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Review

Feedstock Characterization for Enhanced Heat Recovery from Composting Processes: A Review

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Abstract: Compost Heat Recovery Systems (CHRS) sustainably capture heat from composting waste biomass, helping reduce greenhouse gas emissions and fossil fuel reliance. The choice of feedstock affects the performance of CHRSs as it controls the microbial activities and the amount of heat generated. This review evaluates plant-based, animal-derived, and non-agricultural feedstocks to optimize CHRS energy recovery. A systematic review of 244 studies, published from 1996 to 2023 and available on Scopus, Web of Science, and external databases, categorized feedstocks based on properties like carbon-nitrogen ratio (C/N), moisture content, bulk density, and heating value to assess their impact on energy recovery and compost quality. The review followed the PRISMA guidelines, excluding irrelevant documents and those that lacked quantitative data. Animal-based materials, which have high levels of moisture and nutrients, such as nitrogen (14.50–32.20 g/kg TS) and phosphorus (13.0–13.5 g/kg TS), promote rapid growth of microbes and consistent heat production supported by their stable carbon content (353.8–450.0 g/kg TS) and optimal C/N ratios (5.90–28.90). On the other hand, plant-based materials that are rich in volatile solids (327.2–960.0 g/kg TS) and lignin (36.7–290.0 g/kg TS) offer a steady and prolonged release of heat but decompose more slowly.

Keywords: compost heat recovery systems; thermocompost; waste-to-energy ratio; feedstocks; energy recovery; agricultural waste

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1. Introduction

Compost Heat Recovery Systems (CHRSs) represent an eco-friendly approach aimed at capturing the heat generated during the composting of organic waste. This waste management technique supports global sustainability goals by reducing greenhouse gas (GHG) emissions while also reducing dependency on fossil fuels and optimizing resource usage. As organic matter breaks down in composting by microbes, heat is released, and this heat can be effectively captured and utilized for various purposes, such as heating spaces, warming water, and generating electricity when managed efficiently in compost systems. A research project explored a thermoelectric heat recovery system with 120 thermoelectric generators (TEGs), producing 11.3 volts and powering an LED strip while charging supercapacitors and operating sensors over 33 days [1], demonstrating the potential for electricity generation from compost heat.

The ranges of potential thermal power output from CHRSs were reviewed by Malesani et al., who reported values ranging from 0.02 to 0.23 kW/m^3 depending on plant size, biomass type, and biodegradation duration [2]. For real-scale systems (≥30 m^3) operating over one year, the output ranges from 0.05 to 0.1 kW/m^3. For instance, a 55 m^3 plant can generate 2.75–5.5 thermal kW. An average plant using woodchips, running 12 h daily at 0.1 kW/m^3, could produce approximately 24,000 kWh of thermal energy annually. However, these values are provided without accounting for the heat recovery efficiency of the current design of CHRS, a critical yet underexplored parameter that needs further investigation.

CHRSs can be seen as an important process in facilitating the European Union's sustainability aspirations based on the EU Directive 2018/2001 [3] along with the upcoming Common Agricultural Policy (CAP) 2021–2027 [4] with main targets of reducing the overall annual GHG emissions and encouraging the usage of energy produced from renewable sources. CHRSs comply with these targets directly, as these systems can result in the reduction in GHG emissions and advance the benefit of renewable energy, reducing the reliance on heating systems based on fossil fuels as they can capture and reuse thermal energy produced from composting systems [5].

In addition, the CAP 2021–2027 further underscores the importance of sustainable agriculture practices and the usage of renewable energy in rural areas. The adoption of CHRSs will encourage sustainable organic waste management and GHG reduction, as well as providing renewable energy sources up to the farm level, which will support agricultural practices to meet the larger sustainability and climate change mitigation trends expected from the EU. A recent study in Northern Italy described the performance of a large-scale CHRS fed with tree-pruning residues [5]. The research findings indicated that the heat supply costs of these systems were competitive when compared to fossil fuel sources while also leading to carbon emission reductions. The cost per unit of energy from the system was 0.087 EUR/kWh, which decreased to 0.074 EUR/kWh with the installation of two CHRS units. Moreover, it was observed that significant carbon savings up to 0.252 $kgCO_{2\text{-}eq}$/kWh could be achieved by saving energy and promoting carbon sequestration in lands. This emphasizes the advantages of employing CHRSs for energy recovery and as a climate change mitigation strategy.

CHRS applications contribute to the achievement of part of the United Nations Sustainable Development Goals (SDGs) [6]. Specifically, CHRS provides renewable energy that is clean and environmentally friendly, contributing to SDG 7 (Affordable and Clean Energy) by providing a sustainable energy source while reducing reliance on fossil fuels. Additionally, the reduction in greenhouse gas emissions due to compost heat recovery contributes to SDG 13 (Climate Action) by mitigating climate change impacts. Sustainable waste management contributes to the achievement of SDG 12 (Responsible Consumption and Production) by promoting sustainable waste management and resource recovery. In addition, the compost used in agricultural practices increases the soil's nutrient contents, thus assisting in the achievement of SDG 2 (Zero Hunger) by enhancing soil fertility and supporting sustainable agricultural practices. By addressing these interconnected goals, CHRS presents a promising approach to advancing global sustainability.

The success and overall efficiency of CHRSs depend on the types and compositions of the materials used as feedstocks. Selecting feedstock is critical as it directly influences heat generation, reaction rates, and the overall energy output during composting. Different organic materials decompose at varying speeds, leading to different heat generation rates, highlighting the importance of choosing feedstocks to optimize energy recovery in CHRSs. Factors such as moisture content, carbon-to-nitrogen (C/N) ratio, and biodegradability play a role in determining how effectively heat is produced and the quality of compost generated.

Further exploration into the thermal properties of materials used in composting highlights their impact on temperature and biodegradation throughout the composting cycle. Ahn et al. [7] found that well-defined thermal properties of compost materials such as thermal conductivity, thermal diffusivity, and volumetric heat capacity play a vital role in practical thermodynamic strategies. These properties differ based on the type of material used, bulk density, particle size, and water content. Therefore, understanding these characteristics can assist in choosing the most efficient feedstock materials for sustainable waste management practices leading to enhanced temperature control and energy reclamation [7]. When it comes to choosing the materials for composting, one key factor to consider is the ability to deactivate pathogenic microorganisms. Cekmecelioglu et al. [8] investigated how to optimize feedstocks in a vessel composting setup to lower the presence of microorganisms. Their research showed that an ideal mix comprising 50% food waste, 40% manure, and 10% bulking agents led to reaching maximum temperatures that effectively decreased pathogens, like *Salmonella* and *Escherichia coli*. This research emphasizes the significance of feedstock selection for composting not for energy generation only but also for ensuring the safety and quality of the resulting compost [8].

The performance levels of the feedstocks in CHRSs are also subject to some of the parameters considered. The potential energy available, correctly termed as the lower heating value (LHV) of a feedstock, is vital when optimizing the recovery of heat. Nitrogen content parameters, as well as the C/N ratio, determine the necessary conditions for close-to-optimal microbial activity, which in turn facilitates the process of composting and, therefore, the generation of heat. Bulk density has a direct effect on the airflow and insulation within the compost pile, which significantly influences the rates of heat retention as well as the decomposition rates. The moisture content is essential for the development of microorganisms and the generation of heat, whereas volatile solids could be defined as the fraction of organic matter that is potentially biodegradable and, therefore, fuels energy generation. Proper understanding and adjustment of these parameters is critical for increasing heat generation and, therefore, efficiency during CHRS usage, adequately ensuring that the systems satisfy both energy and environmental targets. The primary goal of this study is to systematically review and synthesize findings on selecting the optimum feedstock to improve the effectiveness of CHRSs. Various research works have shown that specific materials can greatly boost heat production, efficiency, and overall usefulness of CHRSs.

However, to the authors' best knowledge, no previous studies have thoroughly explored how the specific properties of feedstocks can be exploited to optimize the heat production in CHRSs. Tackling this gap, this review collected available data on how different types of agricultural feedstocks, both plant-based or animal-derived, can affect the performance of heat production through CHRSs. By presenting an analysis of these results, this review aims to offer guidance on making appropriate feedstock choices, thus propelling the development of CHRSs. This target responds to one of the research questions of TEAPOTS, a Horizon Europe project funded by the European Union [9], which aims at providing farmers and operators of the agri-food sector with solutions for the local valorization of biomass residues. By enhancing efficiencies and lowering environmental impacts, CHRSs can play a role in promoting sustainable waste management practices and renewable energy.

2. Materials and Methods

This systematic critical review methodology was conducted to assess how different feedstocks affect CHRSs. The study's approach involves detailed search methods, strict selection criteria, thorough data extraction, and solid data synthesis. Each step of the methodology is customized to guarantee a thorough examination of the literature on feedstocks that enhance the efficiency and energy recovery potential of CHRSs.

2.1. Search Strategy

The stepwise procedure for literature source selection, as shown in Figure 1, was based on the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) guidelines [10].

In order to conduct a comprehensive literature review, well-known academic databases were consulted, such as the Elsevier Bibliographic Database (Scopus) and Web of Science (WOS). To expand the coverage and capture a diverse range of studies, this approach was enhanced by incorporating information from external sources, i.e., the Stichting Biomeiler company [11]. The investigation was designed to cover a range of CHRS aspects by using an advanced search query that combined different key terms and Boolean operators. The following keywords included were combined with Boolean operators to create a well-structured search string that guarantees the inclusion of all relevant literature: "compost", "feedstock", "biomass", "agricultural waste", "energy recovery", "heat recovery", and "waste-to-energy".

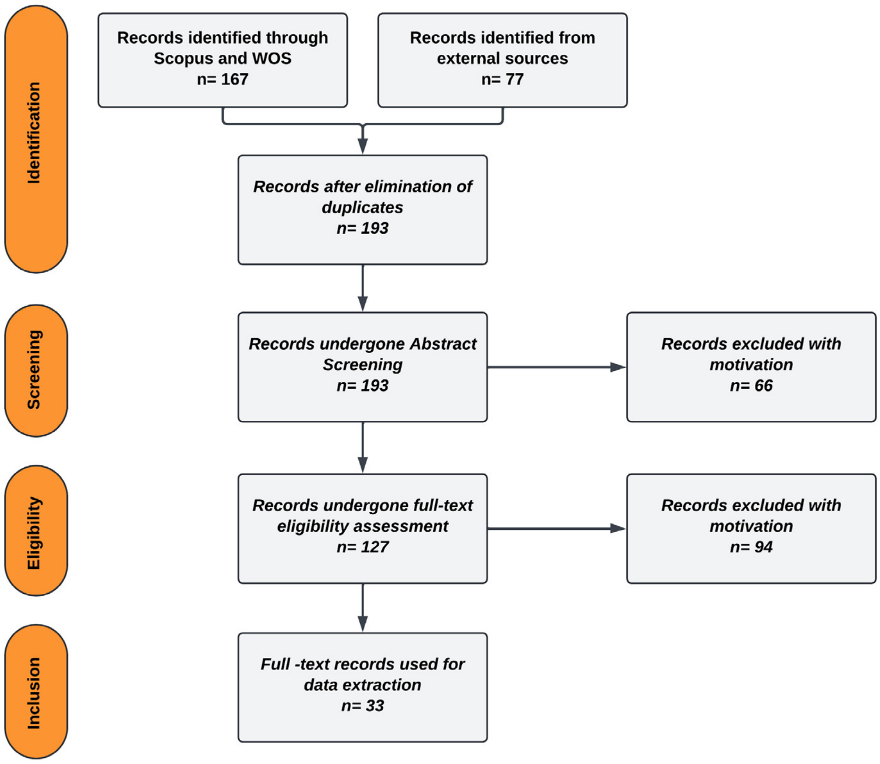

Figure 1. Flow diagram showing the stepwise procedure followed for the performance of the systematic critical review.

2.2. Selection Criteria

The process of selecting the studies was carefully organized to make sure that only the research papers most relevant to the scope of this study were included. At first, all the articles that were collected were screened for duplicates, with 51 duplicates found, which were removed directly. The remaining articles underwent a multi-tier screening process in the following screening stages, as shown in Figure 1:

1. Abstract screening: During this phase, the articles were carefully assessed based on their abstracts to determine how relevant they were to the goal of this review, i.e., if they contained reference to CHRS feedstocks. The screening criteria focused on studies that explored how different feedstocks affect CHRSs. The results of this evaluation were documented, noting reasons for including or excluding each article to ensure a systematic review process.
2. Full-text screening: Articles that passed the abstract screening were subjected to a detailed full-text examination. The selection process at this stage focused on the completeness of the data, the soundness of the studies, and their alignment with the goals of the review. Like the abstract screening phase, every decision regarding whether to include or exclude an article was carefully documented. Papers were excluded for various reasons. For example, studies lacking quantitative data on feedstock characteristics—such as heating values (kJ/kg), moisture content, carbon, and nitrogen contents—were excluded. Additionally, articles focused on economic or environmental analysis without relevant thermal data or those centered around unrelated processes like anaerobic digestion or combustion were removed. Broad discussions on waste management or circular bioeconomy principles without specific details on composting feedstocks were also excluded. These examples illustrate the rigorous screening process, ensuring only the most relevant studies were included.

2.3. Data Extraction

The list of papers included in the subsequent data extraction is included in the Supplementary Material Table S1. Data were carefully gathered using a structured form created to collect all relevant information from the chosen studies. This form is shown in Table 1.

Table 1. Data extraction categories and descriptions.

Data Category	Description
Reference	Internal code for data management.
Feedstock	Specific type of organic material used in the composting process.
Feedstock source	The origin of the feedstock.
Moisture content (MC)	Percentage of water content in the feedstock.
Bulk density	Mass of compost material per unit volume.
Elemental composition	Content of carbon (C), nitrogen (N), phosphorus (P), and potassium (K).
C:N ratio	Ratios indicating carbon-to-nitrogen dynamics.
Other nutrients	Additional nutrients impacting composting process quality that may be extracted.
Organic components	Levels of lignin, cellulose, and hemicellulose.
pH	Acidity or alkalinity of the compost.
LHV, total organic carbon (TOC), and volatile solids (VS)	Energy content and total carbon measures.

2.4. Data Categorization

In order to organize the data extracted in a proper manner and to better frame the discussion of the results, a classification system was utilized based on the predominant material composition of each feedstock. The first category pertains to “Feedstocks with a predominance of plant-based materials”, encompassing those primarily sourced from plants or containing a mix where plant-based materials are most prevalent. The second category, “Feedstocks with a predominance of animal-derived materials”, encompasses materials primarily sourced from animal origin or containing a mix where animal-derived content is predominant. The third category is “Non-agricultural feedstocks”, which deals with a wide array of inputs from non-agricultural feedstock sources that are not primarily made up of plant or animal materials. While “Non-agricultural feedstocks” (NA) are not suitable for composting or CHRSs due to their mixed composition that may include waste other than biomass, they often undergo aerobic stabilization before thermal treatment or disposal. It was decided to include this category anyway in this review because (1) they provide useful data on key parameters, offering valuable comparisons with plant- and animal-based feedstocks, which help gaining a deeper understanding of how they can be used and what characteristics they possess; and (2) to highlight that many researchers use the term “compost” even when aerobically treating mixed waste, whose reference processes are other mechanical-biological treatments like bio-drying or biostabilization.

This method of categorization allows for a clear examination of the feedstocks based on their primary components and is summarized in Table 2, which outlines the number of feedstocks in each category.

Table 2. Feedstock categorization and number.

Feedstock Category	Description	Number of Feedstocks
Feedstocks with a predominance of plant-based materials (PBM)	This category includes feedstocks derived primarily from plant materials such as agricultural residues, forestry residues, and energy crops. It also encompasses mixed waste streams where plant-based materials are the predominant component.	57
Feedstocks with a predominance of animal-derived materials (ABM)	This category consists of feedstocks primarily composed of animal-based materials, such as pig manure, horse manure, and other animal processing by-products. It also covers mixed waste streams where animal-derived materials are the dominant constituents.	31
Non-agricultural feedstocks (NA)	This category includes various inputs from municipal solid waste (MSW). However, it is vital to recognize that many of these materials may not be biodegradable.	18

2.5. Data Standardization and Analysis

Previously extracted data were normalized to achieve a comparable analysis of any input information. MC was expressed as a percentage (%) and bulk density as kg/m^3, while components such as carbon, nitrogen, phosphorus, potassium, lignin, cellulose, hemicellulose, TOC, and VS were expressed as g/kg TS (total solids). Heating values were standardized to the LHV when extracted as a higher heating value (HHV), using the following equation:

$$\text{LHV} = \text{HHV} - 2.442 \times \text{MC}$$

where the constant 2.442 MJ/kg represents the energy lost to vaporize water. All energy measurements were further referred to dry matter content (i.e., MJ/kg TS) to avoid the influence of moisture variations.

Descriptive statistical analysis was carried out in order to interpret the data. Some of the basic measures calculated include the mean, standard deviation, coefficient of variation, minimum, maximum, interquartile range, standard error, margin of error, as well as confidence intervals of each group. These descriptive statistics made it possible to see the spread and distribution of the data with respect to the three categories: animal-derived materials, plant-based materials, and non-agricultural feedstocks. A one-way ANOVA test with a 95% confidence level was also performed to find out if there were any statistically significant differences between the groups. To evaluate differences between the group means, Tukey's test was also performed to assess those differences after the analysis. This combined approach helped assess variability, significance, and group comparisons within the dataset.

3. Results and Discussion

The results and discussion section will be structured around a detailed analysis of compost feedstocks, categorized into three critical areas: nutrient profiles, chemical and physical properties, and energy-related characteristics. By organizing the data in this way, we can extensively study how different types of compost materials—plant-based, animal-derived, and non-agricultural feedstocks—affect the efficiency and performance of CHRSs. Each category will explore key parameters such as nutrient composition, decomposition dynamics, and energy potential, providing a nuanced understanding of how these feedstocks contribute to microbial activity, heat generation, and overall system optimization. By presenting the findings in this way, the goal is to provide a methodical assessment of how well different raw materials perform and how they affect the optimization of CHRSs to their fullest potential.

3.1. Nutrient Profile

The nutrient profile of the feedstocks utilized in the composting process plays an important and vital role in how the compost process works. Particularly for CHRSs, nutrients such as C, P, N, and K are vital for the activity of microorganisms, the breakdown of organic material, and the consequent generation of heat. This section provides an examination of the nutrient composition found across different types of compost feedstocks: plant-based materials, animal-derived materials, and non-agricultural feedstocks. The distributions of data collected for the C/N ratio and N, P, and K concentrations are shown in Figure 2 and Table 3.

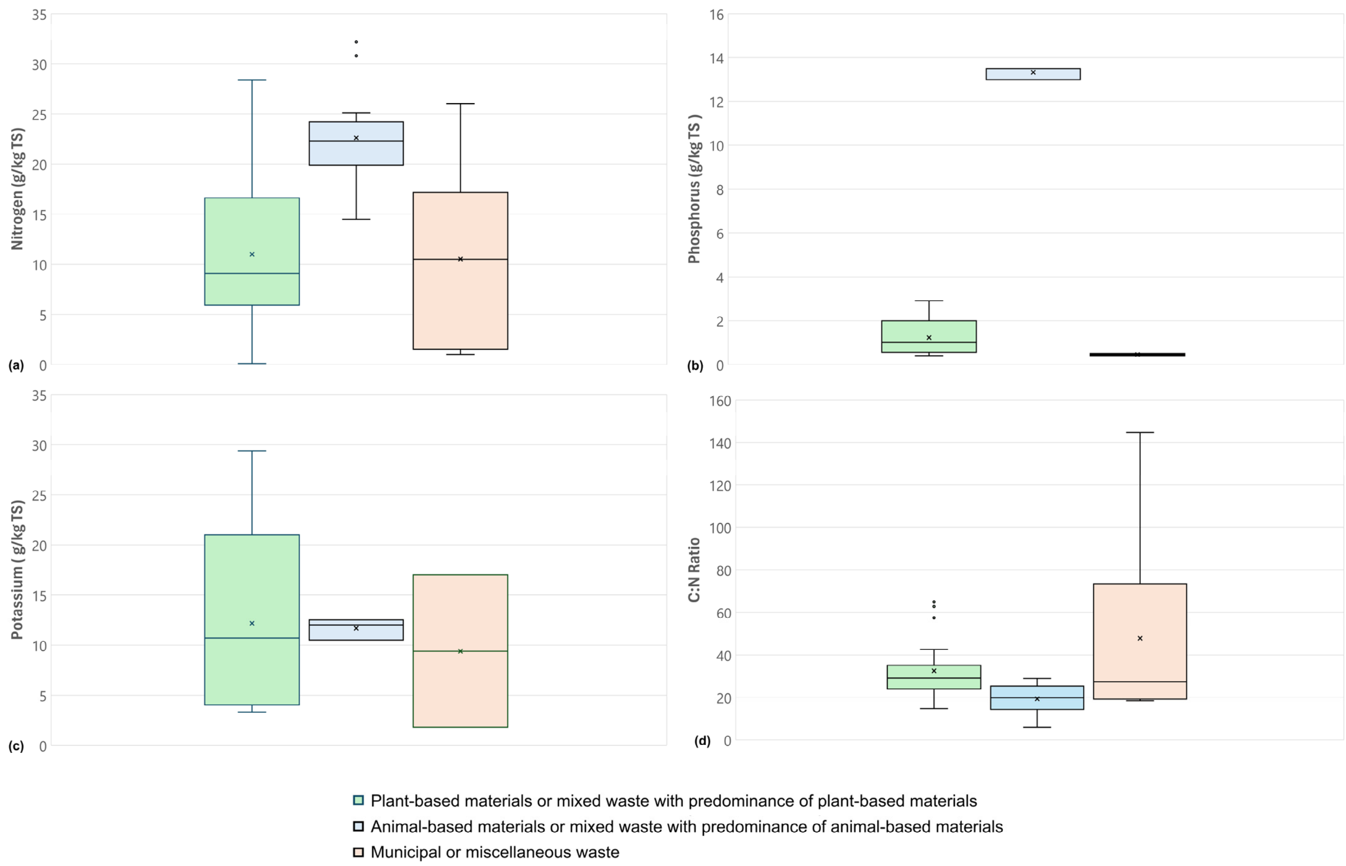

Figure 2. Statistical comparison of different feedstocks: (**a**) N, (**b**) P, (**c**) K, and (**d**) C/N ratio.

Table 3. C/N ratio and N, P, and K contents in different feedstocks (mean values that are not sharing the same letter are significantly different).

Variable	Feedstock	Sample Size	Mean	Median	Minimum	Maximum	Coefficient of Variation
C/N Ratio	PBM	20	32.43 [a]	29.06	14.70	65.00	0.44
	ADM	20	19.36 [a]	19.90	5.90	28.90	0.34
	NA	6	47.82 [b]	27.32	18.46	144.67	1.02
N content (g/kgTS)	PBM	24	10.99 [b]	9.10	0.10	28.40	0.63
	ADM	13	22.62 [a]	22.30	14.50	32.20	0.21
	NA	8	10.53 [b]	10.50	1.00	26.00	0.84

Table 3. *Cont.*

Variable	Feedstock	Sample Size	Mean	Median	Minimum	Maximum	Coefficient of Variation
P content (g/kgTS)	PBM	5	1.22 [b]	1.00	0.40	2.90	0.80
	ADM	3	13.33 [a]	13.50	13.00	13.50	0.02
	NA	2	0.45 [b]	0.45	0.40	0.50	0.16
K content (g/kgTS)	PBM	5	12.60 [a]	10.70	3.30	29.40	0.85
	ADM	3	11.67 [a]	12.00	10.50	12.50	0.09
	NA	2	9.40 [a]	9.40	1.80	17.00	1.14

PBM: plant-based materials; ADM: animal-based materials; NA: non-agricultural feedstocks.

The results of the data analysis show a significant variation in the C/N ratio and of N, P, and K concentrations among the feedstocks utilized in the composting process, which are important factors impacting the overall effectiveness of heat recovery systems in the composting operations. These nutrient profiles mentioned above and C/N ratios affect microbial activity, decomposition rate, and overall heat generation during the composting process.

The mean C/N ratio for plant-based materials, animal-based materials, and non-agricultural feedstocks was 32.43, 19.36, and 47.82, respectively. The minimum C/N ratio resulted in 5.9 when using poultry manure with wood shavings [12], while the highest ratio of C/N ratio was 144.67, and it was recorded in a blend of paper [13]. A significant difference in C/N ratios was observed between animal-derived materials and non-agricultural feedstocks, but no significant differences were found between animal-derived and plant-based materials or between plant-based materials and non-agricultural feedstocks. Lower C/N ratios generally enhance microbial activity, leading to higher heat generation during composting, as observed by Ekinci et al. [14]. Their study demonstrated that relative heat generation increases with the C/N ratio, reaching an optimal point at approximately 36.07. Beyond this point, heat production begins to decline, suggesting that, while microbial efficiency improves with lower C/N ratios, there is a threshold at which both microbial activity and heat generation are maximized. This finding underscores the importance of maintaining an optimal C/N ratio to balance decomposition efficiency and heat output during the composting process. On the other hand, excessive C/N ratios can lead to a decrease in microbial efficiency, slowing down decomposition and reducing heat output. This was shown in research by Larsen and McCartney [15], who found that microbial activity decreased noticeably when the C/N ratio exceeded 29. This suggests that composting systems require careful balancing of the C/N ratio to optimize microbial activity and heat production.

The mean N content for animal-derived materials was 22.62 g/kg TS, significantly higher than both plant-based materials (10.99 g/kg TS) and non-agricultural feedstocks (10.53 g/kg TS). These differences highlight the greater N availability in animal-derived materials, which can enhance microbial activity and heat generation in composting processes. The level of N also has an impact on the efficiency of CHRSs: green waste sourced from public and private gardens, which was ground to a particle size of 20 mm along with biowaste (fruits and vegetables) and paper/cardboard, exhibited a minimum N content of 0.1 g/kg TS [14], whereas pig manure combined with wheat straw showed the highest level at 32.2 g/kg TS [16]. Statistically, significant differences were found between animal-derived materials and non-agricultural feedstocks. An increased amount of N can boost the activity of microorganisms in composting processes by speeding up the breakdown of materials and increasing the production of heat, which is beneficial for heat recovery from composting systems. Materials with a lower C/N ratio than 32.2 demonstrated the most efficient composting, according to a study conducted by Makan and Mountadar [17], which focuses on composting efficiency based on the C/N ratio of different waste materials. This indicates that feedstocks rich in nitrogen, such as those sourced from animals that have a C/N ratio near 32.2, are more effective for heat recovery as they can sustain thermophilic conditions longer and generate more heat. Therefore, it is essential to uphold the optimal level of nitrogen to achieve the maximum potential in heat recovery. However, an excessive amount of N can result in higher ammonia volatilization into the atmosphere, as when there is more N present, particularly in the form of ammonium (NH_4^+), there is a greater potential for ammonia (NH_3) volatilization, resulting in a decrease in the efficiency of microbial processes and potentially triggering odor issues near CHRS plants [18].

The mean P content for animal-derived materials was 13.33 g/kg TS, significantly higher than both plant-based materials (1.22 g/kg TS) and non-agricultural feedstocks (0.45 g/kg TS). Similarly, for K content, animal-derived materials had a mean content of 11.67 g/kg TS, comparable to plant-based materials (12.60 g/kg TS), while non-agricultural feedstocks showed a slightly lower mean value (9.40 g/kg TS). These results indicate that animal-derived materials are notably richer in P, while K levels are more evenly distributed across the different feedstocks. P content also influences the composting process, particularly its role as a co-nutrient for microbial growth. Statistically significant differences were observed between animal-derived materials and both non-agricultural feedstocks and plant-based materials. Phosphorous supports essential microbial processes (e.g., cell division and energy use and production), thus enhancing overall microbial activity and potentially contributing to increased heat production during composting. Moreover, K content varied less among feedstocks, with no significant differences between categories. However, K is not a direct driver of compost heat generation, but it supports overall microbial health and the metabolic processes essential for effective composting. When K-rich mining waste is introduced into the mix of composting, it can promote the growth of thermophilic bacteria. This helps speed up the breakdown of feedstocks and reduces the time needed for composting by enhancing both oxygen intake and microbial processes during high-temperature stages [19].

Overall, from a nutrient-profile point of view, animal-based materials could be considered as the most suitable choice for CHRSs because of their low and consistent C/N ratios and high N content. These features foster rapid microbial activity and sustain thermophilic conditions, which are essential for maximizing heat generation during composting. On the other hand, plant-based materials with moderate C/N ratios and varying nutrient content can also work well but might lead to less predictable and lower heat output. In order to enhance the efficiency of heat recovery systems using plant-based materials, it would be beneficial to mix them with N-rich materials to balance the C/N ratio, which boosts microbial activity and heat production, or closely manage the composting process to ensure stable microbial activity. This approach helps to overcome the variability in nutrient content and maintain consistent heat generation. Conversely, managing non-agricultural feedstocks for heat recovery poses a challenge due to their varying C/N ratios and nutrient variability. These fluctuations can interfere with microbial performance and diminish heat production, resulting in non-agricultural feedstocks being less than ideal as the main feedstock for heat recovery purposes from aerobic processes. Consequently, careful feedstock selection and balancing of nutrient profiles are crucial for optimizing heat recovery, with animal-derived materials offering the most reliable and effective results.

3.2. Chemical and Physical Properties

The physical properties (pH and bulk density) and some chemical constituents (lignin, cellulose, and hemicellulose) of the composting feedstocks play an important role in microbial activity, decomposition rates, and the efficiency of heat generation during composting, which will be discussed in detail in the upcoming section of this paper. This section of the data analysis, as shown in Figure 3 and Table 4, looks closely into these properties of the materials across the considered categories of feedstocks and discusses their implications for optimizing CHRSs.

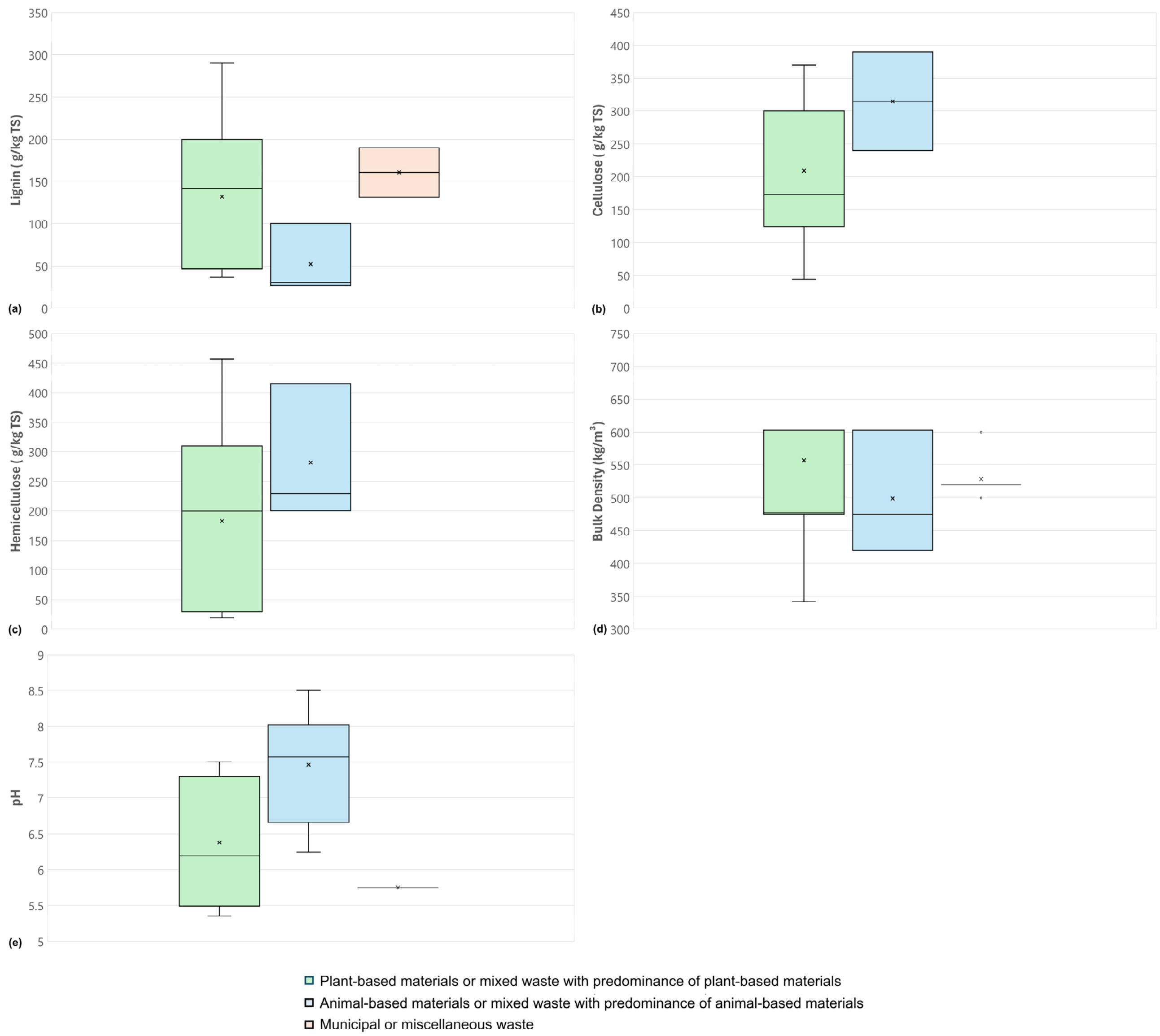

Figure 3. Statistical comparison of different feedstocks: (**a**) lignin, (**b**) cellulose, (**c**) hemicellulose, (**d**) bulk density, and (**e**) pH.

Table 4. Lignin, cellulose, and hemicellulose content, bulk density, and pH in different feedstocks (mean values not sharing the same letter are significantly different).

Variable	Feedstock	Sample Size	Mean	Median	Minimum	Maximum	Coefficient of Variation
Lignin (g/kg TS)	PBM	16	132.05 [a]	141.50	36.70	290.00	0.64
	ADM	3	52.23 [a]	30.00	26.68	100.00	0.79
	NA	2	160.63 [a]	160.63	131.25	190.00	0.26
Cellulose (g/kg TS)	PBM	16	208.96 [a]	173.00	44.10	370.00	0.50
	ADM	2	315.00 [a]	315.00	240.00	390.00	0.34
	NA	-	-	-	-	-	-
Hemicellulose (g/kg TS)	PBM	16	182.90 [a]	200.00	19.60	457.00	0.84
	ADM	3	281.76 [a]	215.00	200.00	415.28	0.41
	NA	-	-	-	-	-	-
Bulk Density (kg/m^3)	PBM	15	556.99 [a]	477.00	204.80	1000.00	0.46
	ADM	3	499.33 [a]	475.00	420.00	603.00	0.19
	NA	7	528.57 [a]	520.00	500.00	600.00	0.06

Table 4. *Cont.*

Variable	Feedstock	Sample Size	Mean	Median	Minimum	Maximum	Coefficient of Variation
pH	PBM	15	6.38 [a]	6.19	5.35	7.50	0.13
	ADM	14	7.46 [b]	7.57	5.55	8.50	0.10
	NA	1	5.75 [a]	5.75	5.75	5.75	-

PBM: plant-based materials; ADM: animal-derived materials; NA: non-agricultural feedstocks.

Lignin plays a crucial role in the decomposition of feedstock because its complex molecular structure makes it highly resistant to microbial breakdown. This resistance slows down the overall decomposition process, leading to reduced microbial activity. Since microbes generate heat during decomposition through their metabolic processes, the slow breakdown of lignin results in decreased heat production. This can significantly affect processes that rely on heat generation during decomposition, such as composting. Therefore, increased lignin levels can slow down microbial activity, resulting in a reduction in the overall efficiency of composting in generating heat. Non-agricultural feedstocks showed the highest mean lignin content (160.63 g/kg TS) with a maximum value of 190 g/kg TS in municipal solid waste organic fractions larger than 2 mm [20]. Plant-based materials showed a mean lignin content of 132.05 g/kg TS with a maximum recorded in palm tree pruning (290 g/kg TS) [21]. Animal-derived materials had the lowest mean lignin content, averaging at 52.23 g/kg TS with a minimum of 26.68 g/kg TS for a mixture of wheat straw and swine manure [22].

However, these findings cannot be generalized due to the small sample size (n = 3) of studies on animal-based materials focusing on this parameter. Studies have shown that the inhibitory impact of lignin on compost effectiveness is widely known, and it is observed that feedstocks with high lignin content tend to be more resistant resulting in slower microbial activity, a reduction in the efficiency of composting, and heat generation [23]. In contrast, the significantly lower lignin content in animal-derived materials allows for faster microbial activity and heat production.

Cellulose is a key carbon source in compost, driving microbial activity. The cellulose content in materials derived from animals averaged at 315 g/kg TS compared to 208.96 g/kg TS in plant-based materials, though this difference was not statistically significant. The non-significant difference in cellulose content between animal-derived and plant-based compost materials may be partly due to the disparity in sample sizes, with 16 samples for plant-based materials versus only two for animal-derived materials, which might affect the reliability of these findings. Thus, the statistical reliability and representation of the data are affected, potentially skewing the comparative results. The increased content of cellulose in animal-based materials helps maintain a suitable environment for microorganisms and thermophilic conditions that are important for effective heat production, according to studies indicating that microbial consortia with high cellulase activities can speed up the composting of agricultural waste with high cellulose contents and promote beneficial microbial activity under thermophilic conditions, which further enhances heat generation [24].

Plant-based materials showed wide variability, with cellulose content ranging from a minimum value of 44.10 g/kg TS (green waste) [25] to a maximum value of 370 g/kg TS (wheat straw and pig manure) [26]. This inconsistency in cellulose content directly affects their heat production potential. However, the absence of cellulose data for non-agricultural feedstocks complicates the assessment of its impact on heat generation in aerobic processes. Hemicellulose, though less resistant to degradation than cellulose, plays a crucial role in microbial decomposition during composting. The hemicellulose content was found to be higher in animal-derived materials, with an average of 281.76 g/kg TS compared to plant-based materials (182.90 g/kg TS), though this difference was not statistically significant. Plant-based materials displayed significant variation in hemicellulose content with a standard deviation of 152.76 g/kg TS and a coefficient of variation of 0.84. The wide range of variability in plant-based feedstocks suggests that they may not consistently produce heat. The 95% confidence interval for hemicellulose content in plant-based materials ranged from 108.05 g/kg TS to 242.51 g/kg TS, further indicating the potential for inconsistent performance. The absence of hemicellulose data for non-agricultural feedstocks limits the ability to fully assess its role in heat generation from aerobic processes. In addition, the small sample size (n = 3) of studies concerning animal-based materials suggests that these findings cannot be generalized for this category of materials and for hemicellulose.

Bulk density plays also a vital role in how composting works since it impacts airflow and the availability of oxygen, both of which are vital factors for supporting aerobic microbial activity and the generation of heat during the process. When bulk density is high, it can hinder the flow of oxygen, resulting in conditions that can decrease the effectiveness of composting and heat production, while lower bulk density leads to increased free air space and air permeability, resulting in improvement of aeration, which is beneficial for microbial activity and organic matter breakdown [27]. In the data analysis carried out, materials derived from plants showed a mean bulk density of 556.99 kg/m^3, with a maximum value of 1000 kg/m^3. Animal-based materials had a mean bulk density of 499.33 kg/m^3, ranging from a minimum of 420 kg/m^3 up to a maximum of 603 kg/m^3. Non-agricultural feedstocks had a relatively consistent mean bulk density of 528.57 kg/m^3, with a maximum of 600 kg/m^3. The findings indicate that plant-based materials have higher variability in bulk density with a coefficient of variation of 0.46, which may potentially cause fluctuations in composting efficiency. In contrast, animal-derived and non-agricultural feedstock materials exhibit more consistent bulk densities with a coefficient of variation of 0.19 and 0.06, respectively, supporting better oxygen availability and microbial activity and ensuring more efficient biodegradation and heat production.

pH is an important parameter during the composting process, directly affecting microbial growth, enzyme function, and nutrient availability. The optimum pH for microbial growth rate and degradation activity is in the 7–8 range [28], at which the maximum thermophilic activity and organic matter degradation occur with the release of heat. The pH for animal-derived materials measured during the study ranged between 5.35 and 8.50, with an average of 7.46, which is within the range for adequate and effective microbial activities for composting. On the opposite end, the mean pH for plant-based materials was 6.38 with a range of 5.35–7.50. Since some of the materials were below the optimal range, it could limit the efficiency of microbial actions. A mean pH of 5.75 was obtained from non-agricultural feedstocks, which falls out of the optimal range, meaning that some adjustments will be necessary to enhance the activity of the microbes and the overall effectiveness of any aerobic process. Animal-derived materials have a mean pH within the optimum range of 7–8 and therefore support optimal microbial growth and microbial degradation activities, which enhance composting and heat production. Materials with plant-based and non-agricultural feedstocks that have lower pH values may require adjustments to achieve optimal microbial activity and ensure consistent aerobic biodegradation.

These findings back the theory that the physical and chemical properties influence microorganism activity and the degradability of materials for composting as well as heat generation. Animal-based materials consistently prove to be optimal for composting due to their composition of lignin and other elements like cellulose and hemicellulose along with bulk density and pH levels. Conversely, plant-based materials exhibit a range of variability that may result in inconsistent microbial activity and heat generation.

As for the case of the non-agricultural feedstocks, the analysis showed bulk density stability but revealed a lack of detailed information regarding cellulose and hemicellulose content. Furthermore, its low pH value may require some modifications in order to optimize the work of the microbes. It is crucial to monitor and make changes, especially when dealing with plant-based and non-agricultural feedstock materials, to maintain consistent performance and maximize heat recovery in their respective aerobic processes.

3.3. Energy-Related Properties

This section delves into the data analysis of the LHV, VS, MC, C content, and TOC across plant-based, animal-derived, and non-agricultural feedstock sources in order to evaluate their suitability for heat recovery from aerobic processes. These properties have a significant impact on the effectiveness of energy recovery driven by microbial activity and decomposition processes. Specifically, the low heating value (LHV) of the feedstock is a key factor in understanding its potential for heat production, as it represents the energy content available for release during aerobic processes. While literature on the direct correlation between LHV and heat output in composting is limited, it is essential to highlight that LHV serves as an indicator of the suitability of feedstocks for energy recovery.

Statistics on these parameters for different feedstock types are presented in Figure 4 and Table 5.

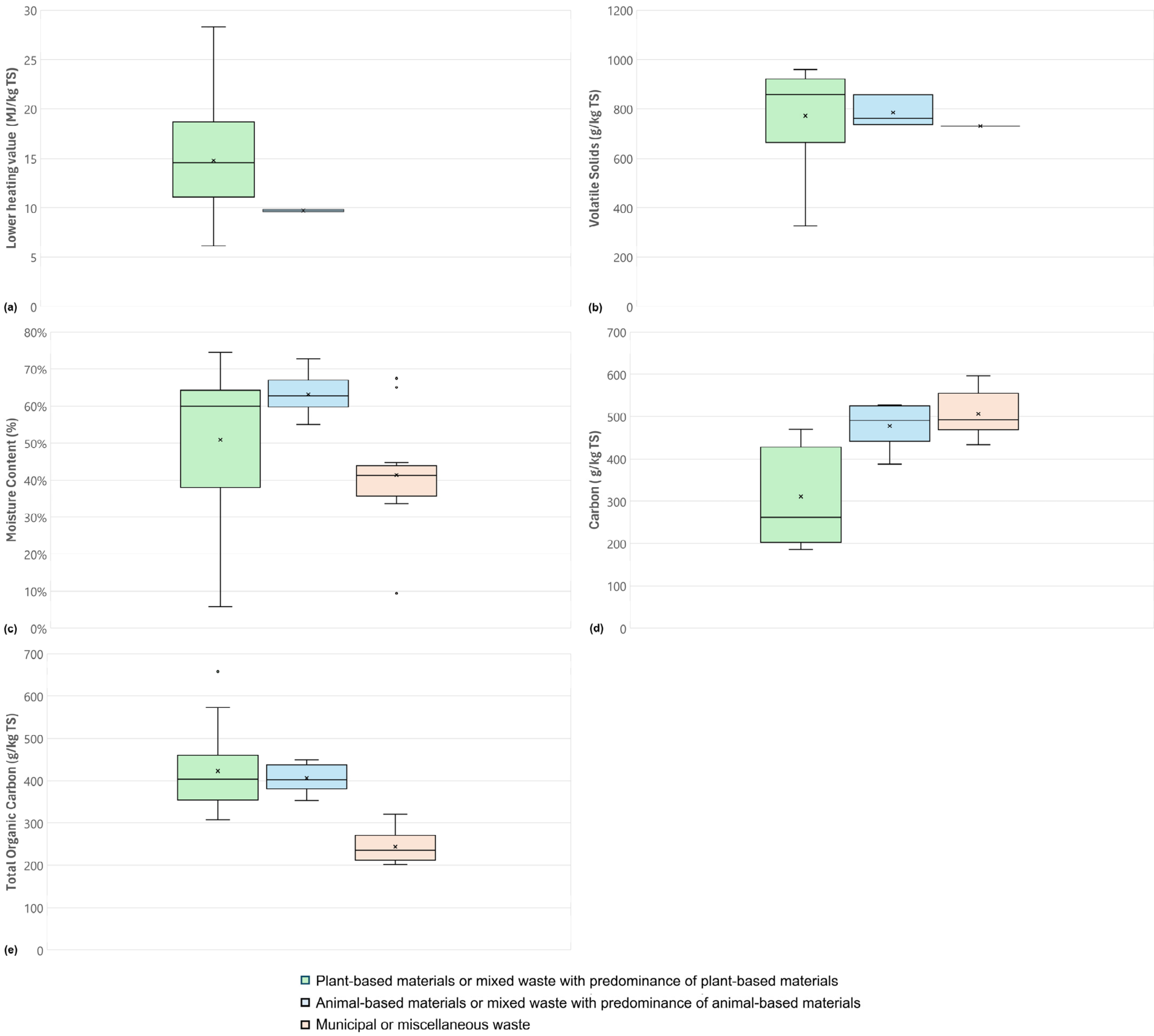

Figure 4. Statistical comparison of different feedstocks: (**a**) LHV, (**b**) VS, (**c**) MC, (**d**) C content, and (**e**) TOC.

Table 5. LHV, VS, MC, C content, and TOC in different feedstocks (mean values that are not sharing the same letter are significantly different).

Variable	Feedstock	Sample Size	Mean	Median	Minimum	Maximum	Coefficient of Variation
LHV (MJ/kg TS)	PBM	16	14.79 [a]	14.57	6.12	28.30	0.39
	ADM	2	9.72 [a]	9.72	9.62	9.82	0.01
	NA				-		
VS (g/kg TS)	PBM	10	772.34 [a]	857.65	327.20	960.00	0.27
	ADM	3	785.70 [a]	762.50	737.60	857.00	0.08
	NA	1	730.90 [a]	730.90	Only one data point		
MC (%)	PBM	49	50.92% [b]	60.00%	5.90%	74.57%	0.39
	ADM	23	63.16 [a]	62.70%	55.00%	72.80%	0.12
	NA	13	42.00% [b]	41.21%	9.50%	67.50%	0.35
C content (g/kg TS)	PBM	11	311.32 [a]	262.00	185.80	469.40	0.35
	ADM	7	477.61 [a]	491.12	388.00	528.00	0.11
	NA	6	506.33 [b]	493.00	434.00	596.00	0.11
TOC (g/kg TS)	PBM	15	422.91 [a]	403.70	308.00	658.00	0.22
	ADM	7	406.19 [a]	402.70	353.80	450.00	0.08
	NA	6	243.73 [b]	235.05	201.40	321.40	0.18

PBM: plant-based materials; ADM: animal-derived materials; NA: non-agricultural feedstocks.

The LHV of composting feedstocks is a parameter of great interest due to the potential use of these feedstocks for energy recovery purposes. Out of all feedstocks, plant-based materials have the highest LHV with a mean value of 14.79 MJ/kg TS but with significant variation (CV = 0.39), ranging from 6.12 MJ/kg TS in soft garden waste [29] to 28.30 MJ/kg TS in woodchips enriched with biochar and inoculants [30]. This variability underscores that certain plant-based feedstocks, particularly those combined with biochar, could enhance heat recovery due to the fact that they have a higher energy potential. The positive effects of biochar in increasing composting efficiency are due to its ability to shorten the composting period and increase the rate of biodegradation of organic materials [30]. On the other hand, the LHV of animal-derived materials is quite lower, with a mean value of 9.72 MJ/kg TS and a range of 9.62–9.82 MJ/kg TS. However, the current sample size for animal-derived materials (n = 2) is insufficient to draw robust conclusions regarding their LHVs. To improve the reliability and applicability of these findings, further data collection in these material categories is necessary. No studies involving non-agricultural feedstocks and composting were found in our analysis. As already mentioned, mixed waste cannot be considered for the production of compost. Thus, the absence of data on this type of feedstock is not a major issue for this study. Non-statistically significant differences in the mean values of LHV for plant-based and animal-based feedstocks were found, suggesting that the suitability of each feedstock may depend on specific energy recovery goals rather than on LHV alone.

VS are a key measure of the organic matter in feedstocks, which include elements of organic materials within composting feedstocks that decompose to generate energy as heat. Since the potential of energy recovery is often higher with higher VS content, it is an important value in determining the feedstock suitability in composting systems. Plant-based materials reported a mean VS content of 772.34 g/kg TS with considerable variability across sources. The VS content ranges from 327.20 g/kg TS in soft garden waste [29] to 960.00 g/kg TS in the organic fraction of MSW [31]. This variability is reflected in a coefficient of variation of 0.27, with some plant-based materials that would be more efficient in energy recovery but some that would offer less energy potential. Such variation in plant-based feedstocks highlights the importance of selecting high-VS sources, as some, due to lower organic content, may not yield consistent energy output in heat recovery applications. In contrast, animal-based materials have a more consistent VS profile, with 785.70 g/kg TS mean VS content, which is slightly higher but with a narrower span (737.60 to 857.00 g/kg TS) than plant-based materials [12,22]. However, it should be noted that the animal-based material data are based on a limited sample size of only three data points. Non-agricultural feedstocks show a VS content of 730.90 g/kg TS based on a single available data point [29], but more data are needed in order to show trend, variability profile, and conduct proper data analysis. While this single point suggests that non-agricultural feedstocks have good energy recovery potential, additional data are necessary to confirm the performance across sources and types of non-agricultural feedstocks.

Statistical analyses reveal that there are no significant differences regarding the VS content in plant-based, animal-based, and even non-agricultural feedstock, thus suggesting that energy potential may be comparable in these types of feedstocks. In this regard, the diversity of VS in plant-based materials shows that some materials could perform better than others, potentially for the use in very efficient CHRSs.

Moisture level is one of the most critical parameters that affect decomposition rates and heat production during composting. High-moisture feedstocks could even need efficient aeration to achieve proper moisture levels since a lack of oxygen results in the possible obstruction of microbial growth and, in turn, diminishing the heat output. According to a study on composting swine manure, high MC (80%) resulted in anaerobic conditions within the composting pile, which negatively affected the composting process [32]. In contrast, lower moisture levels can limit microbial activity due to insufficient water availability, slowing down decomposition and potentially preventing the composting biomass from reaching optimal temperatures for effective pathogen reduction and nutrient stabilization. Animal-derived materials have a mean MC of 63.16% with a range of 55.00–72.80% [21,33]. This consistent MC highlights their tendency to retain water; hence, there is the need to conduct aeration management for optimal composting performance. Research indicates that optimal MC for composting materials can vary significantly depending on the specific material composition. For instance, beef manure mixed with bedding materials like sawdust has an optimal MC of around 70%, while mixtures involving rice hulls are most effective at approximately 57% on a wet basis [34]. Plant-based materials, with an average MC of 50.92%, display greater variability, ranging from 5.90% (olive tree pruning) to 74.57% (grass, tomato, pepper, and eggplant) [21,35]. Their high CV (0.39) suggests inconsistent moisture levels, requiring close monitoring and adjustments. Non-agricultural feedstocks have a lower average MC of 42.0%, ranging from 9.5% to 67.5% [29,36]. This reduced moisture content increases aeration; however, it must be counterbalanced with enough amount of microbial activity for effective biodegradation and heat generation.

The statistical analysis carried out in the present work indicates that there is a statistically significant difference in the average MC of animal waste and non-agricultural feedstocks ($p\text{-adj} < 0.05$), signifying the belief that the increased MC in animal-derived materials might impact their performance in heat recovery systems.

Carbon (C) content is essential for compost heat recovery as it provides energy for microbial processes that generate heat. The mean C content of plant-based material was 311.32 g/kg TS, ranging from 185.8 g/kg TS in grasses [37] to 469.4 g/kg TS in plant mixes with tomato, pepper, and eggplant [35]. This variability (CV = 0.35) suggests potential inconsistency in heat output if plant materials are used as the primary feedstock. Although it is practical and also environmentally friendly to use plant-based materials, the variability in the C content means that heat production may be inconsistent unless integrated with sources characterized by a higher C content. Therefore, adding a stable carbon source from plant-based materials could improve the stability of heat recovery. Reliable carbon sources include hardwoods, such as Acer macrophyllum (bigleaf maple), with a carbon content of 49.64%, and softwoods, such as Sequoiadendron giganteum (giant sequoia), with a carbon content of 54.66% [38].

For animal-based materials, the mean C content was 477.61 g/kg TS, ranging from 388.0 g/kg TS in pig manure mixed with wheat straw [16] to 528 g/kg TS in spent pig litter [39] with low variability (CV = 0.11). This consistency makes animal-derived materials a stable choice for C supply in heat recovery. The low variability of C content in animal-derived materials (CV = 0.11) indicates their suitability for consistent heat generation, making them valuable in compost systems that require predictable heat output.

Non-agricultural feedstocks have a mean C content of 506.33 g/kg TS with moderate variability (CV = 0.11) with a minimum value of 434.0 g/kg TS for mixed paper [13]. Non-agricultural feedstocks offer a reasonable and consistent carbon source for aerobic processes and, if entirely composed of biomass, CHRSs. While it may be effective in combination with other feedstocks, regulatory considerations and variability in waste composition could affect its long-term viability as a primary carbon source. In particular, regulations often address concerns about contaminants, pathogens, and hazardous substances that may be present in non-agricultural waste streams, requiring strict monitoring and compliance with environmental safety standards.

TOC is a key indicator of bioavailable organic matter, directly impacting heat generation during composting. Plant-based materials have a high mean TOC (422.91 g/kg TS), ranging from 308.0 g/kg TS in green waste, fruit, and vegetables [25] to 658.0 g/kg TS in biochar-enhanced mixes [30]. The moderate coefficient of variation (CV = 0.22) highlights the potential to adjust TOC levels with additives, optimizing heat output. Animal-derived materials show a slightly lower mean TOC (406.19 g/kg TS) with minimal variation ranging from 353.8 g/kg TS in pig slurry solids [21] to 450.0 g/kg TS in pig manure with sawdust [40]. This consistency (CV = 0.08) suggests that animal-derived feedstocks are reliable TOC sources for stable heat generation. The steady TOC levels in animal-derived materials are advantageous for consistent heat production, making them suitable for applications where reliability is critical. However, their relatively lower TOC compared to plant-based materials could limit their standalone heat recovery potential. Non-agricultural feedstocks have the least mean TOC content of 243.73 g/kg TS with a limited range from 201.4 g/kg TS for a mixture of organic fraction of MSW, green waste, and paper [41] to 321.4 g/kg TS in mixed refuse [36], exhibiting moderate variability (CV = 0.18).

3.4. In-Depth Feedstock Evaluation for Optimizing CHRSs

The purpose of the radar chart analysis presented in Figure 5 is to estimate the optimal feedstock composition for CHRSs by assessing various materials in terms of standardized composting parameters through the visual comparison of different feedstock types and their performance across a range of variables. This helps determine which materials are most suitable for maximizing both heat recovery and compost quality. The data were subjected to Min-Max normalization, which ensures that all the variables are scaled to fit the range from 0 to 1. This normalization also allows the effective comparison of parameters that are expressed in terms of different units and scales. The radar chart visually identifies the strengths and weaknesses of each feedstock category concerning these normalized values.

Animal-derived materials show a good degree of balance and fulfill all the core parameters that are essential for composting. They are characterized by a high MC (normalized value: 0.7226), which accelerates microbial activity and causes rapid decomposition and higher heat generation. Moreover, such biomass types have high N (0.4588) and P (0.6667) contents, which make these materials nutrient dense. Thus, they can enhance microbial growth and the final compost quality. The C content (0.6400) and the C/N ratio (0.5854) are also well-balanced, facilitating sustained microbial activity over time and contributing to long-lasting heat production. Across most parameters, these materials perform consistently well, making them the most versatile and efficient feedstock for CHRSs. Animal-derived materials are ideal for composting processes where both rapid heat generation and nutrient-rich compost are desired.

Plant-based materials are characterized by relatively high contents of VS (0.7034) and lignin (0.3764), which suggest strong potential for energy recovery through composting. However, the high lignin content slows down decomposition in traditional composting systems, which could limit their efficiency in generating rapid heat for CHRSs. Despite this, plant-based materials still offer moderate performance in key composting parameters such as MC (0.6556), C content (0.4426), and TOC (0.3283). These materials maintain a healthy balance between moisture and C, making them versatile, though this is not necessarily the best choice for maximizing heat recovery in CHRSs. Due to their slower decomposition, plant-based materials excel in situations where long-term heat release is desired, such as in extended composting cycles. However, in systems where rapid heat generation is required, they may need to be combined with faster decomposing feedstocks to optimize performance.

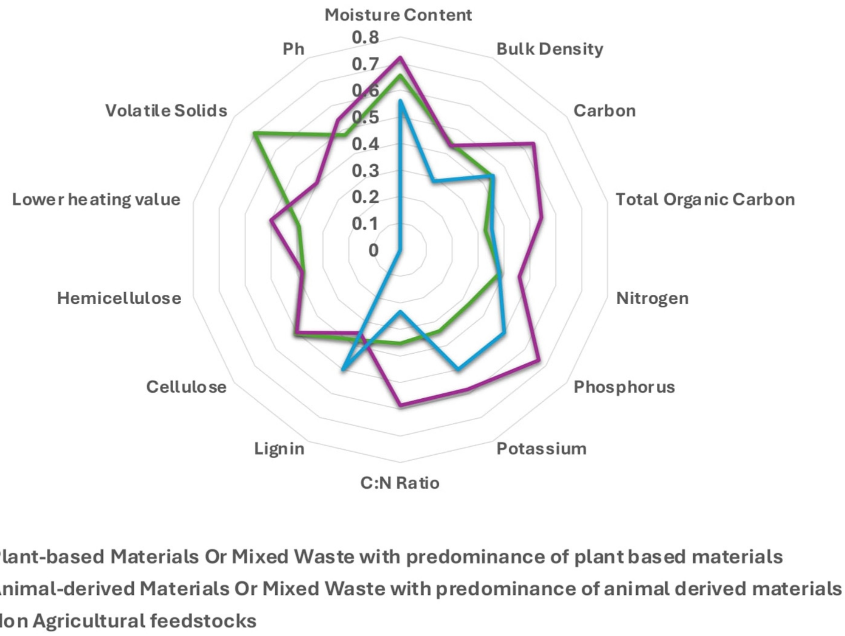

Figure 5. Radar chart of the normalized performance of feedstock variables.

Non-agricultural feedstocks lag behind animal- and plant-based feedstocks with respect to most parameters necessary for efficient heat recovery from aerobic processes. Its low normalized MC of 0.5604 and much lower C/N ratio of 0.2327 may cause slower microbial activity and low heat generation. Moreover, data for several key parameters, including cellulose, hemicellulose, LHV, VS, and pH, are not available for non-agricultural feedstocks. The lack of these data makes it difficult to fully assess the material's potential for heat recovery. However, non-agricultural feedstocks show moderate strength in C content (0.4465) and TOC (0.3528), which indicates some potential for microbial activity. This material may still play a role in aerobic processes if blended with other feedstocks that compensate for its deficiencies in nitrogen and moisture.

In conclusion, based on the radar chart reported in Figure 5, animal-derived materials emerge as the top-performing feedstock for CHRSs due to their balanced nutrient composition and rapid heat generation. Plant-based materials offer long-term heat release but decompose more slowly, while non-agricultural feedstocks, hindered by missing data and lower performance in key areas, may benefit from blending with other materials for optimal heat generation in aerobic processes.

4. Conclusions

The efficiency of CHRSs depends on choosing the best feedstocks as inputs, which control the decomposition rate by microorganisms and the amount of heat produced during composting. This review analyzes three primary feedstock categories: animal-derived, plant-based, and non-agricultural feedstocks, and evaluates their unique contributions, limitations, and combined potentials for optimized CHRS performance.

Overall, animal-derived materials, with balanced C/N ratios (5.90–28.90) and high nitrogen content (14.15–32.20 g/kg TS), can efficiently enhance microbial growth and high thermal energy output but require careful N management to prevent ammonia release.

Plant-based materials, with higher LHVs (6.12–28.30 MJ/kg TS), provide sustained heat release due to slower decomposition, making them valuable for extended energy output, especially when mixed with N-rich animal-derived feedstocks like manure.

The results of this analysis underscore the significance of tailored feedstock combinations to reach efficiency in CHRS operation. Incorporating animal-based feedstocks is recommended due to their high thermal energy output and high nutrient content. Plant-based materials are beneficial for their steady and extended heat generation capacity, especially when paired with biochar or N-enriched sources. Blending feedstocks based on specific energy, compost quality, and nutrient recycling goals can maximize microbial efficiency, extend thermophilic phases, and enhance the overall sustainability of CHRSs to support EU sustainability goals effectively.

Future research should prioritize refining feedstock combinations and exploring innovative enhancements, such as biochar integration and pre-treatment techniques for non-agricultural feedstocks, to improve material consistency and compatibility with CHRSs. Additionally, investigating the economic viability, environmental benefits, and long-term operational efficiency of CHRSs will be critical to advancing their widespread adoption and aligning them with international sustainability and energy policy goals. Expanding CHRSs into diverse waste management contexts, including urban, agricultural, and rural settings, can further demonstrate its role in achieving a sustainable, low-carbon economy. Finally, CHRSs offer a pioneering approach to managing waste sustainably by recuperating energy while lowering GHG emissions and improving compost quality. This evaluation confirms that, by choosing thoughtful feedstock and strategic blending, CHRSs can be optimized to yield both high-energy output and nutrient-rich compost, supporting the European Union's sustainability goals and broader global climate targets. Animal-derived feedstocks emerge as the most reliable core material, plant-based feedstocks offer sustained heat release, and non-agricultural feedstocks (if composed entirely of biomass) provide a useful supplement for system balance. Together, these insights pave the way for CHRSs as an essential tool in renewable energy production, waste management, and environmental stewardship, with immense potential to contribute meaningfully to a sustainable future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app142311245/s1. Table S1: Supplementary table of sources for the systematic critical review.

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