].

2.3. Extraction and Manipulation of Information

Microsoft Excel® was used to extract and organize interesting information in the selected studies. In the mentioned software, a spreadsheet was created containing the following information: identification of the study, authors, year, journal in which it was published, country, region, type of bedding, type of bedding management, physicochemical bedding quality indicators evaluated/characterized, and results achieved.

3. Results and Discussion

3.1. Overview of Included Studies

A search in the WoS and ScP databases returned 162 results, which were added to Mendeley® and, after excluding duplicates, 111 studies remained—Figure 2. Of these 111 studies, 20 were excluded for not meeting the eligibility criteria of first stage (2 were written in languages other than English (Spanish and Portuguese); 12 were published as literature review; 4 were published in conference proceedings; and 2 were published as book chapters), and another 79 for not meeting the eligibility criteria defined in the second stage (14 were carried out in animal production systems other than CBPs; 2 were carried out in facilities for other animal types (beef cattle and horses); and 63 did not carry out a physicochemical evaluation/characterization of the bedding material and/or did not specify the place and period in which the bedding samples were collected). Finally, 12 articles were used to compose this systematic review.

Table 2 lists detailed information on the selected studies of bedding evaluation and/or characterization, including authors, region, country where they were carried out, facility types and ventilation systems used, information related to the bedding being composted, and the study purpose.

The 12 selected studies were published between 2007 and 2023, and this fact reinforces that CBP is a relatively recent housing system, compared to the confinement systems traditionally used in intensive production of dairy cattle (FS and TS). Such results are in line with what was verified by Silva et al. [36], who conducted a bibliometric study and identified that the first article on CBP systems was published in 2007. As highlighted in Table 2, the selected studies were carried out in different countries: Brazil (n = 5), Germany (n = 1), and Italy (n = 1), Spain (n = 1), the Netherlands (n = 1) and the United States of America (n = 3).

3.2. Physicochemical Characterization

The bedding temperature in the aerobically active layer (0.15 to 0.30 m, $t_{B\text{-}Dep.}$) was used as one of the main indicators of quality and/or maintenance of the composting process, present in all selected studies—Table 3. During the composting process, the increase in temperature results from the exogenous chemistry reactions of molecule degradation of the bedding material, provided that adequate moisture levels and oxygen are ensured, as required by the aerobic decomposer microorganisms [29]. For this reason, $t_{B\text{-}Dep.}$ is a good indicator of the population's evolution of these microorganisms and, therefore, of the composting process efficiency [4,16].

The formation of temperature gradients between the interior and bedding surface (normally 20 to 30 °C) indicates that the bedding is biologically active [7]. However, verifying whether the desired activity levels have been achieved is still necessary. Preferably, $t_{B\text{-}Dep.}$ must be kept in the range of between 43 and 65 °C; below 40 °C, the bedding degradation is slow, and above 55 °C, the material sanitization (elimination of pathogens) is maximum [11,13,14]. In some studies, the maxima $t_{B\text{-}Depth}$ reached were lower than 40 °C in at least one of the evaluated periods (when this was the case), which is an indication that the decomposing microorganisms' activity was reduced in these places, and that the bedding degradation occurred more slowly (Shane et al. [19], Biasato et al. [5], Giambra et al. [31], and Llonch et al. [29]—Table 3). The high prevalence of temperatures below 40 °C is considered a potential disadvantage since, under these conditions the decomposing microorganisms' population is more diverse but less efficient in carrying out the degradation of bedding material [5,14]. Therefore, investigating ways to improve the bedding composting process in CBP systems is a potential field for future studies.

Table 2. Characterization of studies that evaluated and/or characterized the physicochemical bedding quality material in compost-bedded pack barn (CBP) systems.

Reference	Place	Facility		Bedding			Study	
		FCT	VST	BM	BAA	BTO	Season	Purpose
Barberg et al. [30]	Minnesota (USA)	12 CBPs with partially open sides [1]	NV LVHS HVLS [2]	Sa. + WC	3.5–14.3 [3]	2	Summer to fall [4]	Describe facility characteristics, bedding materials, and thermal conditions in CBP systems in Minnesota (USA), with design and management recommendations
Shane et al. [19]	Minnesota (USA)	6 CBPs with partially open sides [1]	LVHS HVLS [2]	CS, FSt., OH, Sa., SS, WC, or WS [5]	5.2–8.0 [3]	2	Winter, spring, summer, and fall	Describe management practices in the milk production activity in CBP systems using different bedding materials in Minnesota (USA)
Black et al. [11]	Kentucky (USA)	47 CBPs with partially open sides [1,6]	NS	Sa. + WC, Sa., Sa.G, or SH [5]	9.0 ± 2.2 [3]	1–3 [7]	Fall to spring [4]	Describe management practices applied in CBP systems in Kentucky, their influence on the health, hygiene, production, and animals' reproductive performance, and determine factors that influence the temperature and bedding moisture
Biasato et al. [5]	Cuneo (IT)	1 CBP with partially open sides	NS	HW + VW	25.0	2	Spring, summer, and fall	Determine bedding characteristics, behavior, and milk quality of housed animals, and cheese quality in CBP and FS systems in Northwest Italy [8]
Giambra et al. [31]	Hessen (DE)	3 CBPs with partially open sides [9]	NS	Sa., WC, or OM [10]	7.8–9.4 [11]	3	Winter, spring, summer, and fall	Evaluate bedding parameters in CBP systems for different animal groups and periods, and their effects on thermophilic aerobic spores (TAS)
de Boer and Wiersma [32]	NL	1 CBP with partially open sides	NV + LVHS [12]	WC	13.8	1 [13]	Fall, winter, spring, and summer	Evaluate the conversion of inorganic to organic nitrogen (N), reduction in inorganic N concentration, and loss of volatile N in a CBP for dairy cattle
Llonch et al. [29]	SP	2 CBPs with partially open sides [14]	NS	FB and Sa.	12.5	2	Fall and winter [15]	Study agronomic characteristics of two materials (sawdust and forest biomass) used as bedding substrate in CBP systems for dairy cattle
Nogara et al. [33]	Rio Grande do Sul (BR)	8 CBPs [16]	NS [17]	NS	11.9–32.3 [3]	NS	Winter to spring [4]	Characterize bedding management and milk composition in the bulk tank, and evaluate the influence of bedding variables on milk composition in CBPs in northwest Rio Grande do Sul

Table 2. *Cont.*

Reference	Place	Facility		Bedding			Study	
		FCT	VST	BM	BAA	BTO	Season	Purpose
Oliveira et al. [28]	Minas Gerais (BR)	1 fully closed CBP	MVT-EC	Sa.	9.2–14.2 [18]	2	Spring	Evaluate dependence and spatial distribution of bedding variables in a CBP system with controlled conditions (closed, with mechanical ventilation in tunnel mode (negative pressure) associated with evaporative cooling), used for housing dairy cattle
Andrade et al. [4]	Minas Gerais (BR)	1 fully closed CBP	MVT-EC	CH + WC	7.8–11.0 [19]	2	Summer and winter	Characterize, evaluate, and compare the spatial distribution of bedding variables, animal welfare indicators, and milk production in a closed CBP with negative tunnel ventilation for winter and summer conditions in Brazil
Freu et al. [34]	São Paulo (BR)	7 CBPs [16]	NS	Sa.	8.3–16.0 [3]	2–3 [7]	Summer to fall [4]	Evaluate the frequency and pathogen profiles that cause mastitis in cows housed in CBP systems, and associate the mastitis occurrence with the physicochemical and microbiological characteristics of the bedding material
Oliveira et al. [27]	Minas Gerais (BR)	1 CBP with open sides	LVHS	Sa. + WC	9.9–11.5 [18]	2	Winter	Evaluate and characterize whether bedding variables have spatial dependence and spatial variability in relation to the internal area of a CBP system with positive pressure ventilation during the winter period in Brazil

[1] CBP systems with different typologies, most of which had open sides, with the presence of a movable curtain; [2] distinct types of ventilation systems used, from natural ventilation only to positive pressure mechanical ventilation; [3] available bedding area per animal varies between facilities; [4] obtained average data corresponding to the two stations, without separation by period; [5] bedding material varies between facilities; [6] CPB systems used for housing cows in lactation and with special needs (sick, elderly, etc.) were considered; [7] number of bedding turning operations variable between facilities; [8] other objectives were described in the study but were not of interest in this review; [9] this study used different CBPs treatments. $CBP_{1\text{-lact.}}$, $CBP_{2\text{-lact.}}$, and $CBP_{3\text{-lact.}}$ were considered in this systematic review for composition of average values; [10] other materials, such as cereal husks and crushed cultural remains, were also used; [11] bedding area per animal variable between treatments and periods of the year; [12] in addition to positive pressure ventilation, suction equipment was also used to extract hot and humid air deep into the bedding; [13] intense turning with rotary tiller, associated with ventilation by floor bedding ventilation for periods of 15 min every 6 h; [14] other details about the facility characteristics were not specified; [15] collections carried out at the two indicated stations, as reported by the authors; [16] collections of bedding carried out in CBP systems, without limiting further details about facilities; [17] despite briefly discussing ventilation, it was not clearly mentioned which ventilation systems were used; [18] bedding area per animal variable between lots; [19] bedding area per animal variable between batches and season. BAA—bedding area per animal, in $m^2 \cdot cow^{-1}$; BM—bedding material; BTO—bedding turning operations, in operations$\cdot day^{-1}$; BR—Brazil; CS—corn straw; CH—coffee husk; DE—Germany; FB—forest biomass; FCT—facility constructive typology; FSt.—flax straw; HVLS—high-volume, low-speed mechanical ventilation; HW—household waste; IT—Italy; LVHS—low-volume, high-speed mechanical ventilation; MVT-EC—negative pressure mechanical ventilation (in tunnel mode) associated with evaporative cooling; NL—the Netherlands; NS—not specified; NV—natural ventilation; OH—oat husk; OM—other materials; Sa—sawdust; $Sa._G$—green sawdust; SH—soy husk; SP—Spain; SS—soybean straw; USA—United States of America; VST—ventilation system type; VW—vegetable waste; WC—wood chips; WS—wheat straw.

Table 3. Physicochemical characterization of bedding material in compost-bedded pack barn (CBP) systems, according to studies conducted in various locations and periods of the year.

Reference	Season	BM	t_B (°C)		M_B (%)		pH_B		N (%)	P (%)	K (%)	C (%)	C:N
			Sur.	Dep.	Sur.	Dep.	Sur.	Dep.					
Barberg et al. [30] [1]	Summer to fall [2]	Sa. + WC	—	24.4–58.9 [3]	—	28.0–78.9 [4]	—	6.4–9.9 [4]	0.57–4.22 [4]	0.04–0.67 [4,5]	0.26–2.96 [4,5]	NS [6]	10.9– 87.5 [4]
Shane et al. [19] [7,8]	Winter Summer	VM [9]	— —	7.7–40.6 [4] 31.8–48.1 [4]	— —	— —	— —	8.5–8.9 [4] 8.7–9.1 [4]	0.61–0.89 [4] 0.89–1.23 [4]	0.15–0.26 [4,5] 0.29–0.43 [4,5]	0.78–1.92 [4,5] 1.42–2.27 [4,5]	12.70–20.10 [4] 15.30–17.40 [4]	16.0– 26.0 [4] 13.1– 18.2 [4]
Black et al. [11] [1]	Fall to spring [2]	VM [9]	10.5 ± 8.0	36.1 ± 11.0 [10]	27.0–70.0 [11]	—	—	—	1.00–2.90 [11]	0.20–0.90 [11]	0.40–3.00 [11]	20.90–47.10 [11]	11.3– 43.2 [11]
Biasato et al. [5] [12]	Spring Summer Fall	HW+ VW	— — —	32.0–39.0 [13] 21.1–35.0 [13] 29.2–33.1 [13]	45.8 [11] 39.3 [11] 59.2 [11]	— — —	8.3 [11] 8.9 [11] 8.9 [11]	— — —	2.80 [11] 2.40 [11] 4.40 [11]	— — —	— — —	6.70 [11] 5.80 [11] 15.50 [11]	2.4 [11] 2.4 [11] 3.5 [11]
Giambra et al. [31] [14]	Winter Spring Summer Fall	Sa., WC, OM [15]	— — — —	31.1–34.8 [10] 34.0–36.1 [10] 40.2–42.1 [10] 46.3–56.3 [10]	— — — —	50.2–50.3 [10] 65.3–68.8 [10] 62.5–64.2 [10] 48.2–56.8 [10]	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —
de Boer and Wiersma [32] [16]	Fall [17] Winter [18] Spring [19] Summer [20]	WC	— — — —	18.0–52.8 [21] 43.7–53.2 [21] 46.1–53.5 [21] 43.7–49.4 [21]	— — — —	48.7–51.1 [22] 42.2–55.7 [22] 50.6–55.7 [22] 53.1 [22]	— — — —	5.5–6.8 [13] 7.4–8.6 [13] 7.7–8.8 [13] 9.0 [13,23]	0.33–0.44 [13] 0.52–0.75 [13] 0.69–1.29 [13] 1.25 [13,23]	0.04–0.05 [13] 0.07–0.09 [13] 0.10–0.19 [13] 0.19 [13,23]	0.15–0.26 [13] 0.38–0.80 [13] 0.63–1.50 [13] 1.56 [13,23]	25.20–27.40 [13] 22.90–28.50 [13] 20.80–24.40 [13] 22.00 [13,23]	60.0–77.0 [13] 31.0–51.0 [13] 18.0–35.0 [13] 18.0 [13,23]
Llonch et al. [29] [24]	Fall Winter	Sa.	— —	34.7 ± 5.6 [25] 31.2 ± 5.9 [25]	— —	54.1 ± 17.0 [25] 55.0 ± 16.4 [25]	— —	8.0 [25,26] 9.0 [25,26]	0.96 [25,26] 1.12 [25,26]	0.24 [25,26] 0.28 [25,26]	1.22 [25,26] 1.78 [25,26]	46.08 [25,26,27] 44.80 [25,26,27]	48.0 [25,26] 40.0 [25,26]
	Fall Winter	FB	— —	28.3 ± 6.9 [25] 25.9 ± 3.1 [25]	— —	62.0 ± 14.0 [25] 59.4 ± 7.2 [25]	— —	8.4 [25,26] 7.8 [25,26]	1.19 [25,26] 1.24 [25,26]	0.28 [25,26] 0.25 [25,26]	1.64 [25,26] 1.62 [25,26]	41.65 [25,26,27] 43.40 [25,26,27]	35.0 [25,26] 35.0 [25,26]
Nogara et al. [33] [28]	Winter to spring [2]	NS	14.0–41.5	17.1–54.1 [29]	—	43.8–67.8 [29]	—	6.1–9.7 [29]	—	—	—	—	—
Oliveira et al. [28] [30]	Spring	Sa.	22.0–28.0	35.0–55.0 [10]	10.0–60.0	10.0–60.0 [10]	7.0–11.0	7.0–11.0 [10]	—	—	—	—	—
Andrade et al. [4] [31]	Summer Winter	CH + WC	22.0–27.0 [32] 13.8–17.8 [32]	30.0–47.0 [10] 23.0–44.0 [10]	44.0–58.0 57.0–65.0	46.0–61.0 [10] 58.0–66.0 [10]	8.7–10.1 8.8–9.3	8.7–10.0 [10] 8.8–9.1 [10]	1.12–1.32 [33] 1.43–1.74 [33]	0.20–0.34 [33] 0.15—0.27 [33]	1.76–2.10 [33] 1.46—2.56 [33]	17.49–18.59 [33] 16.63–31.44 [33]	14.46–16.17 [33] 11.63–19.14 [33]

Table 3. *Cont.*

Reference	Season	BM	t_B (°C)		M_B (%)		pH_B		N (%)	P (%)	K (%)	C (%)	C:N
			Sur.	Dep.	Sur.	Dep.	Sur.	Dep.					
Freu et al. [34] [34]	Summer to fall [2]	Sa.	—	26.4–55.0 [29]	—	30.4–61.9 [29]	—	7.4–9.5 [29]	—	—	—	—	9.00– 48.0 [29]
Oliveira et al. [27] [35]	Winter	Sa. + WC	14.1–19.6	17.8–49.6 [10]	25.5–92.6	29.8–84.8 [10]	8.4–9.6	8.3–9.6 [10]	—	—	—	—	—

[1] They also analyzed the bacteriological bedding composition, characterized facilities, environment, and production costs; [2] average data, without individual separation by period; [3] average data from different depths (15, 30, 61, and 91 cm); [4] average data from different depths (15 and 30 cm); [5] results in ppm or $g \cdot kg^{-1}$ were converted to % (standardization); [6] not specified, but subject to calculation, through C:N and N; [7] they also analyzed the bacteriological bedding composition and milk, and characterized facilities, environment, and animal indicators; [8] measurements were also performed in spring and fall periods, but only winter and summer data were listed; [9] several materials were used, and no separation between results is indicated; [10] average data at a depth of 20 cm; [11] average data from surface bedding samples; [12] they also analyzed the bedding bacteriological composition, the animal health and behavior, as well as the cheese quality; [13] not specified at what depth data were collected, but, based on the values, it is understood that these are subsurface data; [14] this study used different CBPs treatments. $CBP_{1\text{-lact.}}$, $CBP_{2\text{-lact.}}$, and $CBP_{3\text{-lact.}}$ were considered in this systematic review for composition of average values; [15] other materials (cereal husks and ground crop residues); [16] the main objective was to evaluate the nitrogen losses during the process; [17] beginning of the composting process (from 13 November 2013 to 20 December 2013); [18] from 21 December 2013 to 20 March 2014; [19] from 21 March 2014 to 20 June 2014; [20] from 21 June 2014 to 8 July 2014; [21] average data from different depths (15 and 25 cm), extracted using graphical interpretation; [22] data obtained by dry matter; [23] only one collection was carried out in the summer; [24] they also evaluated compost piles, after removing the material from the CBPs; [25] average data at depth of 15 cm; [26] data obtained 11 weeks after starting the composting process; [27] data calculated from C:N and N; [28] they also analyzed the chemistry milk composition; [29] average data from different depths (10 and 20 cm); [30] they also examined the bedding mechanical properties; [31] they also analyzed animal welfare and production indicators; [32] data before bedding turning; [33] average data from different layers (0 and 20 cm); [34] they also evaluated the frequency of mastitis pathogens, associating them with bedding quality; [35] they also assessed wind speed at bedding level. BM—bedding material; C—carbon; CH—coffee husk; C:N—carbon:nitrogen ratio; Dep.—depth; FB—forest biomass; HW—household waste; K—potassium; M_B—bedding moisture; N—nitrogen; NS—not specified; OM—other materials; P—phosphorus; pH_B—bedding hydrogen potential; Sa.—sawdust; Sur.—surface; t_B—bedding temperature; VM—various materials; VW—vegetable waste; WC—wood chips.

According to the consulted studies, the prevalence of $t_{B\text{-}Dep.}$ < 40 °C may be associated to different factors:

- Type and particle size of bedding materials used: materials with greater granulometry and organic matter stability tend to have slower decomposition activity [29];
- Turning frequency of the bedding material: performing fewer turning operations reduces the bedding surface aeration and, consequently, the activity of decomposing microorganisms and the heat generation [11,31];
- Sample collection depth: samples collected closer to the bedding surface (such as 5 cm deep, as performed by Biasato et al. [5], for example) tend to have a lower temperature, compared with samples collected at greater depths (>15 cm), as performed in other studies;
- Bedding moisture: high moisture values are negatively correlated with temperature, as they can lead to anaerobic conditions [31,40];
- Season of the year: studies conducted in the winter period tend to record lower $t_{B\text{-}Dep.}$ values [29,32].

Regarding the studies that were carried out in different periods of the year, it was found that $t_{B\text{-}Dep.}$ normally presents lower values in winter compared to the summer period (Shane et al. [19], Giambra et al. [31], de Boer and Wiersma [32], and Andrade et al. [4]—Table 3). This fact was already expected, since fluctuations in $t_{B\text{-}Dep.}$ throughout the year tend to follow changes in ambient temperature [12,19,30]. Additionally, the temperature gradient between ambient air and the bedding interior is greater in winter [11]. As a result, there is a tendency for greater internal cooling in the bed in winter, making the maintenance of higher $t_{B\text{-}Dep.}$ and the evaporation of excess moisture a significant management challenge [29,32].

If lower $t_{B\text{-}Dep.}$ values were recorded during the summer than those obtained in other seasons of the year (spring and fall), as observed in the study conducted by Biasato et al. [5], there was a reduction in decomposition activity. This reduction during the summer could have been caused by a lack or excess of moisture in the bedding. Still, it indicated that material is already completing the composting process in the CBP [5,32]. The first hypothesis, related to moisture, can be verified by observing the animals' soiling, since in conditions of excessive moisture, there is a tendency for bedding particles to adhere, or by directly determining the water content present in bedding samples [8,11,18,41]. The second hypothesis, referring to the completion of the composting process, can be verified through the carbon: nitrogen (C:N) ratio since in the final stage of the composting process, a low C:N is usually found due to the organic C reduction (converted into CO_2) and the increase in total N (mineralized) [13].

Among the studies listed in this systematic review, only in the one conducted by Barberg et al. [30] were values of $t_{B\text{-}Dep.}$ > 55 °C were recorded. Therefore, it is assumed that sufficient temperature levels were not reached in all other cases to promote bedding sanitation. The prevalence of temperatures below this threshold during bedding decomposition in CBP systems indicates that this is a semi-composting process [5,7,41]. As bedding material is not typically sanitized in the CBP system itself, the removed material must be stored in a place protected from rain and sun (preferably covered with compost fleece) so that the composting process is completed, forming humus [13]. If, on the one hand, the nonsanitization of bedding in CBP systems is considered a disadvantage, on the other hand, it makes it possible to reduce nitrogen losses, given that ammonia volatilization is lower when $t_{B\text{-}Dep.}$ is kept below 55 °C [32].

To keep the composting process active, starting the cold season with the bedding material in total decomposition activity is essential, ensuring sufficient heat generation to maintain the moisture in the desired range [11,13]. Preferably, the change of bedding material should be carried out in the fall period, leaving a layer of the old bedding (inoculum), so that at the beginning of the cold season, the heat generation is not compromised [40,42]. This allows for the composting process to be fully active and to have enough metabolizable energy and water retention capacity to maintain bedding moisture during winter [32]. Additionally, lateral closures can be used in winter facilities, to increase the internal temperature due to the reduction of evaporative cooling, ensuring better temperature conditions in the environment and the bedding [11].

Another parameter evaluated in the listed studies was the bedding surface temperature ($t_{B\text{-}Sur.}$), which is related to the thermal comfort of the housed animals and varies typically according to the dry air bulb temperature [12,30]. This occurs because ventilation removes heat from the bedding surface through sensitive and latent pathways, and the bedding materials (usually sawdust and wood shavings) are poor heat conductors, leading to values of $t_{B\text{-}Sur.}$ close to those of the ambient temperature, even if the $t_{B\text{-}Dep.}$ levels are higher [8,11,13,28].

Since $t_{B\text{-}Sur.}$ is essential for the thermal comfort of housed animals, its evaluation can be based on the range of between 4 and 24 °C, usually considered as the level of thermal comfort for lactating dairy cattle [27,43]. Considering this range for the $t_{B\text{-}Sur.}$ assessment, the results of some studies showed that in fall and winter, the $t_{B\text{-}Sur.}$ conditions were thermally comfortable for the animals, allowing them to spend more time lying down and partake in activities of leisure and rumination (Black et al. [11], Andrade et al. [4] and Oliveira et al. [27]—Table 3). However, in spring and summer, conditions of $t_{B\text{-}Sur.} > 24$ °C were recorded, which are considered thermally uncomfortable for housed animals (Oliveira et al. [28] and Andrade et al. [4]—Table 3). If the conditions of $t_{B\text{-}Sur.}$ higher than desired are registered only in specific facility regions (such as those where there is an incidence of direct solar radiation, for example), it is possible to resort to the use of localized thermal conditioning solutions, such as low static pressure vents, which can be activated only when necessary [44]. Otherwise, the general ventilation rate inside the facility should be increased, in order to favor thermal exchanges and reduce $t_{B\text{-}Sur.}$ [8,11].

Other commonly used parameters for evaluating bedding quality in CBP systems are moisture (M_B) and hydrogen ion potential (pH_B)—Table 3. According to Damasceno [13], evaluating the bedding quality through these and other parameters is a crucial subsidy tool for decision-making concerning management practices, to ensure that the composting process occurs satisfactorily.

The water content or moisture in the bedding (M_B) is essential for the survival of the aerobic microorganisms active in the composting process. Maintaining it between 40 and 60% is recommended to ensure aerobic conditions [11,14]. In CBP systems, M_B is considered one of the most challenging parameters to control since it is directly influenced by management and local climatic conditions [7]. The difficulty maintaining M_B was reported through the results achieved in some of the listed studies, in which the minimum and maximum M_B values were less than 10% and greater than 60%, respectively (Barberg et al. [30], Black et al. [11], Giambra et al. [31], Oliveira et al. [28], Llonch et al. [29], Nogara et al. [33], Andrade et al. [4], Freu et al. [34], and Oliveira et al. [27]—Table 3).

Excess of bedding moisture in CBP systems can lead to the occurrence of several problems, such as reduced composting activity, increased emission of harmful gases such as ammonia (NH_3), and worsening of the animals' hygiene and health conditions, as well as milk quality [13,18,34]. Excessive moisture conditions, as observed in some of the listed studies (Barberg et al. [30], Giambra et al. [31], Nogara et al. [33], Andrade et al. [4], and Oliveira et al. [27]—Table 3), can be caused by several factors, such as:

- Low bedding turning frequency, which reduces the exposure of the material to ambient air and, consequently, its drying rate [11,31];
- No supply or supply of insufficient ventilation rates that do not provide adequate drying rates [7,27];
- Longtime use of bedding material used which, due to the reduction in the water retention capacity, causes an increase in M_B [31];
- High density of housed animals which, due to the more significant load of feces and urine deposited per area, can cause an increase in M_B [4].

However, it is important to emphasize that the conditions of excessive M_B are usually registered in specific facility areas, such as near the feeding alley, evaporative cooling systems (when present) and/or in lots with smaller areas per animal, as reported by Oliveira et al. [28], Andrade et al. [4], and Oliveira et al. [27]. Knowing the M_B spatial distribution in CBP systems, as highlighted in these last three studies, makes it possible to identify areas with management failures and adapt and/or propose localized solutions to homogenize the physicochemical bedding quality.

Low M_B conditions (<40%) are also undesirable, as they cause dehydration of the decomposer microorganisms, reduction in their populations and, consequently, limiting of decomposition activity [13,14]. Of the listed studies, low M_B conditions in the aerobically active layer (depth) were observed only in those conducted by Barberg et al. [30], Oliveira et al. [28], Freu et al. [34], and Oliveira et al. [27]—Table 3. Notably, regions with low M_B were observed in places with direct solar radiation and external dry air masses, which caused excessive bedding drying [27,28].

Regarding the different periods of the year, M_B levels are typically higher in winter due to the cooling of the bedding material in the subsurface, which reduces the rate of water evaporation [11,14]. Therefore, keeping the moisture conditions inside CBP systems in the desired range is more challenging in this period [29,32]. In summer, moisture values tend to be lower, as observed in studies conducted by de Boer and Wiersma [32] and Andrade et al. [4] (Table 3), and this can be explained by the high external temperatures, which make it possible to increase the drying rate of the bedding material [12,31].

In order to reduce bedding moisture in winter, some management strategies can be adopted by producers, as highlighted by Black et al. [11] and Llonch et al. [29]:

- Carry out more bedding turning operations;
- Provide more bedding area per animal;
- Reduce the replenishment interval and/or increase the volume of dry bedding replenished;
- Increase the ventilation rate through mechanical ventilation systems.

The provision of adequate ventilation rates, in particular, is significant for M_B maintenance, as it is directly linked to the bedding drying rate, with the favoring of thermal exchanges and gas removal [11,45,46]. For this purpose, mechanical ventilation systems are normally used, such as fans and exhausters, which promote the movement of air masses along interesting regions [47,48]. In addition to ventilation, the bedding material is turned over daily, which, besides promoting homogenization and increasing the drying rate, aims to ensure the oxygen supply to the microorganisms present in the aerobically active layer [30,40,49]. In order to improve the oxygenation rates and direct bedding drying, ventilation systems buried under the bedding can be used, such as the one described by de Boer and Wiersma [32], which made it possible to maintain good aeration levels and, consequently, intense composting activity (>$t_{B\text{-}Dep.}$) and control over M_B—Table 3.

Bedding hydrogen ion potential (pH_B) was another widely used parameter for evaluating bedding quality in CBP systems, being present in 10 of the 12 listed works—Table 3. In these studies, pH_B analyses were performed using bedding samples collected at the surface ($pH_{B\text{-}Sur.}$; *n* = 4) and/or at depth ($pH_{B\text{-}Dep.}$; *n* = 9), and the occurrence of pH_B values ranging from acidic (5.5, de Boer and Wiersma [32]) to basic (11.0, Oliveira et al. [28]) was denoted.

The pH range considered ideal for most decomposing microorganisms is between 5.5 and 8.0 [20,50], which can be extended to 8.5, since most enzymes are active up to this limit [21]. The pH values in CBP systems are variable according to the stage of the semi-composting process: initially, it is predominantly acidic (5.0–6.0) due to the release of short-chain organic acids; throughout the process, these acids are consumed and the pH is raised to neutral or slightly alkaline (7.0–8.0); in the final stage, the organic acids have already been completely consumed, and the pH of the material is normally alkaline (8.0–9.0) [13,22,29,51,52]. In the listed studies, there was a higher prevalence of pH_B values > 7.0, and only in those conducted by Barberg et al. [30], de Boer and Wiersma [32], and Nogara et al. [33] were values below the limit were found—Table 3. The studies carried out by Barberg et al. [30] and Nogara et al. [33] described bedding characteristics in CBP systems located in Minnesota (USA) and Rio Grande do Sul (BR), respectively, and the occurrence of minimum values lower than 7.0 may be related to the short use time and/or with recent bedding replacement with dry materials in some of these systems. In the study conducted by de Boer and Wiersma [32], in which the composting process was comprehensively evaluated over time, the prevalence of pH values < 7.0 occurred only in the first 30 days of composting (from November to December 2013), resulting from the release of organic acids, common in the initial stage [51].

In most studies in which pH_B was evaluated, there was a higher prevalence of values > 8.0 (Shane et al. [19], Biasato et al. [5], Llonch et al. [29], Andrade et al. [4], and Oliveira et al. [27]—Table 3), which is an indication that the semi-composting process in these systems was already in the final stage [51,52]. Even in studies in which minimum pH values lower than 8.0 were obtained, such values were not very representative, as reported in the study conducted by Oliveira et al. [28], in which the pH of the bedding material was greater than 8.0 in 99.0% of the bedding area. According to the latter authors, pH values < 8.0 were determined only for samples from places where there was a high frequency of bedding replacement to reduce moisture, such as in the vicinity of evaporative cooling systems and/or drinking fountains. Notably, the occurrence of very high pH values (>9.0), as reported in some studies, can increase nitrogen losses (Barberg et al. [30], Nogara et al. [33], Oliveira et al. [28], Andrade et al. [4], Freu et al. [34], and Oliveira et al. [27]).

The assessment of bedding quality in CBP systems was also performed using its chemistry or nutritional composition—Table 3. In terms of the composting process, its importance refers mainly to the succession of decomposing microorganisms, which need certain levels of C and N to supply energy and to synthesize proteins, respectively [7,23]. In addition to the C and N contents, the assessment of the chemistry bedding quality usually includes the determination of other nutrients of agronomic interest, such as phosphorus (P) and potassium (K).

In CBP systems, C is supplied by adding organic material (sawdust and/or wood shavings, peanut, coffee husks, etc.). The amount of available C is consumed/reduced throughout the composting process, through the degradation of organic matter, in which organic C is converted into CO_2 [7,13]. In the evaluated studies, the C content was very variable, with minimum and maximum values reported by Biasato et al. [5] and Black et al. [11] (5.8 and 47.1%, respectively—

Table 3). Similar conditions of variation were obtained for the N content, which comes from the manure and urine of housed animals, and ranged from 0.3% [32] to 4.4% [5]—Table 3.

In terms of the composting process, the assessment of C and N contents is usually performed using the ratio between them (C:N). According to Misra et al. [53], the degradation of organic matter occurs more quickly when the C:N ratio is maintained between 25:1 and 30:1. For this reason, this first value is considered the lower desired C:N threshold for maintaining the active composting process [7,13]. In most studies, the determined C:N ratio was less than 25:1 in at least one facility and/or evaluation period (Barberg et al. [30],, Shane et al. [19], Black et al. [11], Biasato et al. [5], de Boer and Wiersma [32], Andrade et al. [4], and Freu et al. [34]—Table 3). This is an indication that, in these situations, the low C content may have been a limiting factor for the decomposition activity, as it did not provide enough energy.

The most challenging situation in terms of maintaining the composting process was observed in the study conducted by Biasato et al. [5], in which the C:N ratio ranged from 2.4 to 3.5. According to the authors, these values can be explained by the low frequency of bedding replacement on local, which occurred due to the low availability of bedding material. Such low C:N ratio values are a strong indication that the decomposing activity in this location was being inhibited, and that the bedding material should be changed [7,54]. In studies conducted by Barberg et al. [30], Black et al. [11], Shane et al. [19], Andrade et al. [4], and Freu et al. [34], even though higher C:N ratios than those reported by Biasato et al. [5] were found, it appears that it would be advisable to change the bedding material. In these systems, the 15:1 ratio is considered the minimum recommended threshold for maintaining the active composting process and not reducing N availability (when applied to the soil as an organic fertilizer) [54,55].

In the study conducted by Llonch et al. [29], in which the analyses were carried out after periods of eleven weeks from the beginning of the use of bedding materials, in fall and winter conditions, the prevalence of high C:N ratios (35:1 to 48:1) was observed for both materials used (sawdust and forest biomass). These results are an indication that there was an excess of C in the bedding [7], which was reflected in lower activity of decomposing microorganisms and, consequently, lower heat production (25.9 ± 3.1 to 34.7 ± 5.6). In cases like this, it may be necessary to add sources of N, such as animal manure (which has a C:N ratio between 15:1 and 19:1 [50,56]) in order to increase the N content up to levels such that the composting process is not compromised by low protein synthesis of decomposing microorganisms [29]. It should be noted that if bedding turning is not effective in spatially homogenizing the material, regions with different C:N ratios may occur and, consequently, distinct levels of decomposition activity.

Following what has already been reported for C and N, the P and K contents varied between studies. For these two nutrients, minimum (P = 0.04% and K = 0.15%) and maximum values (P = 0.90% and K = 3.00%) were described in studies conducted by de Boer and Wiersma [32] and Black et al. [11], respectively—Table 3. In the study by de Boer and Wiersma [32], the low levels of these nutrients were reported in the initial stage (first 30 days), but there was an increase at the end of the composting process (P = 0.19% and K = 1.56%). These results were expected, since during the composting process concentration of these nutrients occurs due to the organic matter reduction [29]. Results such as those reported by Black et al. [11], de Boer and Wiersma [32], and Llonch et al. [29] are indications that the material obtained at the end of the bedding composting process in CBP systems may have nutrient levels capable of meeting the agronomic needs of crops. However, it is important to evaluate the nutrient content of the soil and the requirement of the plant culture where this material will be applied to avoid over- or underapplication of nutrients [11].

3.3. Limitations, Gapsm, and Challenges for Future Research

The evaluation and/or characterization of bedding quality in CBP systems was explored in studies carried out in distinct locations (Brazil, Germany, the Netherlands, Italy, Spain, and the United States of America) and periods of the year, as well as considering different facility types, bedding materials, and management, and using different quality indicators. Therefore, some care in relation to the results extrapolation is necessary. As the selected articles used different parameters for evaluating and/or characterizing bedding quality in CBP systems, a meta-analysis was not performed. Consequently, it was not possible to assess the quality of the studies, which could influence the results achieved. Studies in which peer review was uncertain (annals of events and book chapters) and/or published in languages other than English were excluded, as it was not possible to critically assess the methods and results. However, it was not possible to determine to what extent these exclusions affected the results achieved.

Even though bedding management practices have been described (at least partially) in the selected studies, it is understood that future studies need to provide more detail on such routines, highlighting information such as types and characteristics of equipment used for bedding turning; number, times, and duration of turning operations; and frequency and volume of bedding replacements. Additionally, it is important that future studies specify information such as density, breed and size of housed animals, facility types and ventilation systems present, as well as climatic and topographic characteristics of the place where they were carried out. These and other factors can directly influence the efficiency of the composting process and therefore have the potential to be used as a background in the assessment of bedding quality in CBP systems [32].

Specifically regarding bedding turning, Black et al. [11] observed that increasing the turning depth also makes it possible to increase the temperature in the bedding subsurface due to greater aeration. Despite this, it is estimated that knowledge about the interrelationships between operations and depth of turning, environmental conditions, and bedding temperature in composting, is still limited. Therefore, conducting studies on this topic is, even today, of unique importance.

Many of the studies carried out on this subject had the objective of characterizing average conditions in CBP systems, in terms of thermal comfort and bedding quality, without worrying about the distribution variability of physicochemical variables of the bedding along the resting area. Admittedly, the use of spatialization tools makes it possible to identify regions with management failures and/or more affected by external conditions and, therefore, to propose ways of improvement (localized or not), to homogenize the thermal environmental conditions and physicochemical bedding properties. Therefore, carrying out new monitoring studies over time, using these tools and considering different practical conditions encountered at the field level (in terms of facility types, climatic and geographic conditions, ventilation systems, materials and bedding management practices, size, and breed of housed animals, among others) is also important for the advancement of knowledge in the area.

Due to the proposed objective, this review study did not correlate the welfare and health conditions of the animals housed in CBPs with physicochemical bedding quality. However, current knowledge on the subject indicates that bedding conditions in CBPs are directly associated with the welfare and health of housed animals. [5,12,46,57–63]. Therefore, it is important that new studies (experiments and reviews of the state of the art) be conducted to have a greater understanding of the potential synergies between the physicochemical bedding quality and the welfare and health of dairy cattle housed at CBPs.

Additionally, it is also necessary that future studies seek to analyze the potential correlations between bedding quality in CBPs and environmental quality. These studies are necessary because the physicochemical bedding quality in CBPs can also affect the natural environment, causing alterations in the soil, water, and air, especially when this system type is not well managed.

Finally, it is also important to mention that the projects for future CBP facilities must be designed seeking to favor the bedding composting process and the proper management of the manure and urine produced. At the same time, it is necessary to develop and validate new tools for evaluating the physicochemical bedding quality in this system type, since many of the methods and the equipment used in scientific studies are not familiar to producers, making it difficult, in turn, to apply at farm level.

4. Conclusions

Environmental conditions affect the physicochemical bedding quality in CBP systems used for housing dairy cattle. In this systematic review, it was highlighted that the composting activity is less intense during the winter and, consequently, the physicochemical bedding quality can be affected. However, to maintain the composting process at desired levels during this period, appropriate management practices can be employed, such as increasing the replacement frequency with dry material and bedding turning, use of systems aeration under the bedding and side closures in facilities, etc.

Carrying out this systematic review allowed us to summarize, analyze, and interpret the results on the interrelationships between thermal environmental conditions and physicochemical bedding quality in CBP systems. Even though the results reported do not fully describe how bedding quality in this system type can be affected by environmental conditions, the state of the art on the subject was presented, which can be used in future research. It is noteworthy that conducting new experimental studies on how the physicochemical bedding quality in CBP systems (with different facility types, environmental and geographic conditions, ventilation systems, materials, and bedding management practices, etc.), including its implications on the welfare and health of housed animals, is of great relevance for the knowledge advancement in this area.

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

Funding: This research was funded by the Coordination of Superior Level Staff Improvement, Brazil (CAPES)—Finance Code 001; the National Council for Scientific and Technological Development, Brazil (CNPq)—Process 422912/2018-2; and the Minas Gerais Research Support Foundation, Brazil (FAPEMIG)—Finance Code 001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The authors would like to thank the Federal University of Viçosa (UFV) and University of Firenze (UniFI), whose support is appreciated. This work was conducted with the support of the National Council for Scientific and Technological Development, Brazil (CNPq); Coordination of Superior Level Staff Improvement, Brazil (CAPES); and Research Supporting Foundation of Minas Gerais State, Brazil (FAPEMIG).

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

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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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Citation: 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**, *13*, 9331. https://doi.org/10.3390/app13169331

Academic Editor: Francesca Scargiali

Received: 11 July 2023
Revised: 2 August 2023
Accepted: 8 August 2023
Published: 17 August 2023

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

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)).

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

- 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)).

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

- 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)).

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

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):

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

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].

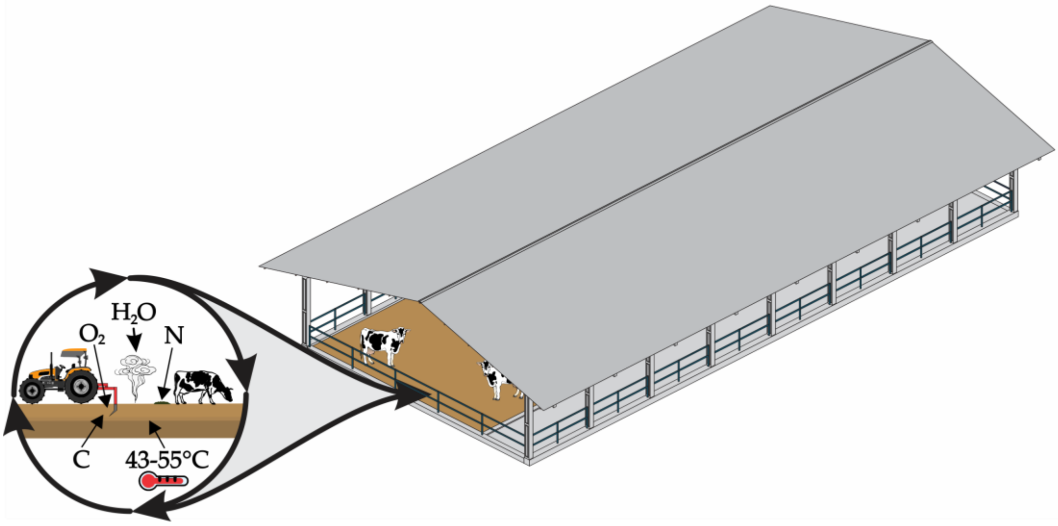

Figure 1. Schematic representation of a Compost-Bedded Pack Barn system (emphasis on the bedding). C—carbon; H_2O—water; N—nitrogen; and O_2—oxygen. Source: Adapted from Damasceno [66].

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].

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).

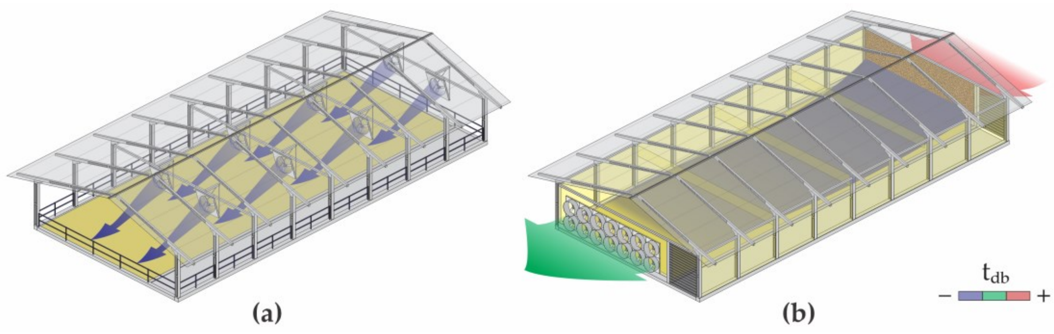

Figure 2. Representation of open Compost-Bedded Pack Barns systems with positive pressure mechanical ventilation (**a**) and closed with negative pressure mechanical ventilation and evaporative cooling (**b**). t_{db}—dry air bulb temperature. Source: The authors.

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 ≥ 5 × H (H = highest height of the facility within the computational domain), as well as the distance to the ends ≥ 10 × 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.

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].

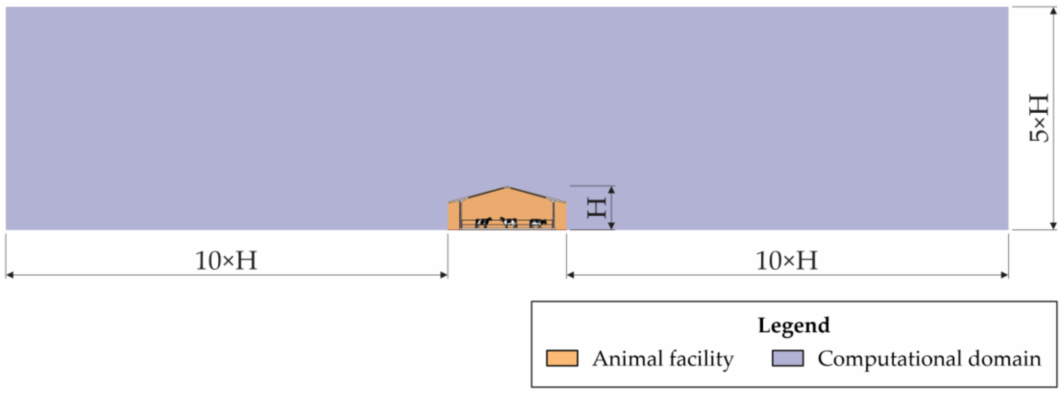

Figure 3. Schematic representation of the computational model needed in facilities with open sides (internal and external environments of the facility represented in a single computational domain). H—highest facility height within the computational domain. Source: Adapted from Lv et al. [22].

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 ≤ 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].

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].

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

N°	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]

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).

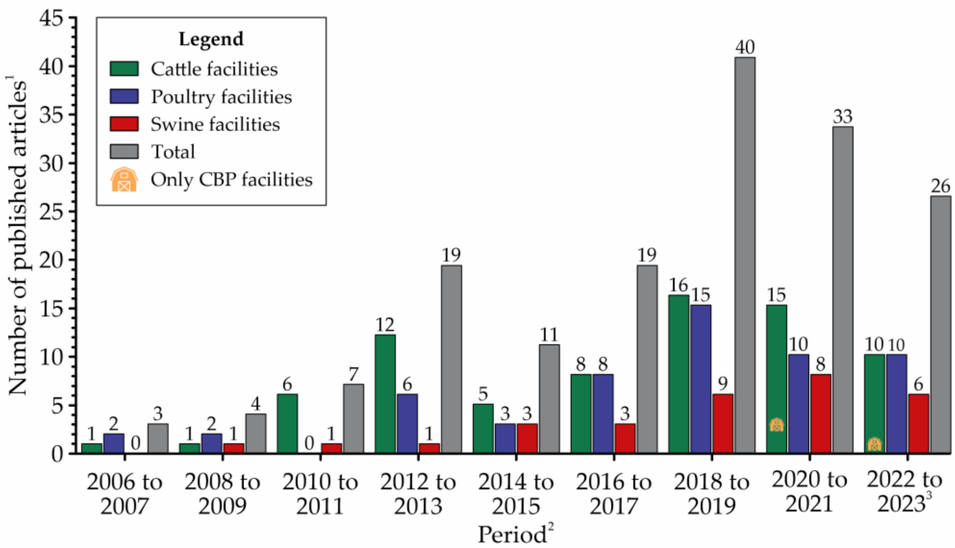

Figure 4. Number of peer-reviewed experimental articles published since 2006 on CFD applied to cattle, poultry, and swine facilities. [1] Only peer-reviewed experimental articles in English were considered (further details in Appendix A); [2] Assessment carried out from 2006 to 2023, coinciding with 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.

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.

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.

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.

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

Funding: This research was funded by the Coordination of Superior Level Staff Improvement, Brazil (CAPES)—Finance Code 001; the National Council for Scientific and Technological Development, Brazil (CNPq)—Process 422912/2018-2; and the Minas Gerais Research Support Foundation, Brazil (FAPEMIG)—Finance Code 001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The authors would like to thank the Federal University of Viçosa (UFV), Federal University of Lavras (UFLA), Federal University of Goiás (UFG), and University of Firenze (UniFI); their support is appreciated. This work was conducted with the support of the National Council for Scientific and Technological Development, Brazil (CNPq), Coordination of Superior Level Staff Improvement, Brazil (CAPES), and Research Supporting Foundation of Minas Gerais State, Brazil (FAPEMIG).

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

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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Temporal and spatial behavior of thermal microenvironment variables in a Compost-Bedded Pack Barn system with positive-pressure ventilation during winter and summer in Brazil

Abstract: In recent decades, the use of the Compost-Bedded Pack Barn (CBP) system for housing dairy cattle has grown significantly worldwide, including Brazil. This system typically features open-sided structures, which present various environmental challenges to the housed animals throughout both the day and year. Therefore, to thoroughly understand the environmental challenges faced by animals in these facilities, further studies on monitoring and characterizing the thermal environment are still required. In this context, aiming to elucidate aspects of the environment in an open CBP system with positive-pressure ventilation, this study was conducted to characterize the temporal and spatial behavior of dry-bulb air temperature (t_{db}, in °C), relative humidity (RH, in %), and Temperature-Humidity Index (THI), during winter and summer in a subtropical mesothermal climate region in Brazil. The CBP system under study is located on a commercial property in Zona da Mata, Minas Gerais, Brazil. For thermal protection, this system features positive-pressure mechanical ventilation (operating 24 hours per day) and a water sprinkler line over the animals, situated in the feeding alley (activated when $t_{db} \geq 24.00$ °C). For 15 days during each experimental period (winter and summer), t_{db} and RH values were continuously monitored at 55 points distributed throughout the animals' occupied zone. The monitoring was carried out using a low-cost embedded system for thermal data acquisition, which was used to map environmental conditions in different scenarios: by period (dawn, morning, afternoon, and night); and under extreme conditions (absolute minimum, and maximum values). Through temporal behavior analyses, it was found that during the winter, the average thermal conditions remained within the indicative range of thermal comfort for lactating Holstein dairy cows (5.00 °C < $t_{db} \leq 24.00$ °C; and THI ≤ 74.00). In summer, the average values of t_{db} and THI exceeded 24.00 °C and 74.00, respectively, between 9:10 a.m. and 6:30 p.m., a period characterized as heat stress for the housed animals. However, during this interval, average RH values ≤ 80.00 % were recorded, indicating potential for more efficient use of evaporative cooling systems. Using geostatistical techniques, maps of the distribution of thermal variables were generated. It was found that there was no uniformity in the distribution of t_{db}, RH, and THI across the CBP system area. Spatial variability was greater during the morning and afternoon periods and at times with absolute minimum and maximum values. The highest values of t_{db} and THI were observed in the Northwest Region of the CBP system, which received direct solar radiation in the afternoon. Based on the observed results, it

was found that the thermal protection methods used in the CBP system under study were insufficient to ensure uniform and thermally comfortable conditions for the housed animals, especially during hot summer afternoons. Consequently, it can be inferred that these systems were either inadequately sized or not properly managed. It is necessary to resize these thermal protection systems and/or employ alternative methods during the hottest periods of both, the day and year.

Keywords: Animal thermal comfort. Dairy cows. Housing systems. Modelling. Monitoring.

1. Introduction

In dairy systems where production cows are kept on pasture, there are recognized difficulties in meeting the animals' ambiance needs, particularly during periods of extreme thermal conditions, such as those observed in summer (Charlton & Rutter, 2017; Pons et al., 2023). The fact is that changes in environmental conditions can directly affect animal physiology and trigger thermal stress (Collier et al., 2019; Nordlund et al., 2019; Chopra et al., 2024). Heat stress occurs more severely when animals are exposed to high dry-bulb air temperature (t_{db}) for extended periods, accompanied by also high relative humidity (RH). These are the two environmental variables with the greatest impact on thermal comfort (Cheng et al., 2024). Exposure of dairy cows to thermal stress conditions can result in reduced food intake (Baumgard & Rhoads, 2013; Collier et al., 2019) and milk production (Gunn et al., 2019; Tao et al., 2020), impair fertility (Schüller et al., 2016; Sammad et al., 2020), and increase the incidence of diseases such as mastitis and lameness (Dahl & McFadden, 2022).

Modern dairy farming has become increasingly intensive to minimize the impact of climatic fluctuations on milk productivity and consistency throughout the year, and to meet the growing and ongoing demand for dairy products (Saitone & Sexton, 2017; Bleizgys et al., 2022). Various confinement systems are used in intensive dairy production, with the Free Stall (FS) system being predominant (Mõtus et al., 2024). In this system, animals remain loose in facilities that include collective areas for movement, exercise, and feeding, and individual areas for resting (stalls with bedding made from materials such as rubber mats, sawdust, sand, or shredded rubber) (Bewley et al., 2017; Beaver et al., 2021; Mõtus et al., 2024). However, in recent decades, the use of the Compost-Bedded Pack Barn (CBP) system has grown significantly worldwide, including in Brazil (Blanco-Penedo et al., 2020; Galama et al., 2020; Leso et al., 2020; Guesine et al., 2023; Andrade et al., 2024).

The CBP system is a model for housing dairy cattle in facilities with a collective bedding area composed of vegetable material (Leso et al., 2020; Llonch et al., 2020; Freu et al., 2023; Pons et al., 2023). In this system, the vegetable material used for bedding, combined with the waste deposited by the animals in the collective resting area, is decomposed over time through composting processes. This is the main difference from other cattle confinement models that use bedding (Biasato et al., 2019; Damasceno, 2020; Andrade et al., 2024). According to numerous studies, the main advantages reported with the use of CBP systems on dairy farms include improvements in productivity, health, and longevity of lactating dairy cows, reductions in milk production costs, and better management of the waste generated by the animals (Bewley et al., 2017; Silva et al., 2019; Blanco-Penedo et al., 2020; Leso et al., 2020; Emanuelson et al., 2022).

Dairy cattle are typically housed in CBP systems within facilities presenting open sides. These facilities use active devices, such as fans or misters (the latter only in the feeding alley and activated only during the hottest periods of the day), to reduce the effects of thermal stress on the animals, renew the air, and maintain the composting process of the bedding (Mondaca & Cook, 2019; Leso et al., 2020; De Masi et al., 2021; Oliveira et al., 2023). As these facilities have open sides, these systems are more exposed to external environmental fluctuations that occur throughout the day and year, due to each location's specific climatic and geographic conditions (Damasceno, 2020; De Masi et al., 2021; Pons et al., 2023). In addition to impacting animal thermal comfort, these climatic fluctuations can alter the dynamics of the bedding composting process and, as a result, affect the physical and chemical quality of the compost produced (Biasato et al., 2019; Leso et al., 2020; Llonch et al., 2020; De Boer & Wiersma, 2021; Giambra et al., 2021). Therefore, in addition to being important for managing animal thermal comfort, monitoring the thermal environment in such systems is crucial for ensuring proper management of the composting bedding (Andrade et al., 2022; Oliveira et al., 2022).

Although it is widely recognized that monitoring and, consequently, controlling the thermal environment in CBP systems are essential for ensuring productive efficiency, this is not the reality for many dairy farms in Brazil. Actually, it often lacks environmental control, or imprecise methods are used for monitoring the thermal environment, such as manual measurements and subjective observations. These practices are considered time-consuming, labor-intensive, and prone to human error (Arshad et al., 2022; Lee et al., 2024). Thus, to address the imposed environmental challenges, it is necessary to adequately monitor and characterize the thermal environment in the facilities over time, across the entire animals' occupied zone (AOZ), and under extreme climatic conditions, such as in winter and summer

(Freitas et al., 2019; Arulmozhi et al., 2021; Leliveld et al., 2024). The results achieved in environmental characterization studies of CBP systems under different climatic conditions are recognized as an important tool, as they can assist designers, technicians, and producers in managing and, consequently, ensuring the overall efficiency of the system (Andrade et al., 2022; Oliveira et al., 2022; Guesine et al., 2023). It is understood that, by gaining a detailed understanding of the environmental challenges posed under extreme climatic conditions, as well as the distribution of t_{db} and RH values in different regions of the AOZ, it becomes possible to employ tailored and specific solutions for different times of the day and/or seasons of the year. Therefore, it can be inferred that it is possible to improve the management of the thermal environment in the facilities, reduce energy consumption, and consequently turning the production more sustainable.

Continuous monitoring of the thermal environment in animal facilities, including CBP systems, should be conducted using appropriate and specific data acquisition sensor networks for this purpose (Brito et al., 2020; Loukatos & Arvanitis, 2021; Li et al., 2024). However, few companies are specialized in the implementation of environmental monitoring systems for this type of facility, and when they do, the systems are often expensive and difficult to operate (Djajadi & Wijanarko, 2016). Thus, there is an urgent demand for the development and use of modern data acquisition systems based on Smart Livestock Farming. These systems should utilize low-cost sensors, actuators, and microprocessors and, when possible, integrate the Internet of Things and Big Data analysis (Arulmozhi et al., 2021; Kaur et al., 2023). It is important to highlight that the data obtained through environmental monitoring should be analyzed using appropriate and current methods to characterize the recorded thermal conditions. Techniques such as exploratory analysis and geostatistics, which are widely used in the field of animal ambiance, are particularly relevant (Ferraz et al., 2019; Oliveira et al., 2021; Peixoto et al., 2021; Vieira et al., 2021; Andrade et al., 2022; Guesine et al., 2023; Silva et al., 2023).

Given the above and seeking to elucidate aspects of the environment in CBP systems from a thermal perspective, this study was designed to characterize the temporal and spatial behavior of thermal environment variables in a CBP system with open sides and positive-pressure mechanical ventilation, during winter and summer, in a region with a mesothermal subtropical climate in Brazil. The study also aimed to present the results achieved as a starting point for adjusting existing facilities and/or designing new CBP systems, indicating that considerations should always be made based on the specific climatic and geographical conditions of each location. By addressing multifaceted aspects of intensive dairy production, including housing systems and thermal environment improvement solutions, the study aimed to contribute to the ongoing and important discourse on sustainability in modern livestock farming. This is particularly relevant in balancing productivity, animal welfare, and energy consumption for environmental conditioning.

2. Material and Methods

2.1. Characterization of the Compost-Bedded Pack Barn system under study and the management of thermal-environmental conditioning systems

This study was conducted under extreme climatic conditions (winter and summer) in a typical Brazilian CBP system with open sides, positive-pressure mechanical ventilation, and water sprinkling in the feeding alley (activated only during the hottest times of the day). The CBP system under study was used for housing lactating dairy cows and was located on a commercial farm in the Zona da Mata region, Minas Gerais, Brazil (latitude 20°46′41″ S; longitude 42°48′51″ W; altitude 670 m). The local climate is classified as Cwa (mesothermal subtropical, with cold winters, and hot and rainy summers), according to the Köppen-Geiger's classification (Monteiro & Martins, 2019).

The CBP system had its longitudinal axis oriented in the Southeast-Northwest direction and featured the following construction characteristics: dimensions of 60.00 m in length, 27.60 m in width, and a right-foot of 5.00 m (Figures 1a and 1b). The roof was a gabled design with a metal structure and a covering, an open ridge with a 1.00 m overhang on the Southwest side, and lateral eaves extending 2.20 m (Figure 1b). The floors in the service, drive-through, and feeding aisles were paved with textured concrete to prevent slips and had a longitudinal slope of 1.00 % to facilitate waste drainage. To separate the bedding area from the feeding and service passages, there were 0.20 m small walls designed to prevent the transfer of bedding material and/or waste from one area to another. At the boundary between the bedding area and the feeding alley, there were also masonry walls 1.20 m high, positioned around the location of the troughs. The purpose was to prevent animals from accessing water directly from the bedding area.

The ventilation at the site was of the positive-pressure mechanical type, provided by six low-volume and high-rotation fans installed in pairs at heights of 0.00 m, 12.00 m, and 36.00 m, from Southeast to Northwest (Figure 1a). These units were installed 3.00 m above the bedding level (Figure 1b), at a 45° angle to the vertical, operated continuously 24 hours per day, and ensured that the dominant airflow direction (AFD) was longitudinal through the building (from Southeast to Northwest).

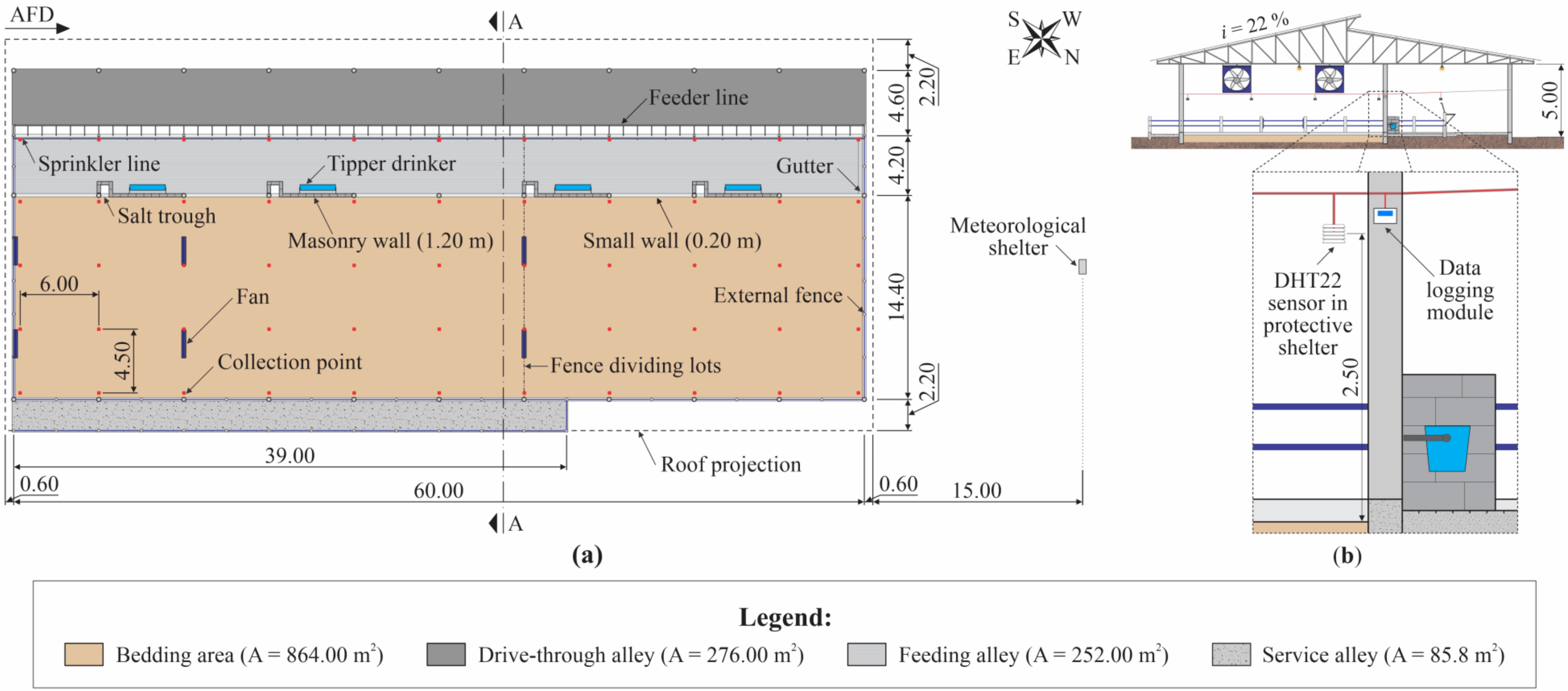

Figure 1. Schematic representations of the Compost-Bedded Pack Barn system with open sides and positive-pressure ventilation, showing **(a)** a floor plan with the arrangement of data collection points, and **(b)** cross-section AA, highlighting the positioning of the embedded system for thermal environment monitoring. A—area; AFD—airflow direction; N—north indication; *i*—roof pitch; dimensions in meters (m).

To promote the animals' body cooling, in addition to the mechanical ventilation, the CBP system was equipped with a 32 mm diameter water sprinkler line, positioned along the feeding line (Figure 1a). The sprinkler line was installed 2.10 m above the feeding alley floor and was equipped with 29 low-pressure nozzles (flow rate of 2.00 L·minute^{-1}, 130° spray angle), spaced 2.00 m apart and angled at 45° relative to the vertical. The management of the water sprinkler system followed the practice already established on the commercial farm: it was activated for one minute at regular five-minute intervals whenever the t_{db} exceeded 24.00 °C (setpoint).

For night-time illumination, the CBP system was equipped with eighteen 100 W LED lights, positioned 4.80 m above the bedding surface. The lights were evenly distributed throughout the facility (nine in the middle area of the bedding and nine at the boundary between the drive-through and the feeding alleys) and were switched on from 6:00 p.m. to 6:00 a.m.

The bedding material used in the CBP system consisted of a mixture of wood shavings and sawdust, with a depth of approximately 0.60 m. At the start of the study (July), the bedding material had been replaced approximately four months prior. At that time, a layer of dry sawdust about 0.30 meters thick was added, which, in combination with the animals' waste, initiated the composting process. Dry bedding material was added whenever a significant increase in bedding moisture was observed (practically determined by increased soiling of the animals, excessive compaction, or anaerobic conditions in the compost). The frequency of addition varied according to the time of year. Also, during the winter experimental phase, conducted from July to August, only two replenishments with dry bedding material were carried out, whereas in the summer phase, from February to March, a single replenishment with wood shavings was made. The bedding in the CBP system was turned twice daily (at 9:00 a.m. and 4:00 p.m.) using a hybrid implement (a rototiller with a cultivator).

All procedures involving animals were approved by the Animal Ethics Committee of the Universidade Federal de Viçosa (CEUA/UFV; process nº 04/2021, approved on 16 May 2022; see Annex A). During the study, Holstein dairy cows in lactation (Purebred, average weight 600 kg) were housed in the CBP system. For each experimental period, details on the number of animals housed, the bedding area available per animal, and daily milk production per animal are listed in Table 1 (milk productivity data extracted from the farm's milk control records).

Table 1. Information on the number of cows housed, bedding area available per animal, and daily milk production per animal in the Compost-Bedded Pack Barn system under study, during the experimental winter and summer periods.

Information	Experimental period	
	Winter	Summer
Number of animals housed (cows)	80.00	83.00
Available bedding area per animal (m^2)	10.80	10.68
Daily milk production per animal ($kg \cdot day^{-1}$)	32.80 ± 13.35	31.12 ± 12.38

The standard daily management routine for the cows housed in the CBP system was maintained, with dry matter being provided. The milking was carried out twice a day at 4:00 a.m. and 4:00 p.m., each lasting approximately 2 hours and 30 minutes. Milking operations were conducted in a 2×6 fishbone-type parlor machine, located in a facility adjacent to the CBP system under study. Water was provided ad libitum through four drinkers positioned in the feeding alley. This alley was cleaned once daily, in the morning, using a water discharge system in conjunction with manual scraping. The wastewater generated from cleaning the feeding alley was not reused.

2.2. *Data acquisition and evaluation of the thermal environment in the Compost-Bedded Pack Barn system under study*

At the beginning of the study, an embedded system was developed and calibrated using low-cost and readily available electronic components. This phase was conducted at the Research Centre on Ambience and Engineering of Agro-industrial Systems, Department of Agricultural Engineering, Universidade Federal de Viçosa (AMBIAGRO/DEA/UFV). The components used to assemble the embedded system were:

- **Arduino Uno R3**—A board based on the ATmega328 microcontroller, featuring 14 digital input/output pins (6 of which can be used as PWM outputs), 6 analog input channels, a 16 MHz crystal oscillator, 1 USB connection, 1 power jack, 1 ICSP connection, and 1 reset button. The operating voltage is 5.00 V (Atmel Corporation, San Jose, USA);
- **CCE 50 × 2 pairs cable**—Electrolytic tin-plated copper conductor with soft temper, 0.50 mm gauge, longitudinal APL tape, and low-density polyethylene insulation (GP Cabos, São Paulo, Brazil);

- **DHT22**—AM2302 model sensor with a temperature measurement range of –40.00 to 80.00 °C and an accuracy of 0.50 °C, and a humidity measurement range of 0 to 100 % with an accuracy of 2 % (Aosong Electronics Co. Ltd, Guangzhou, China);
- **Data Logger Shield with RTC and SD Reader**—Component featuring an SD card slot, integrated real-time clock DS1307, FAT16 or FAT32 card formatting, and a power supply voltage of 3.30 V (Dallas Semiconductor, Dallas, USA);
- **16×2 LCD Display**—I2C Blue Backlight screen with 4 or 8-bit communication and a voltage of 5.00 V (Beijing Qingyun Innovation and Technology Development Co. Ltd., Shenzhen, China).

As it was desirable for the embedded system to be modular and adaptable for monitoring thermal environments in animal housing with different characteristics, the development was carried out in the form of collection modules. Each collection module consisted of a data logging and display unit, which integrated an Arduino Uno R3, a Data Logger Shield with RTC and SD Reader, and a 16×2 LCD Display; and five DHT22 sensors, connected to the data logging and display unit by CCE 50×2 pairs of cables. As well, a functional diagram of each collection module of the embedded system is illustrated in Figure 2a.

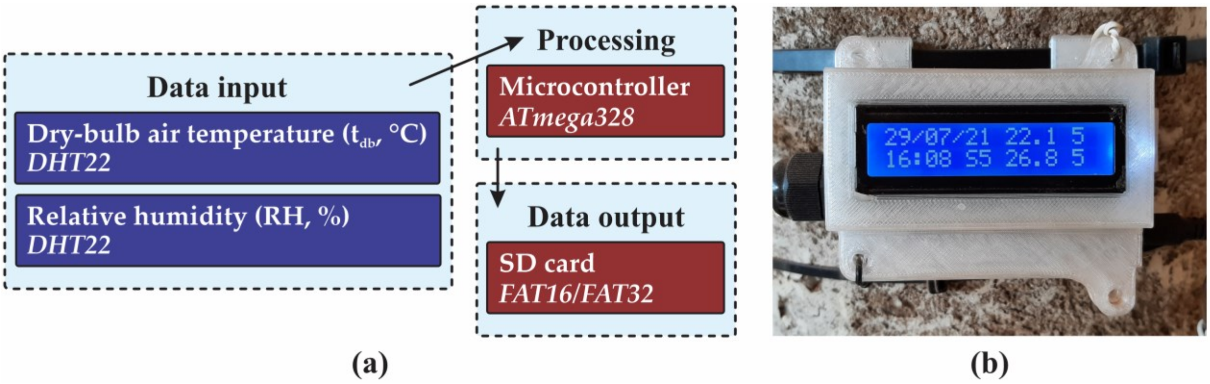

Figure 2. **(a)** Schematic diagram of the operation of the embedded system and **(b)** capture of the data logging module during monitoring of dry-bulb air temperature (t_{db}, in °C) and relative humidity (RH, in %) inside the open Compost-Bedded Pack Barn system under study.

The programming logic was developed in C++ and using the Arduino Integrated Development Environment (IDE), an open-source software development platform. The C++ programming language was chosen for developing the logic due to its status as a universal and high-level language, its support by the microcontroller used for prototyping, and its compatibility with libraries that facilitated the handling of the hardware employed (Montironi et al., 2017; Chang et al., 2020).

For calibration, the system's collection modules and a commercial data logger sensor (HOBO®, model UX100-003; temperature range from –20.00 to 70.00 °C with an accuracy of 0.21 °C, and relative humidity range from 0 to 100 % with an accuracy of 3.50 %), which was used as the standard reference instrument for measuring temperature and humidity, were compared (Freitas et al., 2019), were installed in weather shelters. For 24 hours, values of t_{db} (in °C) and RH (in %) were recorded at regular intervals of 5 minutes. During this period, recorded values of t_{db} and RH were consistently numeric and accurate. Consequently, it was determined that the quality of the data obtained through monitoring with the embedded system in the CBP would not be compromised by NaN (Not a Number) reading errors, an issue that could arise with the use of low-cost sensors, potentially affecting the quality of the data and the overall environmental monitoring (Pramono et al., 2022).

The t_{db} and RH data obtained from the embedded system's sensor modules during validation were close to those recorded by the reference data logger. For greater reliability of the t_{db} and RH data obtained through monitoring, it was understood that calibration curves were necessary for each module, as the DHT22 is a capacitive sensor. To correlate the t_{db} and RH values recorded by each DHT22 sensor module in the embedded system with those recorded by the reference equipment, calibration equations were obtained using linear regression:

$$Y_i = \beta_1 \cdot X_i + \beta_0 \tag{1}$$

where: Y_i—adjusted t_{db} or RH value; β_1—slope coefficient; X_i—t_{db} or RH value recorded by the DHT22 sensor module; e β_0—intercept coefficient.

After calibration, the embedded system was used to monitor t_{db} and RH within the CBP system under study (Figure 2b). Data acquisition of the thermal environment was carried out every 5 minutes, 24 hours per day, for 15 consecutive days during winter (19 July to 2 August) and summer (28 February to 14 March) in the Southern Hemisphere. The choice of these periods for conducting the study was based on the fact that they typically represent times with extreme conditions for managing the thermal environment and bedding in CBP systems. In the study area, high values of t_{db} are typically recorded, and precipitation occurs during the summer, conditions that can compromise the thermal comfort of lactating Holstein cows and increase the moisture content of the bedding material undergoing composting. In winter, low t_{db} values are typically recorded, which are desirable for the thermal comfort of the animals but not ideal for bedding management. This is because bacterial activity decreases, leading to increased bedding moisture, which results in greater soiling of the animals and a decline in milk quality.

Data collection was carried out using a grid composed of 55 equidistant points distributed across the AOZ, which includes the bedding areas and the feeding alley. The collection points were determined based on the structural characteristics of the CBP system under study, creating a rectangular grid (6.00 × 4.50 m) with 44 points located in the bedding area, and 11 points in the feeding alley (see Figure 1a). At each point in the grid, a DHT22 sensor module was installed, positioned 2.50 m above the bedding and the floor of the feeding alley, to allow for the passage of the tractor used for the daily turning of the bedding. According to the manufacturer, the DHT22 sensors do not have a specified ingress protection (IP) rating. Therefore, to protect the sensors from moisture, dust, and corrosive particles, each sensor module was housed in a protective shelter that did not affect the readings of t_{db} and RH.

Near the CBP system under study, a meteorological shelter was installed (see Figure 1a), where data on t_{db} and RH were collected to characterize the external thermal conditions. In the meteorological shelter, data collection was conducted using a commercial data logger (HOBO®, model UX100-003; temperature range of –20.00 to 70.00 °C with an accuracy of 0.21 °C; relative humidity range of 0 to 100 % with an accuracy of 3.50 %; Onset Computer Corporation, Bourne, Massachusetts, USA). Just as in the CBP system under study, external environmental data were collected every 5 minutes, 24 hours per day, for 15 consecutive days during both winter and summer.

The data on t_{db} and RH recorded during both experimental periods (winter and summer) were used to calculate the THI, which represents the combined effect of these two climatic elements on the thermal comfort of the animals (Ji et al., 2020; Yan et al., 2020). The THI calculation was performed using Equation 2, initially presented by Yousef (1985) and later described by Hahn (1995), Hahn (1999) and Mader et al. (2006):

$$\mathrm{THI} = 0.81 \cdot \mathrm{t_{db}} + (\mathrm{t_{db}} - 14.40) \cdot \left(\frac{\mathrm{RH}}{100}\right) + 46.40 \tag{2}$$

The classification of THI ranges specific to lactating Holstein cows was carried out as described by Hahn (1999), considering the following conditions: THI ≤ 74.00—normal; 75.00 ≤ THI ≤ 78.00—alert; 79.00 ≤ THI ≤ 83.00—danger; THI ≥ 84.00—emergency.

2.3. Statistical, geostatistical analyses, and mapping of the thermal environment in the Compost-Bedded Pack Barn system under study

The data sets recorded during the experimental periods of winter and summer were tabulated using Microsoft Excel®, version 2406. Initially, the data sets continuously recorded during each experimental period (winter and summer) were verified and analyzed. Subsequently, the t_{db} and RH values were adjusted using the calibration equations (Appendix A), and the absolute minimum, average, and absolute maximum values (obtained every 5 minutes) were calculated. Curves with the absolute minimum and maximum values of these variables were plotted to temporally evaluate the behavior of t_{db} and RH over the 15 days of data collection for each experimental period (winter and summer). In addition, average values with standard deviations for t_{db}, RH, and THI were calculated and used to plot daily behavior curves for these variables both inside and outside the CBP system under study.

As the research also aimed to evaluate the spatial behavior of the variables in the AOZ within the CBP system, the daily average data for t_{db}, RH, and THI were divided into four periods: dawn (00:00 a.m. to 05:59 a.m.), morning (06:00 a.m. to 11:59 a.m.), afternoon (12:00 a.m. to 05:59 p.m.), and night (06:00 p.m. to 11:59 p.m.). Since the temporal separation described above only allowed for the verification of the average spatial distribution of the data of interest in these four periods of the day, and there was also an interest in obtaining the spatial distributions under the extreme conditions recorded, the times at which the absolute minimum and maximum values of t_{db}, RH, and THI occurred were identified. The datasets concerning these times were used to visualize the spatial behavior of the mentioned variables under the most extreme conditions recorded, in winter and summer.

For all the datasets (mean values, by period; and point values, for times with extreme t_{db} and RH), minimum ($\wedge$), mean ($\overline{x}$), maximum ($\vee$), standard deviation (s), and coefficient of variation (CV) values were calculated using descriptive statistics. The CV was used to assess the dispersion of the data, following the classification suggested by Gomes (2000): CV < 0.10—low dispersion; $0.10 \leq$ CV < 0.20—moderate dispersion; $0.20 \leq$ CV < 0.30—high dispersion; and CV ≥ 0.30—very high dispersion.

The geostatistical technique was used to assess the spatial dependence and distribution of the variables of interest within the CBP system under study. The analyses were conducted using the statistical computing system R, version 4.4.0. Using the GeoR package (Ribeiro Júnior & Diggle, 2001), experimental variograms were fitted to analyze the spatial dependence of the variables. The variograms were obtained using the classical estimator, as shown in Equation 3:

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

where: $\hat{\gamma}(h)$—estimated semivariance; $N(h)$—number of experimental pairs $Z(X_i)$ and $Z(X_i + h)$; $Z(X_i)$—value at a sampled point; e $Z(X_i + h)$—value at a point displaced by a distance h.

To achieve adjustments with adequate representation of field conditions, different methods were used: Ordinary Least Squares (OLS); Weighted Least Squares (WLS); Maximum Likelihood (ML); and Restricted Maximum Likelihood (REML). Each of these four methods was combined with the traditional Spherical, Exponential, and Gaussian models, whose functions are conditionally positive, ensuring that the calculated variances are also positive (McBratney & Webster, 1986; Vieira et al., 2010).

To assess the quality of the adjustments obtained by combining the four methods with the three mentioned models, cross-validation procedures were employed, which are widely used in geostatistics (Ferraz et al., 2019; Ferreira et al., 2021; Silva et al., 2021). Through cross-validation, the mean error (ME), mean-error standard deviation (SD_{ME}), standardized-error (SEr), and standardized-error standard deviation (SD_{SEr}) were calculated. The criteria for choosing the fit were: ME and SEr as close to zero as possible; SD_{ME} as small as possible; and SD_{SEr} as close to one as possible (Vieira, 2000; Ferraz et al., 2014).

From the mathematical models $\hat{\gamma}(h)$ with the best quality, selected based on the indicators ME, SD_{ME}, SEr, and SD_{SEr} during cross-validation, the theoretical model coefficients for the variogram were extracted, namely: nugget effect (C_0), contribution (C_1), sill ($C_0 + C_1$), range (*a*), and practical range (*a'*). Spatial dependence analyses for each variable were conducted using the Spatial Dependence Index (SDI), calculated as the ratio between the nugget effect and the sill [$C_0/(C_0 + C_1)$], and assessed using the classification by Cambardella et al. (1994): SDI $\leq$ 0.25—strong spatial dependence; 0.25 $<$ SDI $\leq$ 0.75—moderate spatial dependence; and SDI $>$ 0.75—weak spatial dependence.

To obtain values of the variables of interest at locations not sampled within the CBP system under study, ordinary kriging was applied, enabling the visualization of the spatial distribution patterns of the variables of interest (Xu et al., 2018; Oliveira et al., 2024). Using the data obtained through interpolation, spatial distribution maps were generated with the software ArcGIS®, version 10.4, by the Spatial Analyst and Geostatistical Analyst extensions.

3. Results and Discussion

3.1. Adjustments and overview of the collected data

Figure 3 illustrates the calibration curves obtained for t_{db} (in °C) and RH (in %), recorded by sensor DHT22 nº 1, which was part of the embedded system for monitoring the thermal environment, compared to the standard reference sensor (HOBO®, model UX100-003). As can be seen from the analysis of the mentioned figure, there was good agreement between the values of t_{db} and RH recorded by the low-cost sensor, with determination coefficients (R^2) of 0.9746 and 0.9685, respectively.

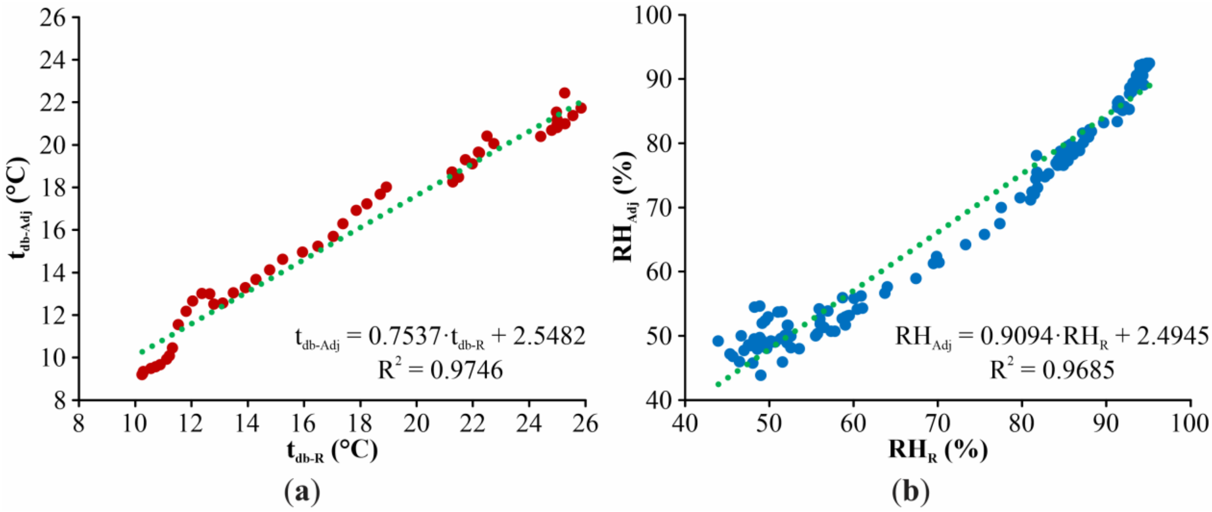

Figure 3. Calibration curves of **(a)** dry-bulb air temperature (t_{db}, in °C) and **(b)** relative humidity (RH, in %), for the DHT22 sensor nº 1, which was part of the embedded system for monitoring the thermal environment, compared to the standard recording sensor. $t_{db\text{-}Adj}$—dry-bulb air temperature adjusted value; $t_{db\text{-}R}$—dry-bulb air temperature value read by the DHT22 sensor; RH_{Adj}—relative humidity adjusted value; RH_R—relative humidity value read by the DHT22 sensor; R^2—coefficient of determination.

For the other sensors in the embedded system, the calibration equations and R^2 values for the adjustments are listed in Table A1. For the t_{db}, excellent agreement was observed between the values recorded by the embedded system's sensor modules and the standard reference sensor, with R^2 values ranging from 0.9722 to 0.9891. Through the calibration curves for RH, good agreement was observed between the recorded and reference values, with R^2 values ranging from 0.9240 to 0.9917, which are considered satisfactory. These results were considered a sign that the sensors in the embedded system could be used for environmental monitoring in the CBP system under study, provided that the measured values were adjusted using the calibration equations. By using this embedded system for acquiring thermal environment data, it was possible to obtain reliable data from multiple points within areas of interest, as the sensor modules employed were less expensive than commercial data loggers.

During the winter and summer periods, continuous data on t_{db} (in °C) and RH (in %) were collected both inside the CBP system under study and at the meteorological shelter installed outside. This resulted in 4,319 pairs of t_{db} and RH data for each experimental point and the shelter, totaling 241,864 pairs for each experimental period. These datasets were adjusted and used in temporal and spatial analyses of the variables and thermal environment index.

3.2. Temporal analyses of variables and thermal-environmental index in the Compost-Bedded Pack Barn system

Figure 4 illustrates curves showing the absolute minimum and maximum values of t_{db} (in °C) and RH (in %), both inside the CBP system under study and for these climatic elements in the external environment, during both experimental periods (winter and summer). During winter and summer, similar behaviors of t_{db} were observed in both the internal and external environments of the CBP system under study (Figure 4a). Since this is a CBP system with open sides, this was expected, as there is a high correlation between the internal and external t_{db} conditions (Endres et al., 2011).

Although the curves showing the behavior of internal and external t_{db} values over the winter and summer experimental periods were close to each other, it was observed that the absolute maximum values of t_{db} inside the CBP system were consistently higher than those recorded in the external environment (Figure 4a). These results support the findings observed by Andrade et al. (2022). However, it is important to note that merely analyzing the temporal distribution of absolute maximum t_{db} values is not sufficient to infer that the environmental conditions within the CBP system were thermally worse than those in the external environment. This is because these values may have occurred only in specific regions of the CBP system area and may not be representative of the entire AOZ.

In winter, the absolute minimum t_{db} recorded was 4.73 °C (on the 13^{th} experimental day, at 6:25 a.m.), whereas in summer it was 15.84 °C (on the 2^{nd} experimental day, at 4:00 a.m.) (Figure 4a). Considering that the t_{db} remained below the lower critical comfort limit for lactating Holstein dairy cows, which is 5.00 °C according to Nääs (1989), for less than 15 minutes, it can be inferred that the recorded absolute minimum values did not constitute significant cold stress.

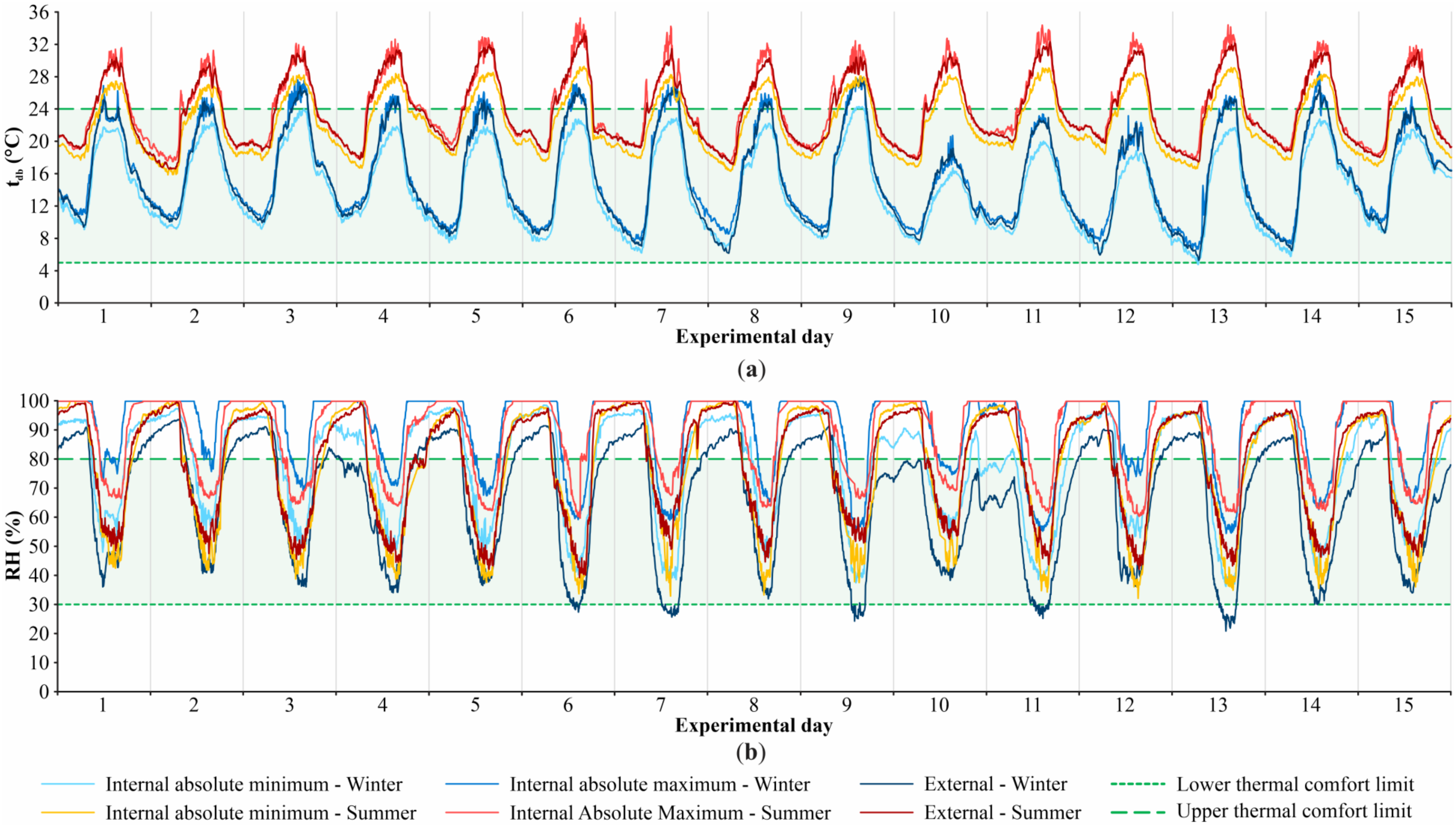

Figure 4. Curves of absolute minimum and maximum values of **(a)** dry-bulb air temperature (t_{db}, in °C) and **(b)** relative humidity (RH, in %), inside and outside the Compost-Bedded Pack Barn system under study, during the experimental periods of winter and summer.

On the other hand, t_{db} values exceeding 24.00 °C, the upper thermal comfort limit (UTCL) for European dairy cattle according to Nääs (1989), were recorded on 12 experimental days during winter and on all 15 days during summer (Figure 4a). In winter, a season typically associated with milder thermal conditions in the study region (Monteiro & Martins, 2019), t_{db} peaks of up to 3.00 °C above the UTCL were recorded. These results suggest that, even during the cold season, the thermal conditions within the CBP system under study occasionally reached t_{db} values above the UTCL for lactating Holstein dairy cows.

In summer, absolute maximum t_{db} values were consistently above 30.00 °C (Figure 4a). During this period, the most challenging thermal conditions for the animals housed in the CBP system under study were observed on the 6th, 7th, 11th and 13th experimental days, when t_{db} peaks were recorded at more than 10.00 °C above the UTCL (35.23 °C, 34.24 °C, 34.37 °C, and 34.40 °C, respectively). In such conditions, the mechanisms for regulating the core body temperature of cows are unable to provide the necessary cooling through physiological and behavioral adaptations to maintain core body temperature within the appropriate range, resulting in heat stress (Nordlund et al., 2019). As a result of heat stress, various negative consequences are reported in the literature, such as reduced food intake (Baumgard & Rhoads, 2013; Collier et al., 2019), decreased milk production (Gunn et al., 2019; Tao et al., 2020), and worsening reproductive indices (Schüller et al., 2016; Sammad et al., 2020). Since the average daily milk production per animal in summer was numerically lower than in winter (32.80 ± 13.35 and 31.12 ± 12.38 $kg \cdot animal^{-1} \cdot day^{-1}$, respectively; Table 1), this can be attributed, among other factors, to the thermal conditions recorded, which were indicated to be more challenging for the animals.

For RH, it was observed that the pattern of behavior for the recorded values (both absolute minimums and maximums) inside and outside the CBP system under study was similar across the monitored periods, despite some lower values being recorded outside the facility during winter (RH ≤ 30.00 %; Figure 4b). Such results were anticipated for the external environment of the CBP during winter, as this season is typically cold and dry in areas with a Cwa climate, influenced by local convective activities and South American monsoons (Monteiro & Martins, 2019).

Inside the CBP system, the absolute maximum values of RH remained higher than those recorded outside the system, always exceeding 30.00 %, and reached saturation at night on all monitored days, both in winter and summer (Figure 4b). Even during the day, there was a tendency for RH values to remain above 50.00 % inside the CBP system. This can be attributed to the increases in relative humidity due to the composting process of the bedding, evaporation and spillage from the tipper drinkers, animal respiration, and the presence of animal waste (Damasceno et al., 2019).

Between 6:00 p.m. and 8:00 a.m., there was a tendency for RH values inside the CBP system to remain above the recommended range for optimal thermal exchange in animals, which is 30.00 % to 80.00 %, according to Leal & Nääs (1992) (Figure 4b). In this case, it can be inferred that the prevalence of high RH values during both winter and summer was associated with the external environmental conditions at the location. It is important to note that consistently high RH values can lead to increased health issues in animals (such as bronchitis, pneumonia, mastitis, etc.) and can raise the moisture levels in the bedding, resulting in dirtier cows and a subsequent decline in milk quality (Black et al., 2014; Eckelkamp et al., 2016; Leso et al., 2020; Witkowska & Ponieważ, 2022). Therefore, consistently high RH values inside animal housing are undesirable from a management perspective and should be addressed through interventions in thermal cooling systems.

If high RH values occur in conjunction with elevated t_{db}, as observed on certain days and times during summer (Figures 4a and 4b), thermal exchanges may be compromised, thereby affecting thermal comfort. When RH is high, the vapor pressure gradient decreases, which reduces heat loss through evaporative pathways (such as sweating and panting) (Baêta & Souza, 2010). Therefore, when combined with high t_{db}, which reduces the thermal gradient between the core body temperature and the surrounding ambient temperature, thereby diminishing the efficiency of thermal exchanges through conduction, convection, and radiation, elevated RH values impair thermal exchanges and lead to heat stress in animals (Collier et al., 2019). Heat stress caused by the prolonged exposure of dairy cows to simultaneously high t_{db} and RH can reduce food intake and milk production, impair fertility, and increase the incidence of diseases such as mastitis and lameness (Dahl & McFadden, 2022).

To analyze the average per hour behavior of t_{db}, RH and THI inside and outside the CBP system under study, the graphs illustrated in Figure 5 were generated.

In both winter and summer, the average t_{db} inside the CBP system was lower than that recorded outside, particularly between 9:00 a.m. and 5:00 p.m., when the average temperature difference between the internal and external environments exceeded 1.50 °C (Figure 5a). The prevalence of lower average t_{db} inside the CBP system compared to the external environment was anticipated, as the presence of a metallic cover in the CBP system, which has high thermal emissivity and reflectance, can reduce the incident solar radiation load by up to 30.00 %, thereby decreasing the average internal t_{db} (Faghih & Bahadori, 2010; Kolokotroni et al., 2018).

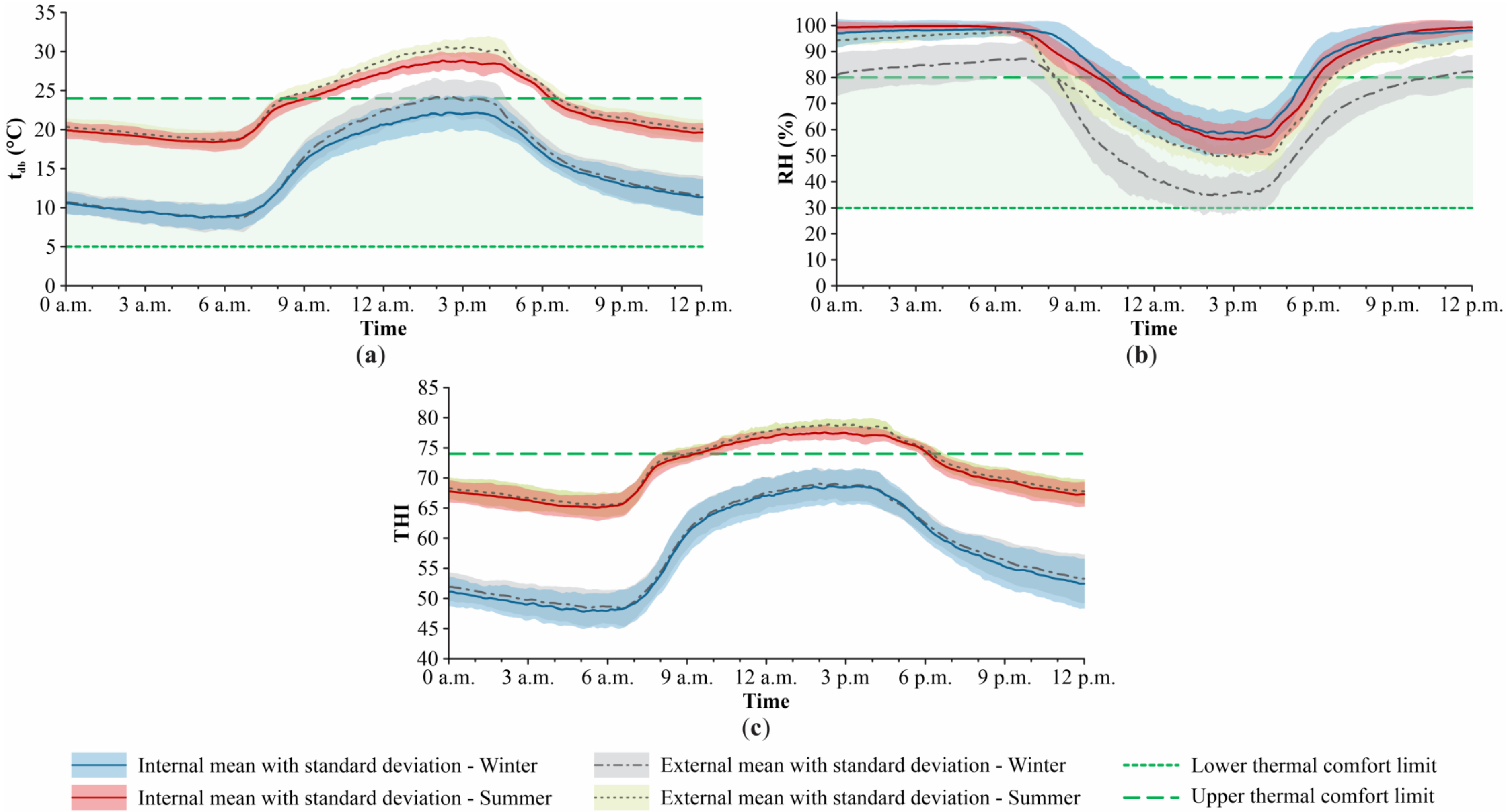

Figure 5. Curves of mean values with standard deviation for **(a)** dry-bulb air temperature (t_{db}, in °C), **(b)** relative humidity (RH, in %), and **(c)** Temperature-Humidity Index (THI), internal and external to the Compost-Bedded Pack Barn system under study, during the experimental winter and summer periods.

The reduction in average t_{db} during the daytime when solar radiation is present can also be partly explained by the operation of mechanical ventilation in the bedding area of the CBP system, which facilitates air movement, enhances thermal exchanges, and consequently lowers the t_{db} (Mrema et al., 2011; Oliveira et al., 2022). Additionally, it is inferred that this may also be related to the water sprinkling in the feeding alley (only during the hottest times of the day), a process implemented to promote the cooling of the animal's body.

Despite the prevalence of lower average t_{db} values inside the CBP system compared to the external environment, the average levels recorded in summer remained above 24.00 °C for about 9 hours and 20 minutes (9:10 a.m. to 6:30 p.m.; Figure 5a). During this time interval, the environmental conditions were considered thermally stressful for lactating Holstein cows. In such situations, dairy cattle tend to spend more time standing rather than resting, a condition that, although an adaptive response to heat, negatively impacts animal welfare and productivity (Allen et al., 2015; Ortiz et al., 2015; Reuscher et al., 2023).

During the time interval when $t_{db} \geq 24.00$ °C, the RH inside the CBP ranged from 56.12 ± 5.78 % (2:55 p.m.) to 84.46 ± 5.88 % (6:30 p.m.), with values predominantly below 80.00 % (Figure 5b). These conditions indicate the potential for exploring animal body cooling and/or air evaporative cooling (through latent heat) in the CBP system during the hottest times of the day.

In this type of confinement system, animal body cooling can be achieved using water sprinkler systems, with droplets ranging from 15 to 50 µm in diameter, capable of wetting the animals' skin (Fournel et al., 2017; Polsky & Von Keyserlingk, 2017). However, this method should only be implemented in the feeding alley area to avoid wetting the bedding and must be combined with mechanical ventilation systems. These systems are essential to create airflow over the animals, facilitate water evaporation, and ensure the expected body cooling of the housed dairy cows (Renaudeau et al., 2012; Arcidiacono, 2018).

Internal thermal conditions can also be improved using evaporative air-cooling methods. In this case, water misting systems (restricted to the feeding alley) combined with positive-pressure mechanical ventilation can be used. Alternatively, evaporative padding systems combined with negative-pressure mechanical ventilation can be employed, but these should be used exclusively in fully enclosed CBP systems (De Masi et al., 2021; Andrade et al., 2024). In both cases, the use of mechanical ventilation is mandatory, and the reduction in t_{db} only occurs when there is a change in the water content of the air and some of the energy (heat) is consumed to evaporate the water (Mrema et al., 2011; Smith et al., 2016).

Regarding the potential use of animal body cooling via water sprinkling in the feeding alley, it is worth noting that the CBP system under study was already equipped with this system, which was activated when $t_{db} \geq 24.00$ °C (for 1 minute at regular intervals of 5 minutes). During this study, it was observed that the water sprinkling system was only activated during the summer when temperatures were predominantly higher than the setpoint used (Figure 5a). This suggests that the placement of the sensor that used to activate the sprinkling system was inadequate, as $t_{db} \geq 24.00$ °C was recorded in some areas of the CBP system even during winter. Therefore, the water sprinkling system should have been activated.

Given the prevalence of high temperatures observed during the summer (Figure 5a), it can be inferred that improvements are needed in the thermal protection systems used in the CBP system under study. For example, installing mechanical ventilation lines in the feed alley could enhance the evaporation of water sprayed on the animals' skin and the flooring, thereby maximizing both body and air cooling in the facility. Other approaches to improve environmental thermal conditioning could also be explored. For example, increasing the overall ventilation rate by redimensioning the entire positive-pressure mechanical ventilation system, using dampened cellulose panels combined with negative-pressure mechanical ventilation (which would involve a complete redesign of the CBP system), or enhancing the building's thermal isolation (such as spraying water on the roof or using insulating barriers) are potential options. Nonetheless, it is essential to understand the distribution of t_{db}, RH and THI within the CBP system to make specific and effective decisions that are viable and sustainable from technical, economic, energy, and social perspectives.

Using THI to assess animal thermal comfort, it was found that the combined effect of t_{db} and RH resulted in THI values showing a daily pattern similar to that of t_{db} (Figure 5c). This can be attributed to the fact that temperature is the most significant component in the determination of THI (Gauly & Ammer, 2020; Ji et al., 2020; Tao et al., 2020).

Despite similar patterns, it was observed that the THI curves during winter and summer exhibited a greater flattening during the hottest part of the day, from 9:10 a.m. to 6:30 p.m. (Figure 5c), when compared to those of t_{db}. Since the lowest average RH values were recorded during this time interval, it is inferred that the process of thermal exchange through latent pathways (sweating and panting) was enhanced, resulting in the observed outcomes.

During the winter period, the average THI values throughout the day ranged from 47.82 ± 2.78 (5:05 a.m.) to 68.63 ± 2.55 (2:30 p.m.), remaining below 74.00. This suggests that the thermal conditions within the CBP system under study were comfortable for Holstein dairy cows in lactation (Figure 5c). In the summer, although the variation range of THI was narrower (around 12.50) compared to winter, higher average hourly values were observed, ranging from 65.07 ± 2.04 (5:30 a.m.) to 77.61 ± 1.08 (2:10 p.m.) (Figure 5c). In this climatic season, the most challenging conditions for lactating cows were observed between 9:20 a.m. and 6:05 p.m., when the THI was ≥ 74.00. This indicates that the combination of t_{db} and RH values recorded during this period exceeded the thermal comfort threshold, signifying a state of thermal stress (Herbut et al., 2018). Therefore, it can be inferred that the Holstein dairy cows in lactation may have undergone physiological and behavioral adjustments, such as reduced food intake (Collier et al., 2019) and decreased resting time (Nordlund et al., 2019), resulting in the immediate consequence of the observed decrease in average daily milk production per animal (Table 1).

Through the analysis of the temporal distribution of t_{db}, RH, and THI, it was observed that there is temporal variation in the data collected during both study periods (winter and summer). To understand not only the range of variation in environmental factors but also the distribution of these variables throughout the interior of the CBP system under study, spatial analysis tools were used. These tools enabled the modeling of data variability and the creation of spatial distribution maps for t_{db}, RH, and THI during both winter and summer periods. These maps were used to identify areas with a prevalence of extreme values for the studied climatic variables (the most challenging conditions), as well as to suggest spatially tailored improvements to the thermal environment, considering the needs of the housed animals (Holstein dairy cows in lactation).

3.3. Spatial analyses of variables and the thermal-environmental index in the Compost-Bedded Pack Barn system under study

Using geostatistical techniques, it was possible to quantify the magnitude of spatial dependence of t_{db}, RH, and THI inside the CBP system under study, across different times of day (dawn, morning, afternoon and night), as well as during the recorded extreme conditions, in both winter and summer in Brazil. Based on cross-validation and the defined selection criteria, the best fits were analyzed and chosen for each of the 36 study scenarios used to assess the thermal conditions (Table 2).

For most study scenarios (n = 32), the best semivariogram fits were obtained using the Spherical model, while the Exponential and Gaussian models provided better semivariograms for two variables each (Exponential—$RH_{Maximum}$ and $THI_{Maximum}$ in summer; and Gaussian—$t_{db\text{-}Maximum}$ and $RH_{Afternoon}$ in summer; Table 2).

Table 2. Methods, models, and parameters obtained from the semivariograms fitted for dry-bulb air temperature (t_{db}), relative humidity (RH), and Temperature-Humidity Index (THI), inside a lactating cow accommodation in an open Compost-Bedded Pack Barn system under study, during winter and summer periods in Brazil.

Variable	Period	Method	Model	C_0	C_1	$C_0 + C_1$	*a*	*a'*	SDI	ME	SD_{ME}	SEr	SD_{SEr}
$t_{db\text{-}Dawn}$	Winter	OLS	Spherical	0.0048	0.0548	0.0596	5.5792	5.5792	0.0813	0.0000	0.2389	0.0000	0.9721
	Summer	OLS	Spherical	0.0035	0.0417	0.0452	5.5295	5.5295	0.0772	0.0000	0.2138	0.0000	0.9991
$t_{db\text{-}Morning}$	Winter	OLS	Spherical	0.0073	0.0760	0.0833	5.3792	5.3792	0.0875	0.0000	0.2885	0.0000	0.9922
	Summer	OLS	Spherical	0.0105	0.0919	0.1024	6.3129	6.3129	0.1024	0.0007	0.3140	0.0011	0.9798
$t_{db\text{-}Afternoon}$	Winter	OLS	Spherical	0.0129	0.1681	0.1810	5.4192	5.4192	0.0714	0.0000	0.4242	0.0001	0.9896
	Summer	REML	Spherical	0.0017	0.3266	0.3283	31.0624	31.0624	0.0053	0.0058	0.2697	0.0102	0.9922
$t_{db\text{-}Night}$	Winter	OLS	Spherical	0.0032	0.0606	0.0638	5.3292	5.3292	0.0501	0.0000	0.2471	0.0000	0.9707
	Summer	REML	Spherical	0.0042	0.0407	0.0449	5.9109	5.9109	0.0933	0.0001	0.2089	0.0002	0.9815
$t_{db\text{-}Minimum}$	Winter	WLS	Spherical	0.0078	0.2003	0.2082	5.8728	5.8728	0.0377	0.0003	0.4461	0.0003	0.9734
	Summer	OLS	Spherical	0.0092	0.1339	0.1430	5.4110	5.4110	0.0641	-0.0001	0.3736	-0.0002	0.9805
$t_{db\text{-}Maximum}$	Winter	ML	Spherical	0.0960	1.3710	1.4670	41.7207	41.7207	0.0654	0.0215	0.6157	0.0174	0.9730
	Summer	REML	Gaussian	0.0850	2.6230	2.7080	10.5300	18.2312	0.0314	0.0113	0.4924	0.0097	0.9833
RH_{Dawn}	Winter	WLS	Spherical	0.1528	1.6724	1.8252	6.0645	6.0645	0.0837	-0.0007	1.3478	-0.0003	0.9949
	Summer	REML	Spherical	0.0095	0.1383	0.1478	8.0372	8.0372	0.0643	0.0011	0.3639	0.0015	0.9998
$RH_{Morning}$	Winter	WLS	Spherical	0.4495	4.7484	5.1979	5.5298	5.5298	0.0865	-0.0006	2.2960	-0.0001	1.0000
	Summer	OLS	Spherical	0.0695	3.0338	3.1033	8.6764	8.6764	0.0224	0.0012	1.6125	0.0004	0.9996
$RH_{Afternoon}$	Winter	WLS	Spherical	0.8395	9.6707	10.5103	5.6319	5.6319	0.0799	-0.0018	3.2218	-0.0003	0.9874
	Summer	REML	Gaussian	1.3598	11.3500	12.7098	6.5210	11.2857	0.1070	-0.0155	2.2947	-0.0033	0.9987

Table 1. *Continuation.*

Variable	Period	Method	Model	C_0	C_1	$C_0 + C_1$	*a*	*a′*	SDI	ME	SD_{ME}	SEr	SD_{SEr}
RH_{Night}	Winter	WLS	Spherical	0.4395	4.8793	5.3188	5.2918	5.2918	0.0826	-0.0002	2.3223	0.0000	0.9989
	Summer	OLS	Spherical	0.1595	1.8776	2.0371	5.7533	5.7533	0.0783	0.0010	1.4340	0.0003	0.9998
$RH_{Minimum}$	Winter	WLS	Spherical	1.4972	16.2998	17.7969	5.4593	5.4593	0.0841	-0.0007	3.1586	-0.0001	0.9785
	Summer	OLS	Spherical	2.0498	24.8757	26.9256	5.5467	5.5467	0.0761	-0.0002	2.9684	0.0000	0.9803
$RH_{Maximum}$	Winter	OLS	Spherical	0.1095	1.2239	1.3334	7.3473	7.3473	0.0821	-0.0011	1.1180	-0.0005	0.9907
	Summer	WLS	Exponential	0.0001	0.0105	0.0106	6.3270	18.9533	0.0094	0.0003	0.0777	0.0018	0.9974
THI_{Dawn}	Winter	OLS	Spherical	0.0180	0.1811	0.1991	5.6348	5.6348	0.0902	0.0000	0.4376	0.0000	0.9745
	Summer	OLS	Spherical	0.0139	0.1371	0.1510	5.5329	5.5329	0.0924	0.0000	0.3817	0.0000	0.9754
$THI_{Morning}$	Winter	OLS	Spherical	0.0195	0.2087	0.2282	5.6193	5.6193	0.0856	0.0000	0.4720	0.0000	0.9818
	Summer	OLS	Spherical	0.0251	0.2222	0.2473	5.6533	5.6533	0.1014	0.0004	0.4946	0.0004	0.9880
$THI_{Afternoon}$	Winter	WLS	Spherical	0.0195	0.2252	0.2447	6.2174	6.2174	0.0798	0.0000	0.4891	0.0000	0.9882
	Summer	OLS	Spherical	0.0191	0.2116	0.2307	9.8302	9.8302	0.0826	0.0051	0.4223	0.0060	0.9965
THI_{Night}	Winter	OLS	Spherical	0.0185	0.1736	0.1921	5.5382	5.5382	0.0964	0.0000	0.4335	0.0000	0.9821
	Summer	WLS	Spherical	0.0108	0.1170	0.1278	5.8472	5.8472	0.0845	0.0002	0.3560	0.0003	0.9911
$THI_{Minimum}$	Winter	WLS	Spherical	0.0494	0.6455	0.6949	5.7829	5.7829	0.0711	0.0005	0.8241	0.0003	0.9832
	Summer	REML	Spherical	0.0396	0.4477	0.4873	22.3283	22.3283	0.0813	-0.0045	0.4305	-0.0051	0.9991
$THI_{Maximum}$	Winter	OLS	Spherical	0.0494	1.1543	1.2037	5.3953	5.3953	0.0410	0.0002	1.0851	0.0001	0.9815
	Summer	ML	Exponential	0.0838	1.3260	1.4098	12.9800	38.8872	0.0594	0.0097	0.7191	0.0064	0.9737

C_0—nugget effect; C_1—contribution; $C_0 + C_1$—sill; *a*—range; *a′*—practical range; SDI—spatial dependence index; ME—mean-error; SD_{ME}—mean-error standard deviation; SEr—standardized-error; SD_{SEr}—standardized-error standard deviation; Dawn—mean values during the dawn; Morning—mean values during the morning; Afternoon—mean values during the afternoon; Night—mean values during the night; Maximum—absolute maximum values; Minimum—absolute minimum values; OLS—Ordinary Least Squares; WLS—Weighted Least Squares; ML—Maximum Likelihood; e REML—Restricted Maximum Likelihood.

For each scenario, regardless of the model that provided the best fit, the selection was based on metrics calculated through cross-validation. The resulting values were ME ≤ 0.0215 and SEr ≤ 0.0174, with SD_{SEr} values very close to one (0.9707 ≤ SD_{SEr} ≤ 0.9999). Based on these results, it was found that the fitted semivariograms adequately represented the spatial variability of these variables. These findings are consistent with those reported by Ferraz et al. (2019), Silva et al. (2020), Andrade et al. (2022), Oliveira et al. (2022), Silva et al. (2023) and Guesine et al. (2023), who also observed that the use of these three models provided the best fits when applying geostatistical techniques to evaluate the spatial dependence of thermal environment variables in animal housing.

One of the most important coefficients in theoretical models for semivariograms in geostatistics is the nugget effect (C_0), which represents the variability that is not explained by the chosen sampling distance (Oliveira et al., 2021; Silva et al., 2021). For all the analyzed variables, the values of C_0 were close to zero, indicating that these variables had low unexplained variability and exhibited continuous semivariograms (Table 2). The highest values of C_0 were observed for the situations with absolute minimum RH values during winter and summer, which recorded C_0 values of 1.4972 and 2.0498, respectively. However, in these two situations, high variance was observed in the data sets (17.7384 and 28.4558, respectively). Therefore, considering the sample variance of the data, the C_0 values obtained from the fitted semivariograms for these variables were not deemed high (Table 2).

Despite its importance, C_0 can be attributed to numerous factors, such as errors in data collection and analysis, local variations, among other factors. Therefore, it is not possible to quantify the individual impact of each of these factors on its composition (Trangmar et al., 1986; Ferraz et al., 2019). Thus, it is important to use methodologies for evaluating C_0 based on other parameters, such as the classification by Cambardella et al. (1994), which establishes the SDI as the ratio between the nugget effect and the sill ($C_0 + C_1$), allowing for comparisons to be made. For all the scenarios of the variables and index analyzed, the SDI values were below 0.25 and therefore characterized as indicating strong spatial dependence (Table 2). The highest values were obtained for the variables $RH_{Afternoon}$ in summer and $t_{db\text{-}Morning}$ in summer, with SDI values of 0.1070 and 0.1024, respectively. Thus, it was found that the data obtained through ordinary kriging for unsampled locations were adequate, given that the weight of C_0 in the composition of $C_0 + C_1$ was consistently low, even in cases where higher values of C_0 were observed [e.g., $RH_{Minimum}$ in winter (1.4972) and summer (2.0498), with SDI values of 0.0841 and 0.0761, respectively].

In geostatistics, another relevant parameter is the range (*a*), which represents the radius beyond which spatial dependence between the data is considered negligible (Deutsch & Journel, 1997; Ferraz et al., 2019). In this study, the evaluated variables exhibited varying values for the *a* (Table 2), but all of them were consistently greater than the minimum sampling distance (4.50 m), thus supporting the hypothesis of spatial dependence (Oliveira et al., 2024). The highest values for the *a* were observed for the variables $t_{db\text{-}Maximum}$ in winter (recorded in the afternoon) and $t_{db\text{-}Afternoon}$ in summer (41.7207 m and 31.0624 m, respectively). These results suggest that t_{db} exhibited greater spatial dependence in the afternoon, which could be related to insufficient air renewal within the studied CBP system during this period (Silva et al., 2021). This may indicate that the mechanical ventilation system in place was inadequate to ensure uniform environmental conditions. On the other hand, the lowest values of *a* were recorded for RH_{Night} and $t_{db\text{-}Night}$ in winter (5.3292 m and 5.2918 m, respectively), indicating that these variables exhibited less spatial dependence at that time. The lowest values of *a* obtained can be used to determine the distance between sampling points in future studies. Specifically, it can be inferred that distances of up to 5.29 m may be considered adequate for evaluating the spatial dependence of t_{db}, RH, and THI.

The results from the geostatistical modeling revealed that the variables and index assessed did not exhibit random spatial distribution. This is because strong spatial dependence was observed, and values of *a* were greater than the minimum distance between sampling points (Silva et al., 2021). Thus, it was possible to apply this tool to obtain values for the thermal environment variables at un-sampled locations (using ordinary kriging) within the CBP system under study and to generate spatial distribution maps for t_{db}, RH and THI (Figures 6-11). Through such maps, it is possible to assess the spatial behavior of the variables of interest and identify problematic areas regarding the management of the thermal environment (Curi et al., 2017; Queiroz et al., 2017).

The CV values obtained for the average datasets of t_{db}, RH and THI used to create the spatial distribution maps were always below 0.10 (Figures 6-11). This indicates that the data recorded during both experimental periods (winter and summer) exhibited low dispersion, according to the classification suggested by Gomes (2000). These results suggest that there was relative homogeneity for all the mapped variables within the CBP system under study (Franco et al., 2022).

In both winter and summer, low spatial variability in the average t_{db} values was observed during the early morning and night, with the variation amplitudes (Δt_{db}) across the CBP system under study being less than 1.00 °C (Figures 6a, 6b, 6g, and 6h). In contrast, during the morning and afternoon periods, higher average variation amplitudes were observed, particularly in the afternoon, when Δt_{db} was 2.06 °C in winter and 2.00 °C in summer (Figures 6e and 6f). Despite similar variation amplitudes for $t_{db\text{-}Afternoon}$ during winter and summer, the thermal conditions were more challenging in summer, when the average t_{db} ranged between 27.37 and 29.37 °C, significantly exceeding the UTCL for lactating dairy cattle (24.00 °C). Certainly, the high t_{db} values recorded during the summer may have negatively impacted the welfare and productive performance of the lactating Holstein cows housed in the CBP system under study (Herbut et al., 2018; Morales-Piñeyrúa et al., 2022).

In both monitored experimental periods (winter and summer), a small gradient of t_{db} was observed throughout the CBP system during the morning and afternoon, with higher values consistently recorded in the northwest region of the CBP system (Figures 6c-f). The high t_{db} values recorded in this region of the CBP system, particularly in the afternoon, further indicate insufficient air renewal in this area of the system, as evidenced by the greater spatial dependence (> *a*).

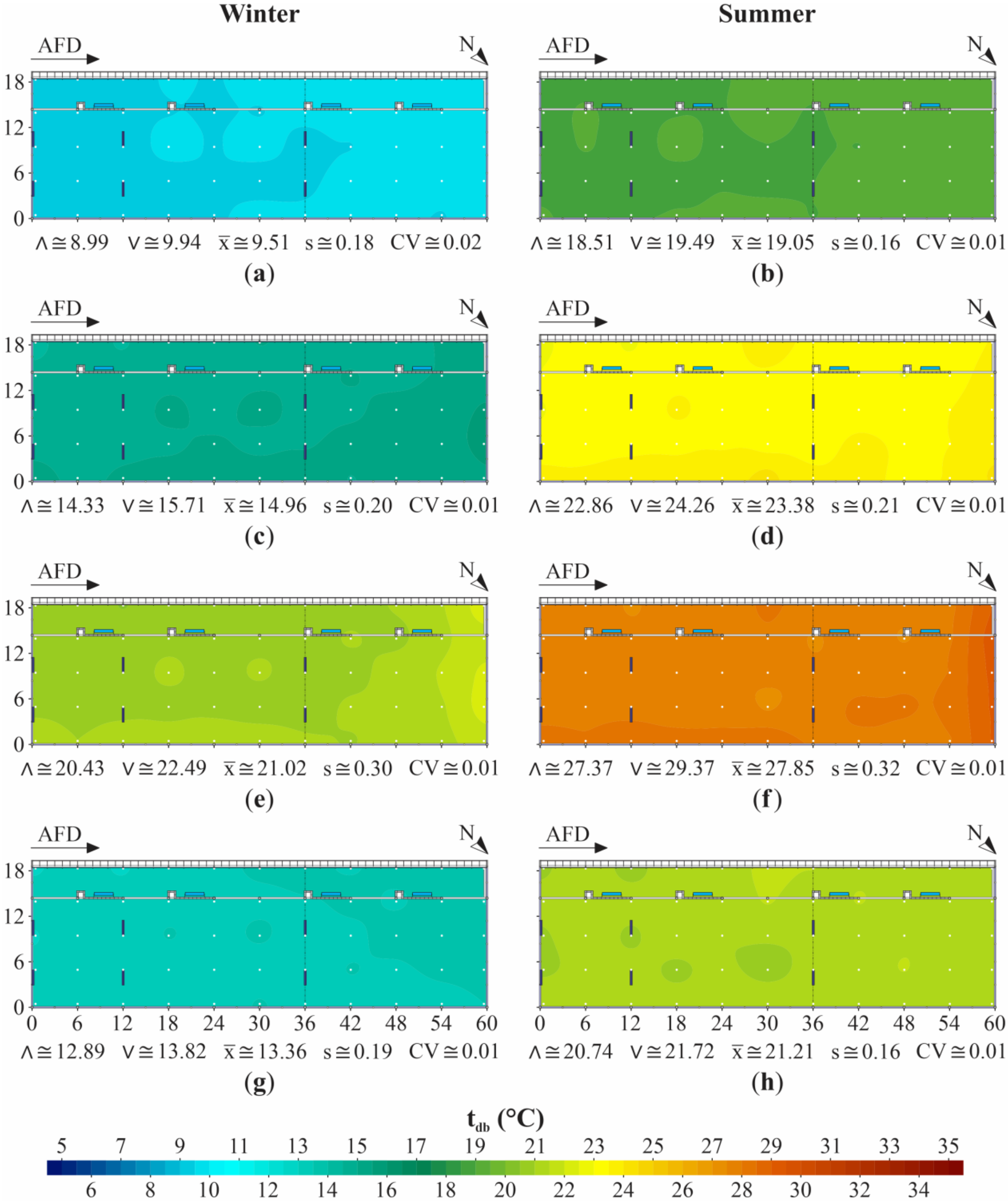

Figure 6. Spatial distribution of dry-bulb air temperature values (t_{db}, in °C) inside the Compost-Bedded Pack Barn system under study: mean values for periods **(a)** dawn, **(c)** morning, **(e)** afternoon and **(g)** night in winter; and mean values for periods **(b)** dawn, **(d)** morning, **(f)** afternoon and **(h)** night in summer. ∧—minimum; ∨—maximum; x̄—mean; s—standard deviation; CV—coefficient of variation; AFD—airflow direction; N—North indication; dimensions in meters (m).

According to Damasceno (2020), in CBP systems with positive-pressure mechanical ventilation using low-volume and high-speed fans, like the CBP system under study, it is recommended that the maximum distance between ventilation lines be 12.00 m to maintain uniform air renewal rates across the AOZ. In this study, it was found that this distance was only met in the Southeast region of the CBP system, between ventilation lines 1 and 2 (Figure 1). Throughout the remaining longitudinal length of the CBP system, there was only one ventilation line (line 3), which was located 24.00 m away from other lines and the Northwest end. Thus, the results observed in the Northwest region of the CBP system suggest that the third ventilation line was inadequate for ensuring homogeneous temperature conditions in its operational area (Figures 6c-f), despite being continuously operational (24 hours per day).

Regarding the formation of the t_{db} gradient across the CBP system area during daylight hours (morning and afternoon), the most problematic scenario for each period occurred in the afternoon. During this time, the highest average values were recorded in the Northwest region of the CBP system ($t_{db} \geq 21.50$ °C in winter; and $t_{db} \geq 28.00$ °C in summer; Figures 6e and 6f), compared to the rest of the AOZ. In the afternoon period, it was observed that direct solar radiation affected the mentioned region. Consequently, the higher t_{db} values recorded in the last 6.00 meters of the CBP system are due to the heating of the air from shortwave radiation (Tao et al., 2020; Andrade et al., 2022).

In the northwestern region of the CBP system, the incidence of direct solar radiation was due to two factors: the incorrect orientation of the facility's longitudinal axis and the lack of frontal closures on the gable ends. The CBP under study had its longitudinal axis-oriented Northwest-Southeast. This orientation, combined with the lack of frontal closures on the gable ends, led to direct solar radiation during the afternoon, resulting in an increase in t_{db} in that region (Damasceno, 2020), as evidenced by the spatial distribution maps (Figures 6e and 6f).

Although the spatial behavior of the average t_{db} conditions by period was examined through the maps in Figure 6, it was also deemed important to assess the spatial distribution at times when absolute minimum and maximum values of this variable were recorded, as these conditions are considered extreme for animal thermoregulation (Figure 7). High t_{db} peaks are particularly challenging for thermal comfort. When sustained for extended periods, they can lead to significant productive and reproductive losses, impair health, or even result in death in the most extreme cases (Gernand et al., 2019; Lovarelli et al., 2020; Cartwright et al., 2022).

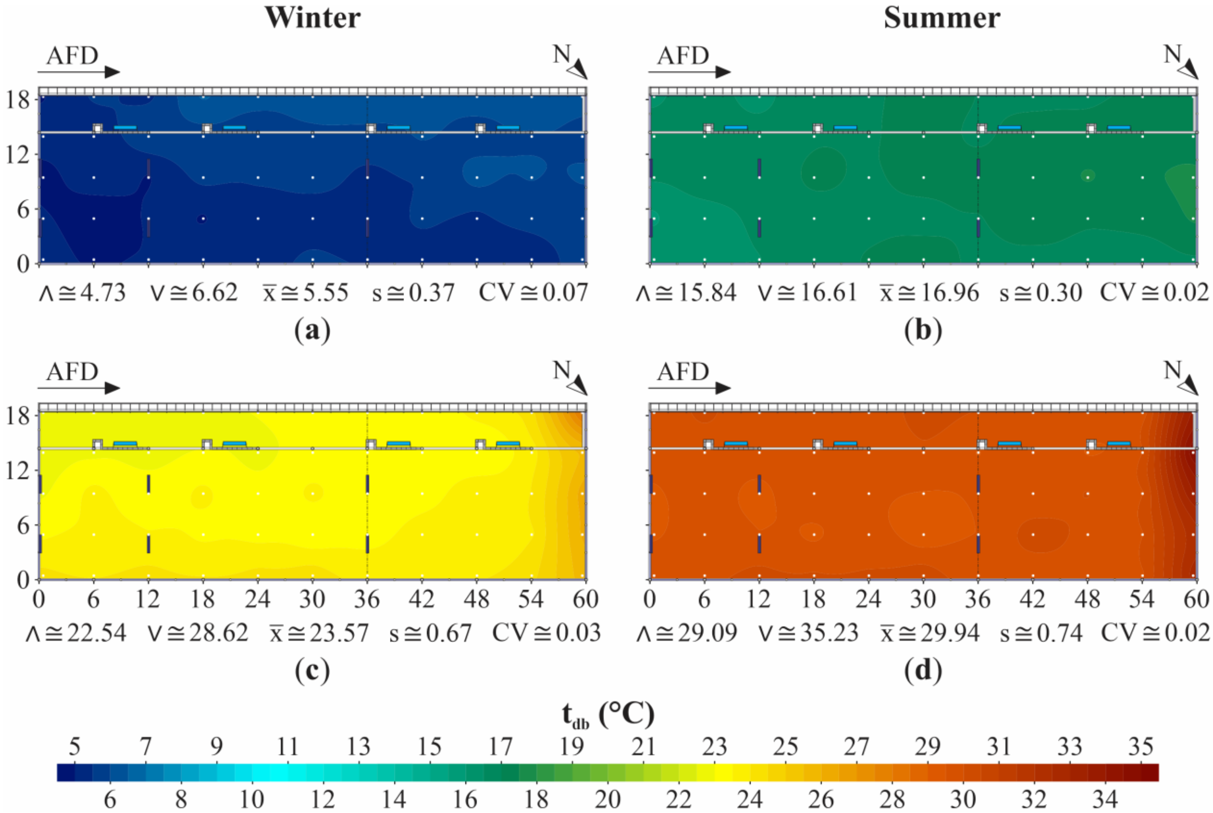

Figure 7. Spatial distribution of dry-bulb air temperature values (t_{db}, in °C) inside the Compost-Bedded Pack Barn under study: **(a)** absolute minimum values and **(c)** absolute maximum values in winter; and **(b)** absolute minimum values and **(d)** absolute maximum values in summer. ∧—minimum; ∨—maximum; x̄—mean; s—standard deviation; CV—coefficient of variation; AFD—airflow direction; N—North indication; dimensions in meters (m).

In both experimental periods, the recorded absolute minimum values of t_{db} were predominantly above 5.00 °C, falling below this threshold only in a small area located between ventilation lines 1 and 2 (only in winter; Figure 7a). Therefore, it can be inferred that there was no significant thermal stress due to cold, as most animals can tolerate this temperature level with relative ease (De Masi et al., 2021).

However, the maps of absolute maximum values of t_{db} [winter: 14th experimental day, at 1:45 p.m. (Figure 4c); and summer: 6th experimental day, at 2:50 p.m. (Figures 4d)] showed that t_{db} exceeded 24.00 °C, even during the cold season (Figures 7c and 7d). In the winter period, values above the UTCL were observed only in the area near the northwest face of the CBP system, within the last 6.00 m (Figure 7c). Consequently, it was found that constructing closure structures on the gables and/or planting vegetation belts in this area (as recommended in Section 3.4) would be sufficient to alleviate thermal conditions during this season.

In contrast, during the summer, the prevalence of t_{db} values ≥ 29.00 °C was observed throughout the entire AOZ, with the highest values also recorded in the Northwest region, where t_{db} ≥ 30.00 °C (Figure 7d). Given that the t_{db} curve during this period exhibited a well-defined pattern (Figure 4a), it was understood that the occurrence of t_{db} values ≥ 29.00 °C was consistent across all monitored days and was not limited to the Northwest region of the CBP system, as was implied by Figure 6f.

In addition to t_{db}, it is crucial to assess the spatial distribution of RH (Figures 8 and 9), a climatic factor that also has a significant impact on the thermal comfort of dairy cattle (Baêta & Souza, 2010; Nääs, 1989). For the average RH values by time of day, very similar spatial patterns were observed in both winter and summer, with values predominantly above 87.00 % during the dawn and night periods (Figures 8a, 8b, 8g, and 8h). During the morning and afternoon periods (Figures 8c, 8d, 8e, and 8f), it was observed that RH levels were decreasing, with less homogeneous spatial distribution within the system. The lowest average values were recorded in the peripheral areas of the CBP system, which are more influenced by external conditions and solar radiation (Oliveira et al., 2022). These RH results align with those reported by Andrade et al. (2022), who mapped thermal conditions in a closed CBP system located in the same region as this study.

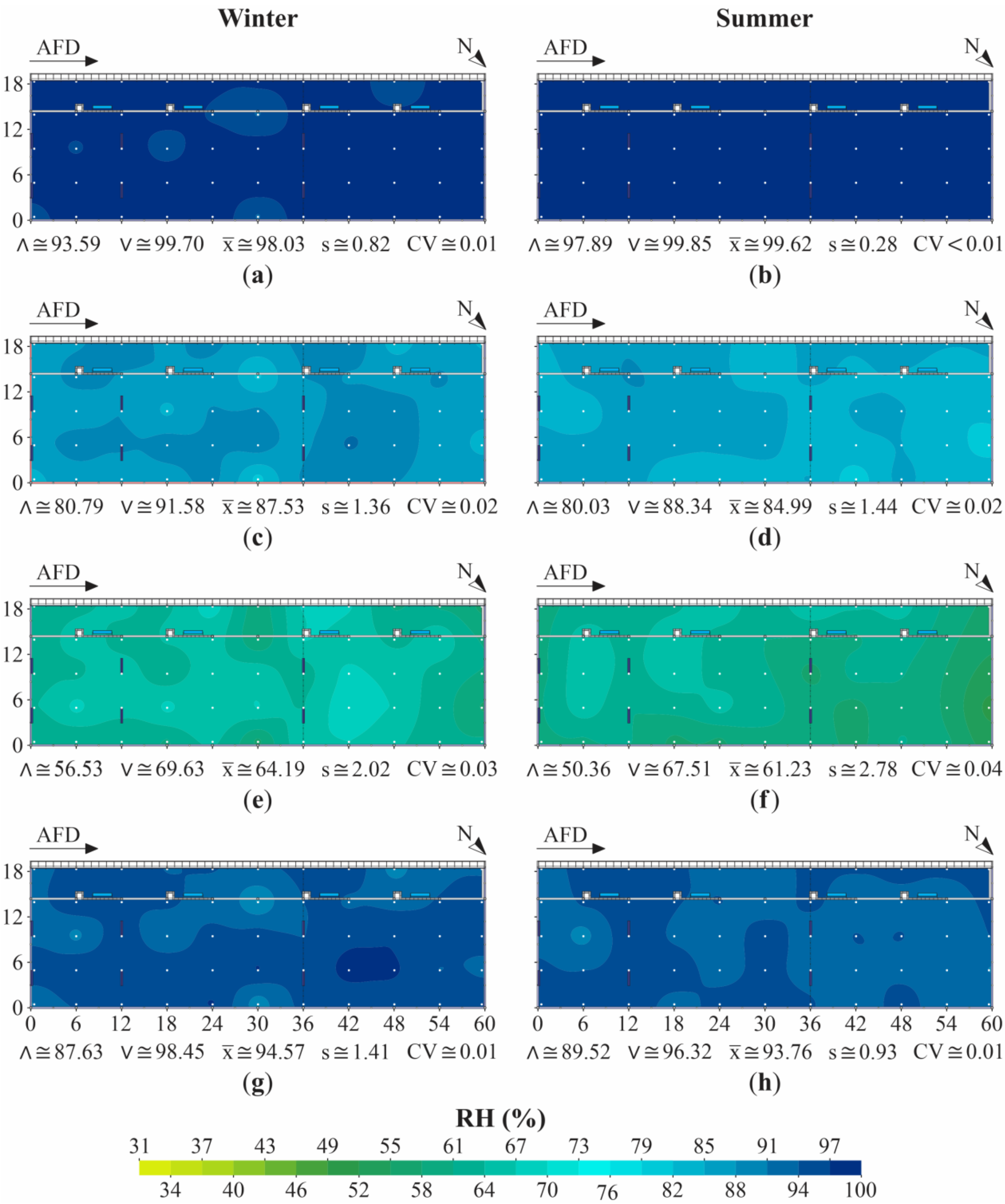

Figure 8. Spatial distribution of relative humidity values (RH, in %) inside the Compost-Bedded Pack Barn system under study: mean values for periods **(a)** dawn, **(c)** morning, **(e)** afternoon and **(g)** night in winter; and mean values for periods **(b)** dawn, **(d)** morning, **(f)** afternoon and **(h)** night in summer. ∧—minimum; ∨—maximum; x̄—mean; s—standard deviation; CV—coefficient of variation; AFD—airflow direction; N—North indication; dimensions in meters (m).

During the dawn, morning, and night periods (Figures 8a, 8b, 8g, and 8h), the average RH levels remained above the recommended range for housing dairy cattle, which is 30.00 % to 80.00 %, according to Leal & Nääs (1992). Although these conditions occurred during times when the average t_{db} levels were considered thermally comfortable (Figures 6a, 6b, 6g, and 6h), it is important to highlight that the prevalence of high RH levels in such a system can lead to excessive bedding moisture, increase animal soiling, compromise milk quality, and cause health issues in the animals (Eckelkamp et al., 2016; Blanco-Penedo et al., 2020; Damasceno, 2020; Leso et al., 2020). Therefore, high RH values are undesirable and further indicate that the mechanical ventilation systems at the location were either inadequately sized and/or managed, and therefore insufficient for effectively reducing RH levels.

On the other hand, the average RH values throughout the internal area of the CBP system studied remained below 70.00 % during the times with the highest average t_{db} values (Figures 5, 6, and 8) and were even lower during the periods with the highest absolute t_{db} values (Figures 7 and 9), as expected. These results suggest that there is potential for leveraging evaporative cooling of the air through the use of evaporative padding cooling panels combined with negative-pressure mechanical ventilation, or even misting combined with positive-pressure ventilation (limited to the feeding alley), in this type of confinement system during the hotter times of the day and year. However, it is important to emphasize that such methods should only be employed during hot and dry periods (Vega et al., 2022). In hot and dry periods, as depicted for summer afternoons in this study (Figures 6, 7, 8, and 9), it can be inferred that the use of the thermal defense systems could effectively reduce t_{db} values, provided these systems are properly designed and managed (Mrema et al., 2011; Arcidiacono, 2018).

For the moments when minimum and maximum absolute RH values were recorded, similar patterns were observed in both winter and summer (Figure 9). Through the analysis of maximum absolute values, it was found that there was low spatial variability, with RH levels always exceeding 94.00 % (Figures 9c and 9d). This condition was observed during the night in both winter and summer on all experimental days (Figure 4b), due to thermal inversion.

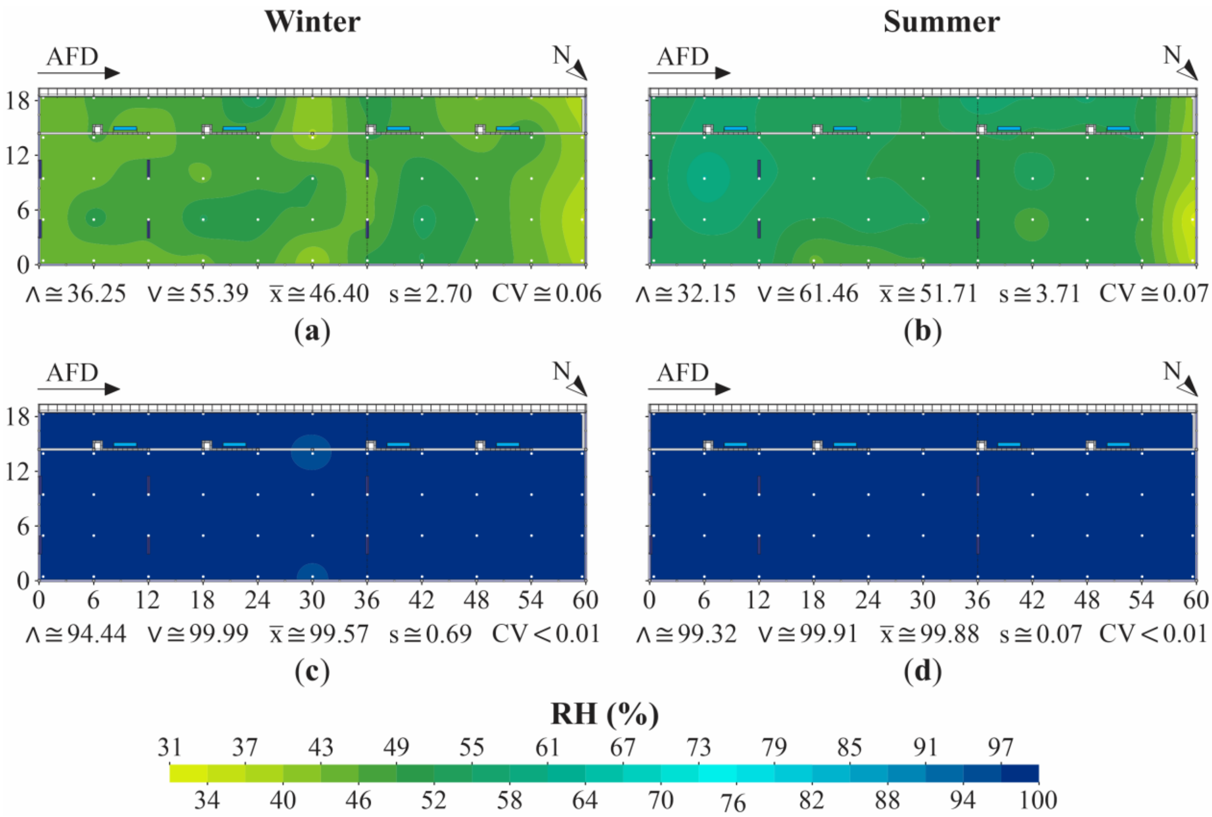

Figure 9. Spatial distribution of relative humidity values (RH, in %) inside the Compost-Bedded Pack Barn under study: **(a)** absolute minimum values and **(c)** absolute maximum values in winter; and **(b)** absolute minimum values and **(d)** absolute maximum values in summer. ∧—minimum; ∨—maximum; x̅—mean; s—standard deviation; CV—coefficient of variation; AFD—airflow direction; N—North indication; dimensions in meters (m).

The spatial distribution maps of the minimum absolute RH values revealed high spatial variability (ΔRH > 15.00 %), with the lowest values consistently recorded in the Northwestern region of the CBP system, attributed to direct solar radiation (Figures 9a and 9b). Although these results indicate that the ventilation system was ineffective in ensuring uniform RH conditions, the values observed fall within the recommended range for housing dairy cattle (30.00 % to 80.00 %).

Since it was of interest in this study to assess the combined effect of t_{db} and RH on the spatial behavior of average thermal conditions at different times of the day, both during winter and summer, spatial distribution maps of THI were also generated (Figure 10).

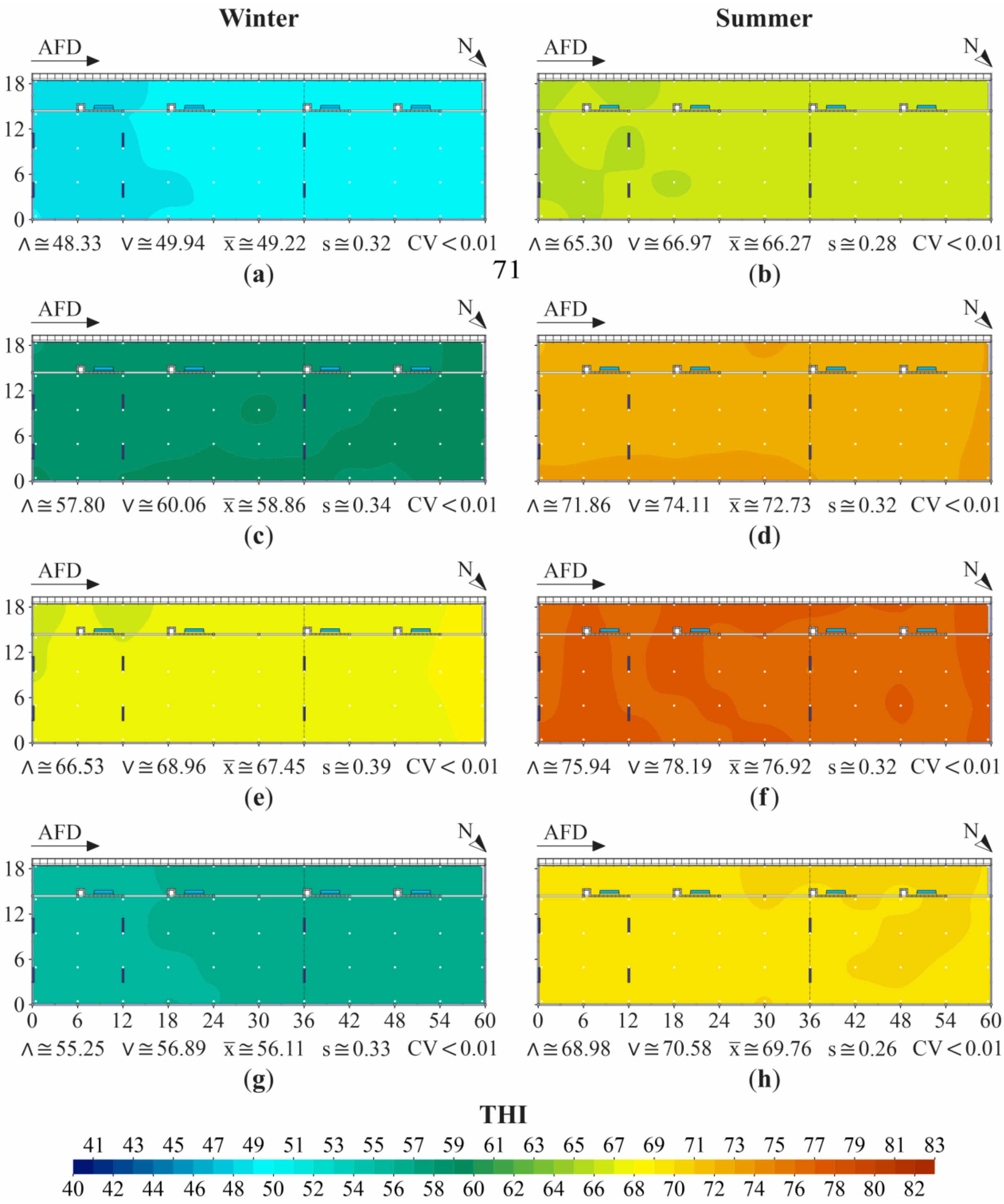

Figure 10. Spatial distribution of Temperature and Humidity Index (THI) inside the Compost-Bedded Pack Barn system under study: mean values for periods **(a)** dawn, **(c)** morning, **(e)** afternoon and **(g)** night in winter; and mean values for periods **(b)** dawn, **(d)** morning, **(f)** afternoon and **(h)** night in summer. ∧—minimum; ∨—maximum; $\bar{x}$—mean; s—standard deviation; CV—coefficient of variation; AFD—airflow direction; N—North indication; dimensions in meters (m).

For the average THI values by time of day, low spatial variability was observed, with the greatest average amplitudes occurring during the morning and afternoon periods (ΔTHI > 2.00). The maps revealed that the average thermal conditions remained approximately homogeneous across the AOZ, except for the Northwest region of the CBP system, where the calculated THI was higher than that in the other regions of the facility (Southeast and Central) during the morning and afternoon (Figures 10c, 10d, 10e and 10f).

When analyzing the thermal environment based on the THI ranges cited by Hahn (1999), it was observed that during winter, the average conditions were maintained at levels considered normal (Figures 10a, 10c, 10e, and 10g), even falling below 72.00, a value deemed by many authors as the UTCL for high-producing dairy cows (Könyves et al., 2017; Herbut et al., 2018; Bleizgys et al., 2022).

For the absolute maximum THI values recorded during winter (Figure 11c), levels exceeding 74.00 were only observed in a small area at the Northwestern end of the CBP system under study, specifically in the feeding alley. Therefore, these values are considered to be of limited representativeness. Thus, based on these results, it can be inferred that throughout the winter, thermally comfortable conditions for the animals were maintained across the entire AOZ.

In contrast, it was observed that the average THI during summer afternoons remained above 74.00 throughout the entire AOZ of the studied CBP system (Figure 10f), thus exceeding the normal range. These conditions were even more challenging during times with absolute maximum values (Figures 11c and 11d), where, in the worst case, THI values exceeded 77.00 across the entire AOZ (alert to danger conditions; Figure 11d).

The average results for THI reported in this study, during the morning and afternoon periods (Figures 10c, 10d, 10e, and 10f), corroborate with those obtained by Mota et al. (2019), who analyzed thermal conditions in an open-sided CBP system with low-volume and high-rotation fans in the South of Minas Gerais, during winter and summer periods. With the ventilation system in operation (the same condition as in this study), the authors observed that average THI values were below 74.00 during the mornings and afternoons in winter. However, the thermal conditions during summer afternoons were considered thermally stressful in some areas of the CBP system (THI ≥ 74.00), although they were characterized as normal thermal comfort conditions during the morning.

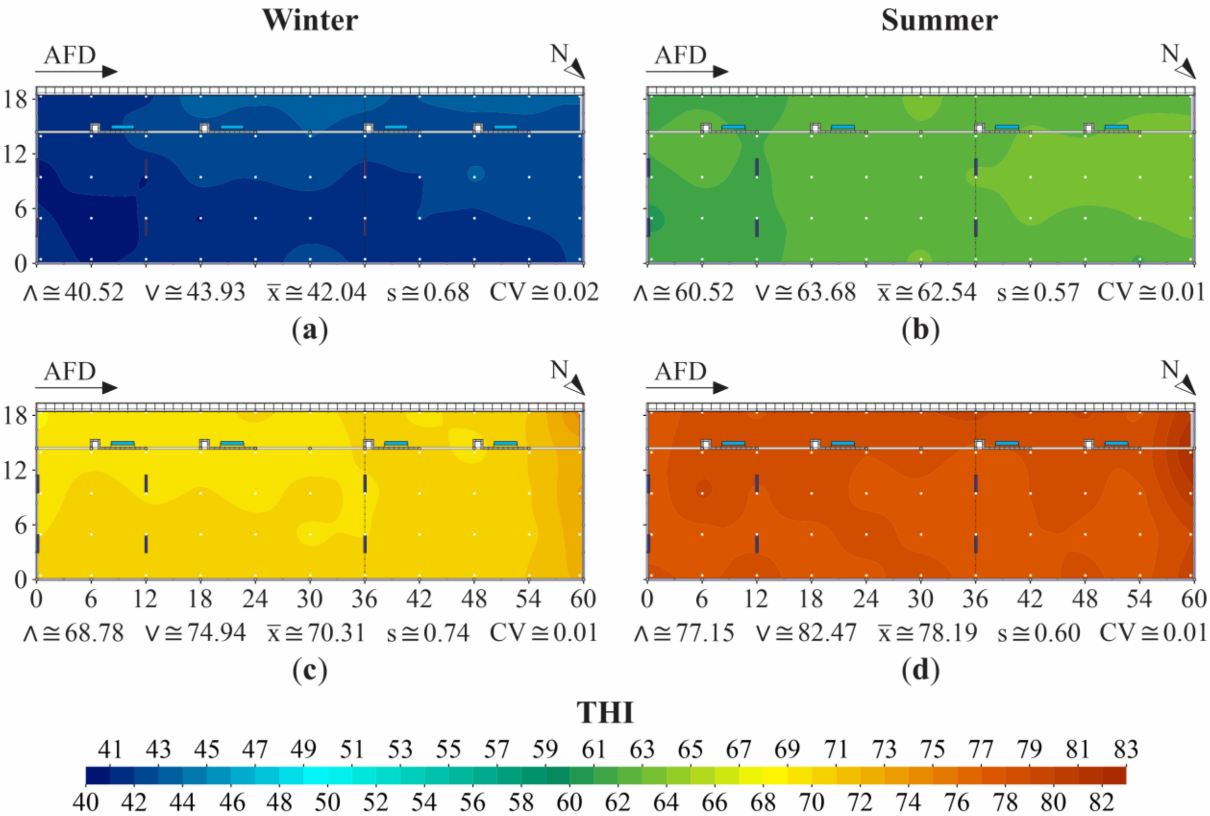

Figure 11. Spatial distribution of Temperature and Humidity Index (THI) inside the Compost-Bedded Pack Barn under study: **(a)** absolute minimum values and **(c)** absolute maximum values in winter; and **(b)** absolute minimum values and **(d)** absolute maximum values in summer. ∧—minimum; ∨—maximum; x̄—mean; s—standard deviation; CV—coefficient of variation; AFD—airflow direction; N—North indication; dimensions in meters (m).

The average THI results also align with those reported by Andrade et al. (2022) for a closed CBP system, which used evaporative cooling pads combined with negative-pressure mechanical ventilation and is located in the same study region (Zona da Mata, Minas Gerais, Brazil). These authors mapped the thermal conditions and found that the average THI values were always below 74.00 during winter. However, they observed average values exceeding this threshold across the entire area of the CBP system during summer afternoons.

Since the housed animals were high-producing dairy cows (30.00 to 35.00 kg·animal^{-1}·day^{-1}), it can be inferred that the elevated THI values observed during summer afternoons (Figures 10f and 11d) may have negatively affected their dry matter intake (Baumgard & Rhoads, 2013; Collier et al., 2019), as well as their lying time, which could be reduced by up to 3.30 hours per day, as suggested by Nordlund et al. (2019). It is also plausible to infer that the reduction in average daily milk production per animal observed during the summer period (Table 1) may be due to physiological and behavioral responses to heat stress, as outlined by Gunn et al. (2019) and Tao et al. (2020). For high-producing dairy cows (> 30.00 kg·day^{-1}), this reduction may be attributed to multiple factors, including decreased dry matter and water intake, as well as reduced milk synthesis, as the animals attempt to lower their heat production (Collier et al., 2019).

In addition to affecting dry matter intake, resting time and milk production, it is important to note that thermal stress conditions, such as those observed in this study during summer afternoons (Figures 10f and 11d), can also trigger health and reproductive issues in the animals. According to Tao et al. (2020), typical summer environmental conditions are often associated with an increase in clinical mastitis incidence and somatic cell count. This is attributed to the greater growth of environmental pathogens, combined with the negative impact of thermal stress on immune function. As animals tend to stand for longer periods under heat stress conditions, there is often an increase in the incidence of hoof problems (such as lesions, white line disease, interdigital hyperplasia, etc.) and lameness, issues frequently become apparent only after some time (Polsky & Von Keyserlingk, 2017; Biasato et al., 2019; Reuscher et al., 2023). In addition, heat stress can negatively impact reproductive indices (Sammad et al., 2020; Tao et al., 2020; Rodríguez-Godina et al., 2024), a condition that is often only observed several months later.

3.4. Recommendations for improving the thermal environment in the Compost-Bedded Pack Barn system

Based on the results obtained and the analyses conducted under various conditions in the studied CBP system (Figures 4-11) and aiming to address the specific extreme climatic scenarios depicted in this research (winter and summer), several suggestions for adjustments and/or improvements have been proposed. These suggestions and/or recommendations were designed to adapt the studied CBP system to meet the thermal needs of the Holstein dairy cows housed there, and/or to serve as a starting point for adjustments in other existing systems and/or new CBP projects, provided that the local climatic and geographical specifics are considered.

In situations like the studied CBP system, where the longitudinal axis was oriented Northwest-Southeast (Figure 1), it is recommended to construct closure structures (wood, metal, fiber cement, etc.), either fixed or movable, at the upper part of the gable. The aim is to reduce the direct entry of solar radiation and, consequently, the average values of t_{db} and THI (Baêta & Souza, 2010; Oliveira et al., 2022). Alternatively, and complementarily, planting deciduous trees (which shed their leaves at the beginning of winter) near the Northwest side of the CBP system could be considered. Provided that the lower trunks are pruned, these trees will not obstruct natural ventilation but will shade the area that receives direct solar radiation during the hottest periods. Consequently, this will help achieve better thermal conditions in that region (De Masi et al., 2021; Pons et al., 2023). It is important to note that the implementation of the latter solution (planting vegetation strips) requires a thorough preliminary study. This study should address aspects such as the type and size of trees to be used, considering the region's climate and soil, and the distance of the vegetation strips from the facility, among other factors.

Values of $t_{db} \geq 29.00$ °C were recorded on all monitored days during the summer, and this condition was not limited to the Northwest region of the CBP system (Figures 5a and 7d). It was therefore found that merely adopting the strategies intended for winter, which aimed to improve the environment in the Northwest region of the CBP system, was not sufficient to improve the thermal conditions. In this case, it would be necessary to consider other methods to improve the thermal environment, such as installing additional fans along the bedding area and feeding alley, increasing the overall ventilation rate, and/or using evaporative cooling methods.

Based on the results depicted for average data (Figures 6f and 10f) and maximum absolute values of t_{db} and THI (Figure 7d and 11f), it was observed that values above 24.00 °C and 74.00, respectively, were prevalent throughout the entire AOZ during summer afternoons. Therefore, it became evident that simply increasing the ventilation rate in this CBP system would not be sufficient to ensure comfortable thermal conditions for the Holstein dairy cows housed in the CBP system under study during this period. Therefore, it was concluded that the use of animal body cooling methods (such as water sprinkling) and/or evaporative air cooling (such as water misting), when combined with well-designed and managed mechanical ventilation systems, would be the most suitable strategy for hotter periods in CBP systems similar to the one evaluated.

In the CBP system under study, animal body cooling via a parallel water sprinkling line positioned next to the cows' feeding troughs was carried out whenever the t_{db} exceeded 24.00 °C. However, it was observed that the t_{db} values in the feeding alley were only minimally affected by the evaporation of water droplets falling onto the floor when this system was in operation, which occurred during the summer in the late morning and throughout the afternoon (Figures 6e, 6f, and 7d). This happened because the fans in the facility were only distributed in the bedding area of the CBP under study, which, due to the presence of guardrails around the water troughs, typically results in the formation of areas with low airspeed in the feeding alley (Oliveira et al., 2023). Certainly, the absence of fans in the feeding alley limited the potential for cooling both the animals and the environment through water spraying, as ventilation is essential for promoting air movement over the animals' bodies and the floor, and for enhancing the evaporation of the sprayed water droplets (Fournel et al., 2017; Polsky & Von Keyserlingk, 2017; Arcidiacono, 2018). Additionally, it can be inferred that cooling the animals in the feeding alley as it was done may not be sufficient to mitigate the adverse effects of heat stress during extremely hot periods. Therefore, it would be necessary to either redesign this body cooling system or combine it with air cooling methods during the hottest periods of the day throughout the year.

A third alternative to improve the thermal environment during hot periods in this CBP system would be to enclose the installation and use wetted cellulose pads, necessarily in combination with negative-pressure mechanical ventilation systems. This setup channels and moves the entire air volume with greater uniformity and pressure through the action of exhaust fans. This air-cooling method aims to force hot air through a wetted porous material pad. As the air passes through the wetted pad, simultaneous heat and mass exchange occurs: sensible heat is converted into latent heat and used for the phase change of water (reducing t_{db}); and some of the water in the air is converted into vapor (increasing RH). The result of these simultaneous exchanges is the reduction of the t_{db} that exits the wetted pads and is carried throughout the installation by the exhaust system (Mrema et al., 2011; Fournel et al., 2017; Andrade et al., 2024). However, it is important to note that the use of evaporative cooling systems for reducing t_{db}, whether through misting or wetted pads, is primarily recommended for hot and dry periods (when RH is lower), as a gradient in vapor pressure between the air entering and exiting the wetted pad is necessary (Harner et al., 2009; Arcidiacono, 2018). In addition, when using evaporative cooling methods in CBP systems, it is essential to increase the available bedding area per animal, as there is a tendency for increased moisture in the compost bedding (Oliveira et al., 2021; Andrade et al., 2024).

4. Conclusions

In this study, data collected using a low-cost embedded system were used to characterize the temporal and spatial behavior of thermal environment variables and indices [dry-bulb air temperature (t_{db}, in °C); relative humidity (RH, in %); and Temperature-Humidity Index (THI)] in an open CBP system with positive-pressure ventilation, during winter and summer periods in Brazil. The findings were as follows:

In winter, the average environmental conditions of t_{db} and THI were considered thermally comfortable for lactating dairy cows, despite the occurrence of t_{db} peaks and elevated levels of RH. During summer, the average values of t_{db} and THI remained above 24.00 °C and 74.00, respectively, from 9:10 a.m. to 6:30 p.m., which were characterized as thermally stressful for the housed animals. However, within this time frame, there was a trend of decreasing RH (≤ 80.00 %).

Using geostatistical techniques to characterize the spatial dependence of the variables of interest in various scenarios (by period: dawn, morning, afternoon and night; and in extreme conditions: minimum and maximum absolute values of t_{db} and RH), it was observed that there was strong spatial dependence, allowing the generation of distribution maps for these variables. The generated maps revealed that there was heterogeneity in the distribution of t_{db}, RH and THI throughout the animals occupied zone in the CBP system. Spatial variability was higher during daytime periods (morning and afternoon) and at times of extreme conditions.

Based on the results presented, it can be concluded that the thermal protection methods used in the studied CBP system (positive-pressure mechanical ventilation combined with water sprinkler along the feeding line) were insufficient to ensure homogeneous and thermally comfortable conditions for the housed Holstein dairy cows, particularly during the hot summer afternoons. Therefore, it can be inferred that it is necessary to resize these methods and/or use additional animal cooling techniques and/or air-cooling methods during the hottest times of the day and year to meet the thermal needs of the animals.

Declaration of competing interest

The authors declare to have no conflicts of interest.

Funding

This work was supported by the: National Council for Scientific and Technological Development, Brazil (CNPq; project number 422912/2018-2); Coordination of Superior Level Staff Improvement, Brazil (CAPES; finance Code 001); and Research Supporting Foundation of Minas Gerais State, Brazil (FAPEMIG; Finance Code 001).

Acknowledgments

The authors would like to thank the following for their financial support of this project: the National Council for Scientific and Technological Development (CNPq, Brazil); the Coordination of Superior Level Staff Improvement (CAPES, Brazil); and the Research Supporting Foundation of Minas Gerais State (FAPEMIG, Brazil).

Appendix A – Calibration curves for the DHT22 sensors that comprised the embedded system used for monitoring the thermal environment in the Compost-Bedded Pack Barn

Table A1. Calibration curves obtained for the DHT22 sensors that comprised the embedded system used for monitoring the thermal environment in the Compost-Bedded Pack Barn system.

Sensor	Dry-bulb air temperature (t_{db})		Relative humidity (RH)	
	Equation	R^2	Equation	R^2
1	$t_{db\text{-}Adj} = 0.7537 \cdot t_{db\text{-}R} + 2.5482$	0.9746	$RH_{Adj} = 0.9094 \cdot RH_R + 2.4945$	0.9685
2	$t_{db\text{-}Adj} = 0.7652 \cdot t_{db\text{-}R} + 2.5025$	0.9727	$RH_{Adj} = 0.9456 \cdot RH_R - 2.4435$	0.9771
3	$t_{db\text{-}Adj} = 0.7938 \cdot t_{db\text{-}R} + 1.8508$	0.9778	$RH_{Adj} = 0.9262 \cdot RH_R - 2.4946$	0.9787
4	$t_{db\text{-}Adj} = 0.7836 \cdot t_{db\text{-}R} + 1.7469$	0.9765	$RH_{Adj} = 0.9204 \cdot RH_R + 1.6783$	0.9787
5	$t_{db\text{-}Adj} = 0.8216 \cdot t_{db\text{-}R} + 1.6044$	0.9804	$RH_{Adj} = 0.8582 \cdot RH_R + 1.5946$	0.9695
6	$t_{db\text{-}Adj} = 0.9013 \cdot t_{db\text{-}R} + 0.7191$	0.9816	$RH_{Adj} = 1.0081 \cdot RH_R - 6.8639$	0.9790
7	$t_{db\text{-}Adj} = 0.9153 \cdot t_{db\text{-}R} + 0.5547$	0.9802	$RH_{Adj} = 1.1801 \cdot RH_R - 24.408$	0.9733
8	$t_{db\text{-}Adj} = 0.9068 \cdot t_{db\text{-}R} + 0.3220$	0.9816	$RH_{Adj} = 1.1809 \cdot RH_R - 22.444$	0.9288
9	$t_{db\text{-}Adj} = 0.9067 \cdot t_{db\text{-}R} + 0.3482$	0.9889	$RH_{Adj} = 1.0204 \cdot RH_R - 9.0888$	0.9761
10	$t_{db\text{-}Adj} = 0.8539 \cdot t_{db\text{-}R} +1.5322$	0.9804	$RH_{Adj} = 1.0168 \cdot RH_R + 8.9198$	0.9855
11	$t_{db\text{-}Adj} = 0.9189 \cdot t_{db\text{-}R} + 0.5240$	0.9810	$RH_{Adj} = 1.1351 \cdot RH_R - 16.352$	0.9917
12	$t_{db\text{-}Adj} = 0.9284 \cdot t_{db\text{-}R} + 0.6750$	0.9805	$RH_{Adj} = 1.0948 \cdot RH_R - 16.639$	0.9798
13	$t_{db\text{-}Adj} = 0.9253 \cdot t_{db\text{-}R} + 0.0879$	0.9789	$RH_{Adj} = 1.0211 \cdot RH_R - 12.561$	0.9823
14	$t_{db\text{-}Adj} = 0.9005 \cdot t_{db\text{-}R} + 0.6915$	0.9872	$RH_{Adj} = 0.9802 \cdot RH_R - 9.4452$	0.9816
15	$t_{db\text{-}Adj} = 0.8694 \cdot t_{db\text{-}R} + 1.3275$	0.9799	$RH_{Adj} = 1.0134 \cdot RH_R - 11.409$	0.9856
16	$t_{db\text{-}Adj} = 0.9277 \cdot t_{db\text{-}R} + 0.7873$	0.9830	$RH_{Adj} = 1.1184 \cdot RH_R - 20.527$	0.9815
17	$t_{db\text{-}Adj} = 0.9279 \cdot t_{db\text{-}R} + 0.2991$	0.9804	$RH_{Adj} = 1.2398 \cdot RH_R - 30.023$	0.9852
18	$t_{db\text{-}Adj} = 0.9285 \cdot t_{db\text{-}R} + 0.4795$	0.9791	$RH_{Adj} = 1.1164 \cdot RH_R - 18.294$	0.9888
19	$t_{db\text{-}Adj} = 0.8995 \cdot t_{db\text{-}R} + 0.5891$	0.9857	$RH_{Adj} = 1.0216 \cdot RH_R - 11.148$	0.9905
20	$t_{db\text{-}Adj} = 0.8611 \cdot t_{db\text{-}R} + 1.4975$	0.9737	$RH_{Adj} = 1.2139 \cdot RH_R - 27.851$	0.9887
21	$t_{db\text{-}Adj} = 0.9464 \cdot t_{db\text{-}R} + 0.4159$	0.9779	$RH_{Adj} = 1.2080 \cdot RH_R - 27.993$	0.9791
22	$t_{db\text{-}Adj} = 0.9447 \cdot t_{db\text{-}R} + 0.4105$	0.9782	$RH_{Adj} = 1.2727 \cdot RH_R - 32.147$	0.9825
23	$t_{db\text{-}Adj} = 0.9316 \cdot t_{db\text{-}R} + 0.6428$	0.9780	$RH_{Adj} = 1.0272 \cdot RH_R - 7.0332$	0.9899
24	$t_{db\text{-}Adj} = 0.8901 \cdot t_{db\text{-}R} + 1.2578$	0.9808	$RH_{Adj} = 1.0548 \cdot RH_R - 12.509$	0.9854
25	$t_{db\text{-}Adj} = 0.8751 \cdot t_{db\text{-}R} + 1.4145$	0.9826	$RH_{Adj} = 1.1630 \cdot RH_R - 24.294$	0.9813

Table A1. *Continuation.*

Sensor	Dry-bulb air temperature (t_{db})		Relative humidity (RH)	
	Equation	R^2	Equation	R^2
26	$t_{db\text{-}Adj} = 0.9601 \cdot t_{db\text{-}R} - 0.0063$	0.9745	$RH_{Adj} = 1.0260 \cdot RH_R - 6.9375$	0.9857
27	$t_{db\text{-}Adj} = 0.9405 \cdot t_{db\text{-}R} + 0.7319$	0.9793	$RH_{Adj} = 1.0696 \cdot RH_R - 15.738$	0.9830
28	$t_{db\text{-}Adj} = 0.9240 \cdot t_{db\text{-}R} + 0.3840$	0.9791	$RH_{Adj} = 1.1473 \cdot RH_R - 22.956$	0.9819
29	$t_{db\text{-}Adj} = 0.9058 \cdot t_{db\text{-}R} + 1.0860$	0.9854	$RH_{Adj} = 1.0427 \cdot RH_R - 15.139$	0.9834
30	$t_{db\text{-}Adj} = 0.8669 \cdot t_{db\text{-}R} - 1.5592$	0.9832	$RH_{Adj} = 1.1377 \cdot RH_R - 11.453$	0.9773
31	$t_{db\text{-}Adj} = 0.9770 \cdot t_{db\text{-}R} - 0.0086$	0.9722	$RH_{Adj} = 1.2049 \cdot RH_R - 25.813$	0.9755
32	$t_{db\text{-}Adj} = 0.9466 \cdot t_{db\text{-}R} + 0.5894$	0.9796	$RH_{Adj} = 0.9710 \cdot RH_R - 11.285$	0.9338
33	$t_{db\text{-}Adj} = 0.9315 \cdot t_{db\text{-}R} + 0.6602$	0.9788	$RH_{Adj} = 1.0682 \cdot RH_R - 15.226$	0.9787
34	$t_{db\text{-}Adj} = 0.9079 \cdot t_{db\text{-}R} + 0.7816$	0.9859	$RH_{Adj} = 1.1824 \cdot RH_R - 25.563$	0.9847
35	$t_{db\text{-}Adj} = 0.8682 \cdot t_{db\text{-}R} + 1.4586$	0.9843	$RH_{Adj} = 0.9528 \cdot RH_R - 5.2431$	0.9849
36	$t_{db\text{-}Adj} = 0.9908 \cdot t_{db\text{-}R} - 0.1879$	0.9783	$RH_{Adj} = 1.0916 \cdot RH_R - 14.711$	0.9743
37	$t_{db\text{-}Adj} = 0.9566 \cdot t_{db\text{-}R} + 0.4404$	0.9810	$RH_{Adj} = 1.1064 \cdot RH_R - 16.967$	0.9704
38	$t_{db\text{-}Adj} = 0.9191 \cdot t_{db\text{-}R} + 0.5877$	0.9816	$RH_{Adj} = 1.0945 \cdot RH_R - 11.555$	0.9791
39	$t_{db\text{-}Adj} = 0.9101 \cdot t_{db\text{-}R} + 0.7754$	0.9873	$RH_{Adj} = 0.9947 \cdot RH_R - 10.818$	0.9360
40	$t_{db\text{-}Adj} = 0.8731 \cdot t_{db\text{-}R} + 1.3869$	0.9850	$RH_{Adj} = 1.0296 \cdot RH_R - 5.3328$	0.9802
41	$t_{db\text{-}Adj} = 0.9732 \cdot t_{db\text{-}R} + 0.6118$	0.9846	$RH_{Adj} = 1.0001 \cdot RH_R - 8.5347$	0.9686
42	$t_{db\text{-}Adj} = 0.9745 \cdot t_{db\text{-}R} + 0.2066$	0.9794	$RH_{Adj} = 1.1552 \cdot RH_R - 30.174$	0.9240
43	$t_{db\text{-}Adj} = 0.9127 \cdot t_{db\text{-}R} + 1.1926$	0.9814	$RH_{Adj} = 1.0722 \cdot RH_R - 15.271$	0.9725
44	$t_{db\text{-}Adj} = 0.9114 \cdot t_{db\text{-}R} + 1.0636$	0.9836	$RH_{Adj} = 0.9942 \cdot RH_R - 9.3188$	0.9749
45	$t_{db\text{-}Adj} = 0.8748 \cdot t_{db\text{-}R} + 1.4462$	0.9825	$RH_{Adj} = 0.9548 \cdot RH_R - 2.6107$	0.9757
46	$t_{db\text{-}Adj} = 0.9563 \cdot t_{db\text{-}R} + 0.5488$	0.9852	$RH_{Adj} = 0.9804 \cdot RH_R - 7.9585$	0.9694
47	$t_{db\text{-}Adj} = 0.9860 \cdot t_{db\text{-}R} + 0.0824$	0.9821	$RH_{Adj} = 1.0390 \cdot RH_R - 11.573$	0.9709
48	$t_{db\text{-}Adj} = 0.9282 \cdot t_{db\text{-}R} + 0.6633$	0.9803	$RH_{Adj} = 1.1384 \cdot RH_R - 13.574$	0.9506
49	$t_{db\text{-}Adj} = 0.9242 \cdot t_{db\text{-}R} + 0.7245$	0.9891	$RH_{Adj} = 1.0996 \cdot RH_R - 18.539$	0.9747
50	$t_{db\text{-}Adj} = 0.8838 \cdot t_{db\text{-}R} + 1.4488$	0.9862	$RH_{Adj} = 0.9708 \cdot RH_R - 4.2192$	0.9754
51	$t_{db\text{-}Adj} = 0.9853 \cdot t_{db\text{-}R} + 0.6378$	0.9847	$RH_{Adj} = 1.0589 \cdot RH_R - 10.780$	0.9613
52	$t_{db\text{-}Adj} = 0.9945 \cdot t_{db\text{-}R} + 0.2702$	0.9852	$RH_{Adj} = 1.0832 \cdot RH_R - 13.591$	0.9607
53	$t_{db\text{-}Adj} = 0.9789 \cdot t_{db\text{-}R} + 0.4313$	0.9835	$RH_{Adj} = 1.0536 \cdot RH_R - 10.890$	0.9663
54	$t_{db\text{-}Adj} = 0.9601 \cdot t_{db\text{-}R} + 0.4122$	0.9827	$RH_{Adj} = 1.0126 \cdot RH_R - 9.3971$	0.9635
55	$t_{db\text{-}Adj} = 0.9340 \cdot t_{db\text{-}R} + 0.4523$	0.9855	$RH_{Adj} = 1.0929 \cdot RH_R - 11.233$	0.9691

$t_{db\text{-}Adj}$— dry-bulb air temperature adjusted value; $t_{db\text{-}R}$— dry-bulb air temperature value read by the DHT22 sensor; RH_{Adj}— relative humidity adjusted value; RH_R—relative humidity value read by the DHT22 sensor; R^2— coefficient of determination.

Annex A – Certificate of approval by the Ethics Committee on Animal Use

CERTIFICADO

A Comissão de Ética no Uso de Animais - CEUA/UFV certifica que o processo nº 04/2021, intitulado "**Avaliação e caracterização de sistema de confinamento de bovinos leiteiros em instalação *compost barn* aberta e semiclimatizada via ventilação por pressão positiva**", coordenado pela professora Ilda de Fátima Ferreira Tinôco do Departamento de Engenharia Agrícola, está de acordo com a Legislação vigente (Lei Nº 11.794, de 08 de outubro de 2008), as Resoluções Normativas editadas pelo CONCEA/MCTIC, a DBCA (Diretriz Brasileira de Prática para o Cuidado e a Utilização de Animais para Fins Científicos e Didáticos) e as Diretrizes da Prática de Eutanásia preconizadas pelo CONCEA/MCTIC, portanto sendo aprovado definitivamente em 16/05/2022.

CERTIFICATE

The Ethic Committee in Animal Use/UFV certify that the process number 04/2021, named **"Evaluation and characterization of a dairy cattle feedlot system in an open and semi-climatic compost barn facility via positive pressure ventilation",**, is in agreement with the a ctual Brazilian legislation (Lei Nº 11.794, 2008), Normative Resolutions edited by CONCEA/MCTIC, the DBCA (Brazilian Practice Guideline for the Care and Use of Animals for Scientific Purposes and Teaching) and the Guidelines of Practice the Euthanasia recommended by CONCEA/ MCTIC therefore being definitive approved on May 16, 2022.

Fabricio Luciani Valente

Prof. Fabrício Luciani Valente
Coordenador
Comissão de Ética no Uso de Animais – CEUA/UFV

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GENERAL CONCLUSIONS

This study aimed to elucidate aspects of the environment in Compost-Bedded Pack Barn (CBP) systems by characterizing and evaluating indicators of thermal comfort, animal health, and the physicochemical quality of compost bedding.

Based on the methodology of this study and using the systematic data on health and thermal comfort indicators of dairy cows housed in Compost-Bedded Pack Barn (CBP) systems, compared to Free Stall (FS), Loose Housing (LH), and/or Tie-Stall (TS) systems, the following conclusions can be drawn:

- The incidence of health problems such as lameness, limb injuries, and reproductive disorders is significantly lower in CBP systems;
- An increase in somatic cell count and the prevalence of mastitis may occur if bedding management is not efficient in providing dry, comfortable, and healthy surfaces for the housed animals; and
- Higher temperatures in summer and lower temperatures in winter were observed inside CBP systems with open sides and positive-pressure ventilation, compared to FS-CV systems (negative-pressure ventilation combined with evaporative padding cooling).

Regarding the indicators of the physicochemical quality of compost bedding in CBP systems, characterized under different conditions through a comprehensive systematic literature review, it can be concluded that:

- External environmental conditions affect the physicochemical bedding quality, with the composting process being less intense and more challenging during the winter; and
- To keep the composting process active, it is necessary to adopt more efficient and intensive management practices during winter, such as increasing the frequency of bedding replacement with dry material, more frequent turning, using aeration systems under the bedding, installing side closures, among other measures.

From the review of the state of the art on the use of Computational Fluid Dynamics (CFD) for analyzing heat and mass transfer in CBP systems for dairy cattle, it was found that:

- So far, few studies have used CFD to model internal conditions in CBP systems. However, it has been found that this tool provides a better understanding of heat and mass transfer phenomena within such systems; and
- The use of CFD tools appears promising for evaluating the thermal environment and the compost bedding process in CBP systems. It could contribute to the re-engineering of existing CBP installations and the proper design of new facilities of this type.

Based on the field experiment's conduct and the results obtained for thermal environment variables (dry-bulb air temperature—t_{db}; relative humidity—RH; and Temperature-Humidity Index—THI) within a typical CBP system (with open sides and positive-pressure ventilation) during different periods (winter and summer) in a mesothermal subtropical climate region in Brazil, it can be concluded that:

- During winter, the average thermal conditions inside the CBP housing were maintained within the comfort range for lactating dairy cows ($t_{db} \leq 24.00$ °C; THI ≤ 74.00), despite the prevalence of high RH values;
- During the summer, the average thermal conditions inside the CBP system were unsuitable for lactating Holstein dairy cows, especially between 9:10 a.m. and 6:30 p.m., when the average t_{db} and THI remained above 24.00 °C and 74.00, respectively;
- In the summer, the average RH values recorded during the period identified as heat stress (RH $\leq$ 80.00 %) indicate that there was potential for more efficient use of evaporative cooling systems;
- Using maps generated with geostatistical techniques, it was observed that there was heterogeneity in the distribution of t_{db}, RH, and THI across the area of the CBP system under study, particularly during the morning and afternoon periods, and at times of absolute minimum and maximum values;
- The methods used to improve the thermal environment in the CBP system under study were insufficient to maintain homogeneous and thermally comfortable conditions for the Dutch dairy cows housed there, particularly during the hot summer afternoons. This indicates that the system was either poorly designed and/or inadequately managed; and

- In open CBP systems, such as the one studied, thermal control is always more challenging. Special attention must be given to the design of environmental thermal control systems, as well as to the management of these systems and the bedding. Adjustments should be made according to the time of day and the season.

SUGGESTIONS FOR THE FUTURE

This study has facilitated the summarization, analysis, and interpretation of results related to thermal comfort, animal health, and the physicochemical quality of bedding in open CBP systems, particularly in the context of Brazilian conditions. It is important to note, however, that further studies—whether experimental or involving modelling tools—on CBP systems with various construction types, climatic and/or geographical conditions, environmental thermal conditioning systems, bedding materials, and management practices, are highly relevant for advancing knowledge and building the still nascent database in this field of animal production, both in Brazil and globally.