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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

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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].

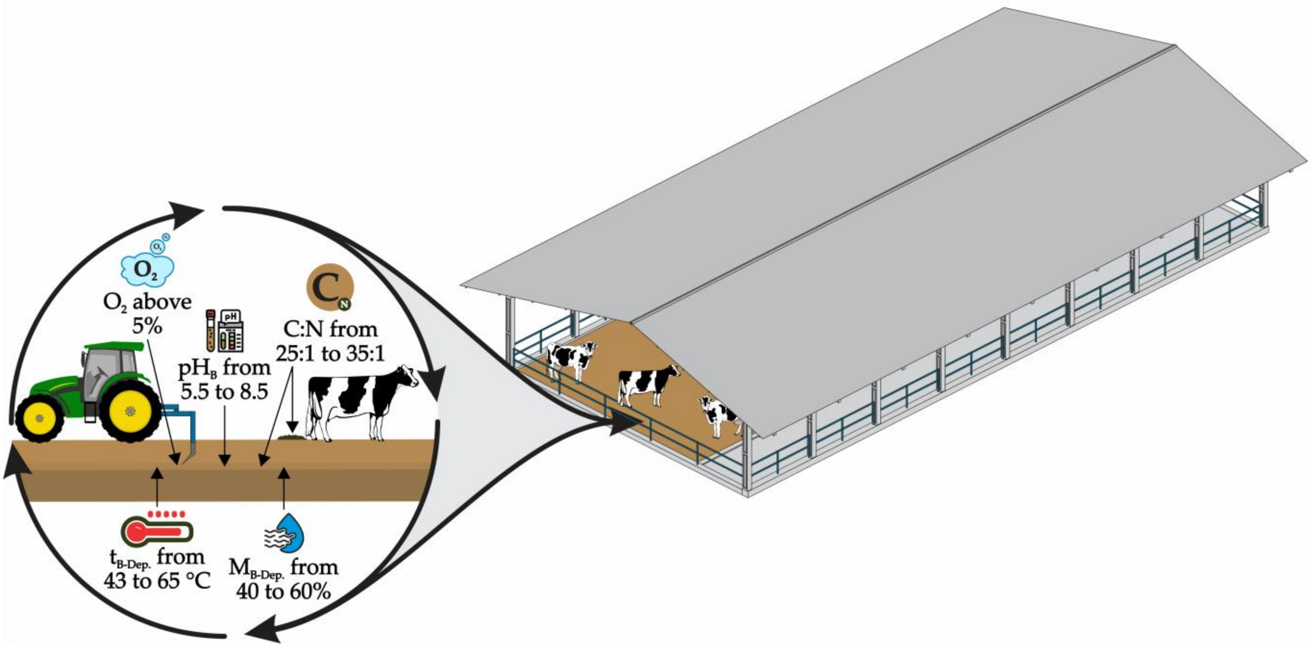

Figure 1. Schematic representation of the bedding composting process in a compost-bedded pack barn system (emphasis on the bedding turning). C:N—carbon:nitrogen ratio; $M_{B\text{-}Dep.}$—moisture in the aerobically active layer; O_2—oxygen available; pH_B—bedding hydrogen potential; and $t_{B\text{-}Dep.}$—temperature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

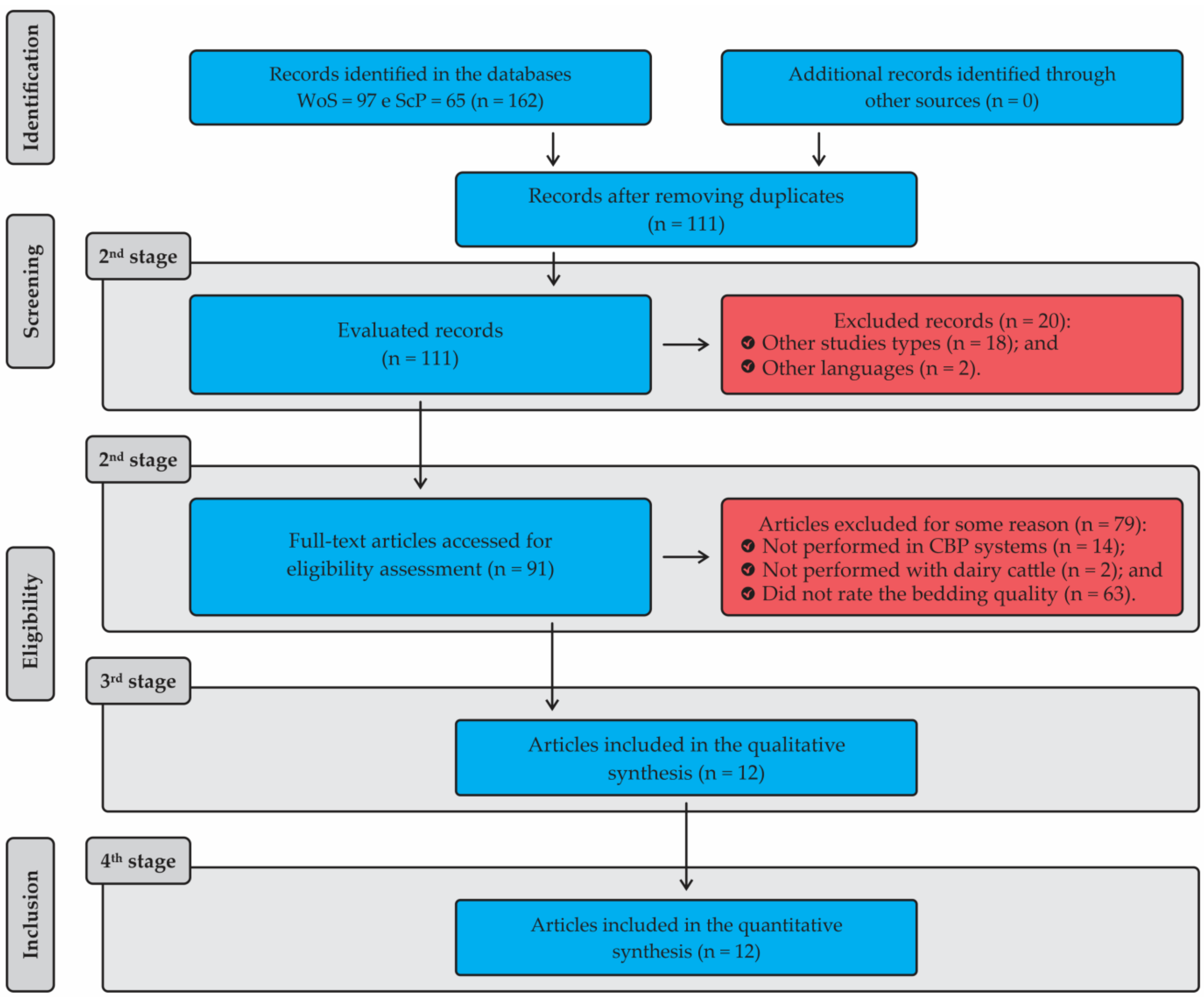

Figure 2. Information flow indicates the number of studies identified and filtered at each stage of the systematic review process. Source: Adapted from Moher et al. [35].

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.

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.

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
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.

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].

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	VM [9]	—	7.7–40.6 [4]	—	—	—	8.5–8.9 [4]	0.61–0.89 [4]	0.15–0.26 [4,5]	0.78–1.92 [4,5]	12.70–20.10 [4]	16.0–26.0 [4]
	Summer		—	31.8–48.1 [4]	—	—	—	8.7–9.1 [4]	0.89–1.23 [4]	0.29–0.43 [4,5]	1.42–2.27 [4,5]	15.30–17.40 [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	HW+ VW	—	32.0–39.0 [13]	45.8 [11]	—	8.3 [11]	—	2.80 [11]	—	—	6.70 [11]	2.4 [11]
	Summer		—	21.1–35.0 [13]	39.3 [11]	—	8.9 [11]	—	2.40 [11]	—	—	5.80 [11]	2.4 [11]
	Fall		—	29.2–33.1 [13]	59.2 [11]	—	8.9 [11]	—	4.40 [11]	—	—	15.50 [11]	3.5 [11]
Giambra et al. [31] [14]	Winter	Sa., WC, OM [15]	—	31.1–34.8 [10]	—	50.2–50.3 [10]	—	—	—	—	—	—	—
	Spring		—	34.0–36.1 [10]	—	65.3–68.8 [10]	—	—	—	—	—	—	—
	Summer		—	40.2–42.1 [10]	—	62.5–64.2 [10]	—	—	—	—	—	—	—
	Fall		—	46.3–56.3 [10]	—	48.2–56.8 [10]	—	—	—	—	—	—	—
de Boer and Wiersma [32] [16]	Fall [17]	WC	—	18.0–52.8 [21]	—	48.7–51.1 [22]	—	5.5–6.8 [13]	0.33–0.44 [13]	0.04–0.05 [13]	0.15–0.26 [13]	25.20–27.40 [13]	60.0–77.0 [13]
	Winter [18]		—	43.7–53.2 [21]	—	42.2–55.7 [22]	—	7.4–8.6 [13]	0.52–0.75 [13]	0.07–0.09 [13]	0.38–0.80 [13]	22.90–28.50 [13]	31.0–51.0 [13]
	Spring [19]		—	46.1–53.5 [21]	—	50.6–55.7 [22]	—	7.7–8.8 [13]	0.69–1.29 [13]	0.10–0.19 [13]	0.63–1.50 [13]	20.80–24.40 [13]	18.0–35.0 [13]
	Summer [20]		—	43.7–49.4 [21]	—	53.1 [22]	—	9.0 [13,23]	1.25 [13,23]	0.19 [13,23]	1.56 [13,23]	22.00 [13,23]	18.0 [13,23]
Llonch et al. [29] [24]	Fall	Sa.	—	34.7 ± 5.6 [25]	—	54.1 ± 17.0 [25]	—	8.0 [25,26]	0.96 [25,26]	0.24 [25,26]	1.22 [25,26]	46.08 [25,26,27]	48.0 [25,26]
	Winter		—	31.2 ± 5.9 [25]	—	55.0 ± 16.4 [25]	—	9.0 [25,26]	1.12 [25,26]	0.28 [25,26]	1.78 [25,26]	44.80 [25,26,27]	40.0 [25,26]
	Fall	FB	—	28.3 ± 6.9 [25]	—	62.0 ± 14.0 [25]	—	8.4 [25,26]	1.19 [25,26]	0.28 [25,26]	1.64 [25,26]	41.65 [25,26,27]	35.0 [25,26]
	Winter		—	25.9 ± 3.1 [25]	—	59.4 ± 7.2 [25]	—	7.8 [25,26]	1.24 [25,26]	0.25 [25,26]	1.62 [25,26]	43.40 [25,26,27]	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	CH + WC	22.0–27.0 [32]	30.0–47.0 [10]	44.0–58.0	46.0–61.0 [10]	8.7–10.1	8.7–10.0 [10]	1.12–1.32 [33]	0.20–0.34 [33]	1.76–2.10 [33]	17.49–18.59 [33]	14.46–16.17 [33]
	Winter		13.8–17.8 [32]	23.0–44.0 [10]	57.0–65.0	58.0–66.0 [10]	8.8–9.3	8.8–9.1 [10]	1.43–1.74 [33]	0.15—0.27 [33]	1.46—2.56 [33]	16.63–31.44 [33]	11.63–19.14 [33]
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·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.

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.

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.

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References

1. Saitone, T.L.; Sexton, R.J. Agri-Food Supply Chain: Evolution and Performance with Conflicting Consumer and Societal Demands. *Eur. Rev. Agric. Econ.* **2017**, *44*, 634–657. https://doi.org/10.1093/ERAE/JBX003.
2. Symeonaki, E.; Arvanitis, K.G.; Piromalis, D.; Tseles, D.; Balafoutis, A.T. Ontology-Based IoT Middleware Approach for Smart Livestock Farming toward Agriculture 4.0: A Case Study for Controlling Thermal Environment in a Pig Facility. *Agronomy* **2022**, *12*, 750. https://doi.org/10.3390/AGRONOMY12030750.
3. Bewley, J.M.; Robertson, L.M.; Eckelkamp, E.A. A 100-Year Review: Lactating Dairy Cattle Housing Management. *J. Dairy Sci.* **2017**, *100*, 10418–10431. https://doi.org/10.3168/JDS.2017-13251.
4. Andrade, R.R.; Tinôco, I.F.F.; Damasceno, F.A.; Ferraz, G.A.S.; Freitas, L.C.S.R.; Ferreira, C.F.S.; Barbari, M.; Baptista, F.J.F.; Coelho, D.J.R. Spatial Distribution of Bed Variables, Animal Welfare Indicators, and Milk Production in a Closed Compost-Bedded Pack Barn with a Negative Tunnel Ventilation System. *J. Therm. Biol.* **2022**, *105*, 103111. https://doi.org/10.1016/j.jtherbio.2021.103111.
5. Biasato, I.; D'Angelo, A.; Bertone, I.; Odore, R.; Bellino, C. Compost Bedded-Pack Barn as an Alternative Housing System for Dairy Cattle in Italy: Effects on Animal Health and Welfare and Milk and Milk Product Quality. *Ital. J. Anim. Sci.* **2019**, *18*, 1142–1153. https://doi.org/10.1080/1828051X.2019.1623095.
6. Arshad, J.; Rehman, A.U.; Othman, M.T.B.; Ahmad, M.; Tariq, H.B.; Khalid, M.A.; Moosa, M.A.R.; Shafiq, M.; Hamam, H. Deployment of Wireless Sensor Network and IoT Platform to Implement an Intelligent Animal Monitoring System. *Sustainability* **2022**, *14*, 6249. https://doi.org/10.3390/SU14106249.
7. Leso, L.; Barbari, M.; Lopes, M.A.; Damasceno, F.A.; Galama, P.; Taraba, J.L.; Kuipers, A. Invited Review: Compost-Bedded Pack Barns for Dairy Cows. *J. Dairy Sci.* **2020**, *103*, 1072–1099. https://doi.org/10.3168/jds.2019-16864.
8. Llonch, L.; Castillejos, L.; Mainau, E.; Manteca, X.; Ferret, A. Effect of Forest Biomass as Bedding Material on Compost-Bedded Pack Performance, Microbial Content, and Behavior of Nonlactating Dairy Cows. *J. Dairy Sci.* **2020**, *103*, 10676–10688. https://doi.org/10.3168/jds.2020-18496.
9. Peixoto, M.S.M.; Barbosa Filho, J.A.D.; Machado, N.A.F.; Viana, V.S.S.; Costa, J.F.M. Thermoregulatory Behavior of Dairy Cows Submitted to Bedding Temperature Variations in Compost Barn Systems. *Biol. Rhythm Res.* **2021**, *52*, 1120–1129. https://doi.org/10.1080/09291016.2019.1616904/FORMAT/EPUB.
10. Guesine, G.D.; Silveira, R.M.F.; Silva, I.J.O. Physical and Environmental Characteristics of the Compost Barn System and Its Effects on the Physical Integrity, Reproduction and Milk Production of Dairy Cattle: A Scoping Review. *J. Anim. Behav. Biometeorol.* **2023**, *11*, 2023010. https://doi.org/10.31893/JABB.23010.
11. Black, R.A.; Taraba, J.L.; Day, G.B.; Damasceno, F.A.; Bewley, J.M. Compost Bedded Pack Dairy Barn Management, Performance, and Producer Satisfaction. *J. Dairy Sci.* **2013**, *96*, 8060–8074. https://doi.org/10.3168/jds.2013-6778.
12. Eckelkamp, E.A.; Taraba, J.L.; Akers, K.A.; Harmon, R.J.; Bewley, J.M. Understanding Compost Bedded Pack Barns: Interactions among Environmental Factors, Bedding Characteristics, and Udder Health. *Livest. Sci.* **2016**, *190*, 35–42. https://doi.org/10.1016/j.livsci.2016.05.017.
13. Damasceno, F.A. Processo de Compostagem. In *Compost Barn Como uma Alternativa para a Pecuária Leiteira*; Gulliver: Divinópolis, Brazil, 2020; pp. 127–147.

14. Stentiford, E.I. Composting Control: Principles and Practice. In *The Science of Composting*; Springer: Dordrecht, The Netherlands, 1996; pp. 49–59.
15. Epstein, E. *Industrial Composting: Environmental Engineering and Facilities Management*, 1st ed.; CRC Press Inc.: Boca Raton, FL, USA, 2011.
16. Valente, B.S.; Xavier, E.G.; Morselli, T.B.G.A.; Jahnke, D.S.; Brum, B., Jr.; Cabrera, B.R.; Moraes, P.; Lopes, D.C.N. Fatores Que Afetam o Desenvolvimento Da Compostagem de Resíduos Orgânicos. *Arch. Zootec.* **2009**, *58*, 59–85. https://doi.org/10.21071/az.v58i224.5074.
17. Pedrosa, T.D.; Farias, C.A.S.; Pereira, R.A.; Farias, E.T.R. Monitoramento Dos Parâmetros Físico-Químicos Na Compostagem de Resíduos Agroindustriais. *Nativa* **2013**, *1*, 44–48. https://doi.org/10.14583/2318-7670.v01n01a08.
18. Fávero, S.; Portilho, F.V.R.; Oliveira, A.C.R.; Langoni, H.; Pantoja, J.C.F. Factors Associated with Mastitis Epidemiologic Indexes, Animal Hygiene, and Bulk Milk Bacterial Concentrations in Dairy Herds Housed on Compost Bedding. *Livest. Sci.* **2015**, *181*, 220–230. https://doi.org/10.1016/j.livsci.2015.09.002.
19. Shane, E.M.; Endres, M.I.; Janni, K.A. Alternative Bedding Materials for Compost Bedded Pack Barns in Minnesota: A Descriptive Study. *Appl. Eng. Agric.* **2010**, *26*, 465–473.
20. Pereira Neto, J.T. *Manual de Compostagem*; UNICEF: Belo Horizonte, Brazil, 1996; Volume 1.
21. Rodrigues, M.S.; Silva, F.C.; Barreira, L.P.; Kovacs, A. Compostagem: Reciclagem de Resíduos Sólidos Orgânicos. In *Gestão de Resíduos na Agricultura e Agroindústria*; Spadotto, C.A., Ribeiro, W.C., Eds.; FEPAF: Botucatu, Brazil, 2006; pp. 63–94.
22. Hanajima, D.; Kuroda, K.; Morishita, K.; Fujita, J.; Maeda, K.; Morioka, R. Key Odor Components Responsible for the Impact on Olfactory Sense during Swine Feces Composting. *Bioresour. Technol.* **2010**, *101*, 2306–2310. https://doi.org/10.1016/j.biortech.2009.11.026.
23. Sharma, V.K.; Canditelli, M.; Fortuna, F.; Cornacchia, G. Processing of Urban and Agro-Industrial Residues by Aerobic Composting: Review. *Energy Convers. Manag.* **1997**, *38*, 453–478. https://doi.org/10.1016/S0196-8904(96)00068-4.
24. Cotta, J.A.O.; Carvalho, N.L.C.; Brum, T.S.; Rezende, M.O.O. Compostagem versus Vermicompostagem: Comparação Das Técnicas Utilizando Resíduos Vegetais, Esterco Bovino e Serragem. *Eng. Sanit. Ambient.* **2015**, *20*, 65–78. https://doi.org/10.1590/S1413-41522015020000111864.
25. El Kader, N.; Robin, P.; Paillat, J.; Leterme, P. Turning, Compacting and the Addition of Water as Factors Affecting Gaseous Emissions in Farm Manure Composting. *Bioresour. Technol.* **2007**, *98*, 2619–2628. https://doi.org/10.1016/j.biortech.2006.07.035.
26. Guesine, G.D.; Silveira, R.M.F.; Silva, I.J.O. Spatial Modeling via Geostatistics of the Bed in a Compost Barn System: Thermal Performance Assessments. *Int. J. Biometeorol.* **2023**, *1*, 1–14. https://doi.org/10.1007/S00484-023-02538-9/FIGURES/5.
27. Oliveira, C.E.A.; Tinôco, I.F.F.; Oliveira, V.C.; Rodrigues, P.H.M.; Silva, L.F.; Damasceno, F.A.; Andrade, R.R.; Sousa, F.C.; Barbari, M.; Bambi, G. Spatial Distribution of Bedding Attributes in an Open Compost-Bedded Pack Barn System with Positive Pressure Ventilation in Brazilian Winter Conditions. *Animals* **2023**, *13*, 786. https://doi.org/10.3390/ANI13050786.
28. Oliveira, C.E.A.; Damasceno, F.A.; Ferraz, G.A.S.; Nascimento, J.A.C.; Vega, F.A.O.; Titôco, I.F.F.; Andrade, R.R. Assessment of Spatial Variability of Bedding Variables in Compost Bedded Pack Barns with Climate Control System. *An. Acad. Bras. Cienc.* **2021**, *93*, 20200384. https://doi.org/10.1590/0001-3765202120200384.
29. Llonch, L.; Gordo, C.; López, M.; Castillejos, L.; Ferret, A.; Balanyà, T. Agronomic Characteristics of the Compost-Bedded Pack Made with Forest Biomass or Sawdust. *Processes* **2021**, *9*, 546. https://doi.org/10.3390/PR9030546.
30. Barberg, A.E.; Endres, M.I.; Janni, K.A. Compost Dairy Barns in Minnesota: A Descriptive Study. *Appl. Eng. Agric.* **2007**, *23*, 231–238.
31. Giambra, I.J.; Jahan, Y.; Yin, T.; Engel, P.; Weimann, C.; Brügemann, K.; König, S. Identification of Thermophilic Aerobic Sporeformers in Bedding Material of Compost-Bedded Dairy Cows Using Microbial and Molecular Methods. *Animals* **2021**, *11*, 2890. https://doi.org/10.3390/ANI11102890/S1.
32. De-Boer, H.C.; Wiersma, M. Thermophilic Composting of the Pack Can Reduce Nitrogen Loss from Compost-Bedded Dairy Barns. *Biosyst. Eng.* **2021**, *210*, 20–32. https://doi.org/10.1016/J.BIOSYSTEMSENG.2021.07.015.
33. Nogara, K.F.; Busanello, M.; Haygert-Velho, I.M.P.; Zopollatto, M.; Frigeri, K.D.-M.; Almeida, P.S.G. Characterization and Relationship between Bulk Tank Milk Composition and Compostbedded Variables from Dairy Barns in Rio Grande Do Sul State, Brazil. *Turkish J. Vet. Anim. Sci.* **2021**, *45*, 890–900. https://doi.org/10.3906/vet-2101-85.
34. Freu, G.; Garcia, B.L.N.; Tomazi, T.; Di Leo, G.S.; Gheller, L.S.; Bronzo, V.; Moroni, P.; Dos Santos, M.V. Association between Mastitis Occurrence in Dairy Cows and Bedding Characteristics of Compost-Bedded Pack Barns. *Pathogens* **2023**, *12*, 583. https://doi.org/10.3390/PATHOGENS12040583.
35. Moher, D.; Liberati, A.; Tetzlaff, J.; Altman, D.G. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *Int. J. Surg.* **2010**, *8*, 336–341. https://doi.org/10.1016/J.IJSU.2010.02.007.
36. Silva, G.G.B.S.; Ferraz, P.F.P.; Damasceno, F.A.; Zotti, M.L.A.N.; Barbari, M. Compost Barns: A Bibliometric Analysis. *Animals* **2022**, *12*, 2492. https://doi.org/10.3390/ANI12192492.
37. Vitorino Filho, V.A.; Goi, M.Y.O. Supply Chain Management 4.0: Content Analysis in the Most Relevant Articles from Scopus and Web of Science Databases. *Brazilian J. Dev.* **2021**, *7*, 117868–117889. https://doi.org/10.34117/BJDV7N12-511.
38. Frigeri, K.D.M.; Deniz, M.; Damasceno, F.A.; Barbari, M.; Herbut, P.; Vieira, F.M.C. Effect of Heat Stress on the Behavior of Lactating Cows Housed in Compost Barns: A Systematic Review. *Appl. Sci.* **2023**, *13*, 2044. https://doi.org/10.3390/APP13042044.
39. Whiting, P.; Savović, J.; Higgins, J.P.T.; Caldwell, D.M.; Reeves, B.C.; Shea, B.; Davies, P.; Kleijnen, J.; Churchill, R. ROBIS: A New Tool to Assess Risk of Bias in Systematic Reviews Was Developed. *J. Clin. Epidemiol.* **2016**, *69*, 225–234. https://doi.org/10.1016/J.JCLINEPI.2015.06.005.
40. Janni, K.A.; Endres, M.I.; Reneau, J.K.; Schoper, W.W. Compost Dairy Barn Layout and Management Recommendations. *Appl. Eng. Agric.* **2007**, *23*, 97–102. https://doi.org/10.13031/2013.22333.

41. Black, R.A.; Taraba, J.L.; Day, G.B.; Damasceno, F.A.; Newman, M.C.; Akers, K.A.; Wood, C.L.; McQuerry, K.J.; Bewley, J.M. The Relationship between Compost Bedded Pack Performance, Management, and Bacterial Counts. *J. Dairy Sci.* **2014**, *97*, 2669–2679. https://doi.org/10.3168/JDS.2013-6779.
42. Galama, P.J.; de Boer, H.C.; van Dooren, H.J.C.; Ouweltjes, W.; Poelarends, J.J. *Vrijloopstallen Voor Melkvee in de Praktijk*; Wageningen UR Livestock Research: Lelystad, The Netherlands, 2014.
43. Nääs, I.A. *Princípios de Conforto Térmico Na Produção Animal*, 1st ed.; Ícone: São Paulo, Brazil, 1989.
44. Mondaca, M.R.; Choi, C.Y.; Cook, N.B. Understanding Microenvironments within Tunnel-Ventilated Dairy Cow Freestall Facilities: Examination Using Computational Fluid Dynamics and Experimental Validation. *Biosyst. Eng.* **2019**, *183*, 70–84. https://doi.org/10.1016/j.biosystemseng.2019.04.014.
45. Guerra-Galdo, E.H.; Sanz, S.C.; Barber, F.E.; López-Jiménez, P.A. CFD Model for Ventilation Assessment in Poultry Houses with Different Distribution of Windows. *Int. J. Energy Environ.* **2015**, *6*, 411–424.
46. Lobeck, K.M.; Endres, M.I.; Shane, E.M.; Godden, S.M.; Fetrow, J. Animal Welfare in Cross-Ventilated, Compost-Bedded Pack, and Naturally Ventilated Dairy Barns in the Upper Midwest. *J. Dairy Sci.* **2011**, *94*, 5469–5479. https://doi.org/10.3168/JDS.2011-4363.
47. Norton, T.; Sun, D.-W.; Grant, J.; Fallon, R.; Dodd, V. Applications of Computational Fluid Dynamics (CFD) in the Modelling and Design of Ventilation Systems in the Agricultural Industry: A Review. *Bioresour. Technol.* **2007**, *98*, 2386–2414. https://doi.org/10.1016/J.BIORTECH.2006.11.025.
48. Morais, J.M.d.S.C.; Labaki, L.C. CFD Como Ferramenta Para Simular Ventilação Natural Interna Por Ação Dos Ventos: Estudos de Caso Em Tipologias Verticais Do "Programa Minha Casa, Minha Vida". *Ambient. Construído* **2017**, *17*, 223–244. https://doi.org/10.1590/s1678-86212017000100133.
49. Damasceno, F.A.; Ferraz, G.A.S. Materiais e Manejo Da Cama. In *Compost Barn Como uma Alternativa para a Pecuária Leiteira*; Gulliver: Divinópolis, Brazil, 2020; pp. 95–123.
50. Rynk, R.; van-de-Kamp, M.; Willson, G.B.; Singley, M.E.; Richard, T.L.; Kolega, J.J.; Gouin, F.R.; Laliberty, L.; Kay, D.; Murphy, D.W.; et al. *On-Farm Composting Handbook (NRAES 54)*; Northeast Regional Agricultural Engineering Service: Ithaca, NY, USA, 1992.
51. Sundberg, C.; Smårs, S.; Jönsson, H. Low PH as an Inhibiting Factor in the Transition from Mesophilic to Thermophilic Phase in Composting. *Bioresour. Technol.* **2004**, *95*, 145–150. https://doi.org/10.1016/J.BIORTECH.2004.01.016.
52. Yang, F.; Li, G.X.; Yang, Q.Y.; Luo, W.H. Effect of Bulking Agents on Maturity and Gaseous Emissions during Kitchen Waste Composting. *Chemosphere* **2013**, *93*, 1393–1399. https://doi.org/10.1016/J.CHEMOSPHERE.2013.07.002.
53. Misra, R.V.; Roy, R.N.; Hiraoka, H. *On-Farm Composting Methods*; UN-FAO: Rome, Italy, 2003.
54. Galama, P.J. *On Farm Development of Bedded Pack Dairy Barns in The Netherlands*; Wageningen UR Livestock Research: Lelystad, NL, USA, 2014.
55. Qian, P.; Schoenau, J.J. Availability of Nitrogen in Solid Manure Amendments with Different C:N Ratios. *Can. J. Soil Sci.* **2002**, *82*, 219–225. https://doi.org/10.4141/S01-018.
56. Leonard, J. Composting: An Alternative Approach to Manure Management. *Adv. Dairy Technol.* **2001**, *13*, 441.
57. Lobeck, K.M.; Endres, M.I.; Janni, K.A.; Godden, S.M.; Fetrow, J. Environmental Characteristics and Bacterial Counts in Bedding and Milk Bulk Tank of Low Profile Cross-Ventilated, Naturally Ventilated, and Compost Bedded Pack Dairy Barns. *Appl. Eng. Agric.* **2012**, *28*, 117–128. https://doi.org/10.13031/2013.41280.
58. Burgstaller, J.; Raith, J.; Kuchling, S.; Mandl, V.; Hund, A.; Kofler, J. Claw Health and Prevalence of Lameness in Cows from Compost Bedded and Cubicle Freestall Dairy Barns in Austria. *Vet. J.* **2016**, *216*, 81–86. https://doi.org/10.1016/j.tvjl.2016.07.006.
59. Costa, J.H.C.; Burnett, T.A.; von-Keyserlingk, M.A.G.; Hötzel, M.J. Prevalence of Lameness and Leg Lesions of Lactating Dairy Cows Housed in Southern Brazil: Effects of Housing Systems. *J. Dairy Sci.* **2018**, *101*, 2395–2405. https://doi.org/10.3168/JDS.2017-13462.
60. Bran, J.A.; Costa, J.H.C.; von-Keyserlingk, M.A.G.; Hötzel, M.J. Factors Associated with Lameness Prevalence in Lactating Cows Housed in Freestall and Compost-Bedded Pack Dairy Farms in Southern Brazil. *Prev. Vet. Med.* **2019**, *172*, 104773. https://doi.org/10.1016/J.PREVETMED.2019.104773.
61. Emanuelson, U.; Brügemann, K.; Klopčič, M.; Leso, L.; Ouweltjes, W.; Zentner, A.; Blanco-Penedo, I. Animal Health in Compost-Bedded Pack and Cubicle Dairy Barns in Six European Countries. *Animals* **2022**, *12*, 396. https://doi.org/10.3390/ANI12030396/S1.
62. Witkowska, D.; Ponieważ, A. The Effect of Housing System on Disease Prevalence and Productive Sifespan of Dairy Herds: A Case Study. *Animals* **2022**, *12*, 1610. https://doi.org/10.3390/ANI12131610.
63. Kogima, P.d.A.; Diesel, T.A.; Vieira, F.M.C.; Schogor, A.L.B.; Volpini, A.A.; Veloso, G.J.; Ferraz, P.F.P.; Zotti, M.L.A.N. The Welfare of Dairy Cows in Pasture, Free Stall, and Compost Barn Management Systems in a Brazilian Subtropical Region. *Animals* **2022**, *12*, 2215. https://doi.org/10.3390/ANI12172215.