

Article

Beyond the Essential Oil: Circular Economy Strategies for Lavender Solid Residues

Milica Aćimović ^{1,*} , Djorđe Djatković ² , Aleksandar Nesterović ² , Stanko Milić ¹ , Nikolina Dizdar ¹,
Nebojša Kladar ³ , Zorica Tomićić ⁴ , Slađana Rakita ⁴  and Ivana Čabarkapa ⁴ 

- ¹ Institute of Field and Vegetable Crops, Novi Sad—National Institute of the Republic of Serbia, Maksima Gorkog 30, 21000 Novi Sad, Serbia; stanko.milic@ifvcns.ns.ac.rs (S.M.); nikolina.dizdar@ifvcns.ns.ac.rs (N.D.)
² Faculty of Technical Sciences, University of Novi Sad, Trg Dositeja Obradovica 6, 21000 Novi Sad, Serbia; djordjedjatkovic@uns.ac.rs (D.D.); aleksandarnesterovic@uns.ac.rs (A.N.)
³ Department of Pharmacy, Faculty of Medicine, University of Novi Sad, Hajduk Veljkova 3, 21000 Novi Sad, Serbia; nebojsa.kladar@mf.uns.ac.rs
⁴ Institute of Food Technology in Novi Sad, University of Novi Sad, Bul. Cara Lazara 1, 21000 Novi Sad, Serbia; zorica.tomicic@fins.uns.ac.rs (Z.T.); sladjana.rakita@fins.uns.ac.rs (S.R.); ivana.cabarkapa@fins.uns.ac.rs (I.Č.)
* Correspondence: acimovicbabicmilica@gmail.com

Abstract

The aim of this study was to comprehensively characterize lavender pellets produced from post-distillation residues and evaluate their multifunctional valorization potential. Physicochemical properties, including moisture, ash, heating value, organic matter, total and organic carbon, macro- and micronutrients, potentially toxic heavy metals, polyphenols, microbiological safety, and nutritive composition, were assessed. The pellets demonstrated an energy content comparable to other agricultural residues, with a higher heating value of 18,900 kJ/kg and a lower heating value of 16,603 kJ/kg. High organic matter (87%) and a slightly acidic pH support soil moisture retention, while favorable macronutrient levels enhance their suitability as a soil amendment. Water-based extractions (infusion and decoction) achieved higher yields (15.60–21.66%) than ethanol (13.04%) and more effectively recovered bioactive polyphenols, particularly rosmarinic and chlorogenic acids. Low moisture and water activity ensured storage stability and minimal microbial growth, which was confirmed by microbiological safety tests. Nutritionally, pellets contained moderate protein (9.38%), high cellulose (33.38%), and low fat (2.18%), with total amino acids of 8.91 g/100 g and 36.7% essential amino acids, along with a favorable fatty acid profile rich in polyunsaturated fractions. Overall, these findings highlight lavender pellets as a sustainable resource for energy, soil improvement, bioactive compound recovery, and complementary animal feed within circular economy frameworks. However, future research should focus on investigating whether residual compounds remain in lavender residues that could exert antifeedant or phytotoxic effects. Additionally, the potential for the sequential valorization of lavender residues should be explored, initially through the extraction of bioactive phenols, followed by pellet production for use as fuel or soil amendments. This approach would enable multiple cascading uses and maximize their contribution to comprehensive circular economy strategies.

Keywords: nutritional profiling; waste valorization; polyphenols; post-distillation residue utilization; soil amendment; circular bioeconomy; biomass pellets



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1. Introduction

Lavender (*Lavandula* sp.) is a globally significant medicinal and aromatic genus, extensively cultivated for its essential oils, which are widely used in cosmetics, pharmaceuticals, food, and aromatherapy products [1,2]. Its cultivation has expanded due to the high economic value of its essential oils, which are primarily obtained from true lavender (*Lavandula angustifolia* Mill.) and its hybrid lavandin (*L. × intermedia*), with global production reaching approximately 1500 tons annually [3]. Industrial essential oil yields can vary, but for the calculation of fresh biomass entering the distillation chain, we consider a typical yield of 0.3–0.7%, while the essential oil content in dry biomass typically ranges between 1% and 3% [4]. Based on reported production volumes and typical yields, approximately 300,000 tons of fresh lavender biomass enter the distillation chain each year. In addition to solid residues rich in bioactive compounds and polysaccharides, essential oil production also generates wastewater and hydrolates, posing environmental and economic challenges [5]. The valorization of these by-products through recycling and the development of value-added products therefore represents a key strategy for reducing waste and supporting circular bioeconomy approaches aligned with green innovation principles [6–10].

A mini-review from 2015 points to the great potential of *Lavandula* species post-distillation solid residues in the circular bioeconomy; however, the largest number of papers dealing with this topic were published after this work [11]. Specifically, in the case of lavender post-distillation solid residues, their application as fertilizers [12], compost [13,14], growing substrates for mushroom cultivation [15–17], and biosorbents for copper removal has been demonstrated [18], along with their use as a raw material for the extraction of bioactive compounds with biological activity [19–22], such as antioxidant [19,22] and antimicrobial activity [23,24], and as bioherbicides [25] applicable in food, the pharmaceutical industry, and agriculture. Moreover, lavender post-distillation solid residues can serve as an environmentally friendly feedstock rich in polysaccharides [26,27] suitable for energy production, as with the production of syngas via pyrolysis [28,29], biomethane via anaerobic digestion [30,31], or solid fuel via hydrothermal carbonization [32]. Additionally, lavender post-distillation solid residues have been reported as valuable bio-additives for cement mortars, enhancing the properties of traditional mortars while simultaneously contributing to waste management [33,34]. In addition, lavender post-distillation solid residues have been successfully valorized as a low-cost fermentation substrate for the production of high-value-added biomaterials, such as bacterial cellulose/gum Arabic composites obtained via in situ modification [35]. Moreover, the successful pelletization of lavender post-distillation solid waste has been noted [36–38], making this material convenient for storage, reducing storage space and reducing the dust fraction, and enabling its use for energy purposes.

The aim of this work was to produce pellets from lavender post-distillation solid residues after drying and milling that are suitable as a final product on farms cultivating medicinal and aromatic plants. By integrating complementary analytical approaches, this study advances current knowledge, establishes a foundation for sustainable valorization pathways, and supports circular bioeconomy strategies, highlighting practical applications in the energy, agriculture, feed, and pharmaceutical sectors. The study examined the chemical composition of the pellets, including the moisture, ash content, and energy-related properties; characteristics relevant for soil amendment, such as total nitrogen and carbon, macronutrients (P, K, Ca, Mg), micronutrients (Al, B, Cu, Fe, Na, Mn, Zn), and heavy metals (Cd, Cr, Ni, Pb); the recovery of bioactive compounds, including phenolic acids and flavonoids; microbiological safety; and nutritive value, including cellulose, fat and fatty acid composition, proteins, and amino acid composition. This comprehensive analysis aimed to assess the potential use of pellets from lavender post-distillation residues as a

source of energy, organic fertilizer, raw material for the pharmaceutical industry, or as a feed or food product, highlighting circular bioeconomy potential and significance. Although individual valorization pathways of lavender post-distillation residues have been explored, their comprehensive assessment as a multipurpose resource remains limited. This study addresses this gap through a systematic characterization of pellet properties, providing a foundation for future cascading uses and advancing circular economy strategies.

2. Materials and Methods

2.1. Chemicals and Solvents

Formic acid, methanol and ethanol were purchased from POCH (Gliwice, Poland). Gallic acid, caffeic acid, chlorogenic acid, ferulic acid, rutin, rosmarinic acid, *p*-coumaric acid, *trans*-cinnamic acid, quercetin-dihydrate and quercitrin were purchased from Sigma-Aldrich GmbH (Sternheim, Germany).

2.2. Experimental Workflow

Lavender (*L. angustifolia* cv. Primorska) was grown in Bački Petrovac at the experimental fields of the Department of Alternative Crops, Institute of Field and Vegetable Crops Novi Sad (IFVCNS). Aerial parts (flowers, leaves, and stems) from a three-year-old plantation were manually harvested at full bloom at the end of June 2025 and distilled using a semi-industrial distillation unit at the same department. Briefly, approximately 100 kg of fresh plant material was placed in a stainless-steel vessel, supplied with steam, and distilled for 3 h.

After the distillation process was completed, the lavender solid waste was transferred from the stainless-steel vessel to a solar dryer, where it was dried for 2 days (final moisture content: 7.96%), and then ground using an industrial electric hammer mill with a 1.5 mm sieve. The ground plant material was subsequently pelletized using water (approximately 1.5 L per 10 kg of plant material) without any additional binders, with a pellet press machine (model KL200B; Henan Yishen Machinery Co., Ltd., Zhengzhou, China) operating at temperatures between 80 °C and 100 °C with a die diameter of 6 mm.

The overall methodology is schematically presented in Figure 1, providing a visual overview of the process from lavender plant material in the field to steam distillation, the drying of post-distillation residues, milling, and pellet production as the final product.

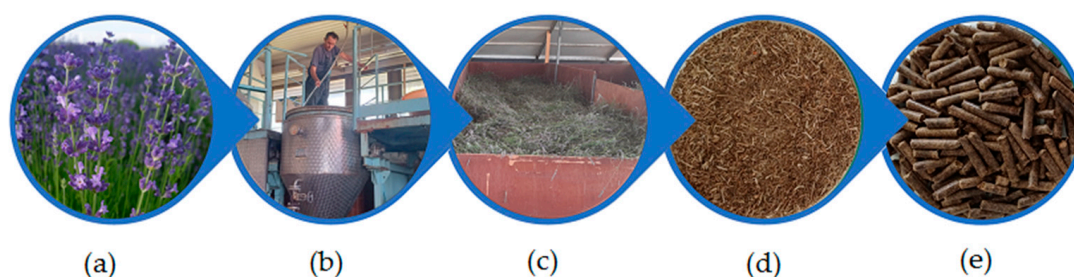


Figure 1. Workflow of lavender post-distillation residue processing: (a) lavender plant material; (b) preparation for steam distillation—filling a stainless-steel vessel with plant material; (c) drying post-distillation lavender residue in a solar dryer; (d) milled post-distillation residues (sieve size 2 mm); and (e) produced lavender pellets.

2.3. Moisture and Ash Analysis

Moisture content was determined in accordance with EN 14774-2 [39] (biofuels), EN 12048 [40] (solid fertilizers), and ISO 6496 [41] (animal feeding stuffs) standards. The procedure was based on a gravimetric method involving measurement of the sample mass before and after drying. Ash content was determined in accordance with EN 14775 [42], EN

13040 [43], and ISO 5984 [44] standards for biofuels, solid fertilizers, and animal feeding stuffs, respectively. Samples previously dried for moisture analysis were placed in a furnace at 550 °C for 6 h.

2.4. Energy Characterization of Lavender Pellets

The higher heating value (HHV) of the samples was determined using an IKA C2000 calorimeter, in accordance with the standard procedure defined by the EN 14918 standard [45]. Before measurement, the samples were oven-dried to ensure consistent and comparable results. Approximately 1 g of the sample of lavender pellets was weighed with an analytical balance (accuracy ± 0.0001 g) and placed into the combustion crucible. The crucible was inserted into the decomposition vessel (bomb), which was then filled with oxygen at a pressure of 30 bar. The bomb was placed into the calorimeter's inner vessel, which was filled with a known quantity of water. The system was sealed, and the measurement was initiated. During the process, the sample underwent complete combustion in the oxygen-rich environment, and the released heat was transferred to the surrounding water. A high-precision sensor continuously recorded the temperature increase in the water. Based on the temperature rise and the known heat capacity of the system (previously calibrated), the calorimeter calculated the HHV of the sample. All measurements were performed in triplicate to ensure accuracy and repeatability. Results were expressed in kJ/kg on a dry basis.

Then, the lower heating value (LHV) was calculated on a dry basis (1), ash-free dry basis (2), and wet basis (3) for lavender pellets using the following formulas:

$$\text{LHV}_{\text{db}} = \text{HHV}_{\text{db}} - 206 \cdot \text{H}_2 \quad (1)$$

$$\text{LHV}_{\text{af}} = \text{LHV}_{\text{db}} \cdot \frac{100}{100 - A_{\text{d}}} \quad (2)$$

$$\text{LHV}_{\text{wb}} = \text{LHV}_{\text{db}} \cdot \frac{100 - M}{100} - 23 M \quad (3)$$

where

HHV_{db}—higher heating value on a dry basis (kJ/kg),

LHV_{db}—lower heating value on a dry basis (kJ/kg),

LHV_{af}—lower heating value on an ash-free dry basis (kJ/kg),

LHV_{wb}—lower heating value on a wet basis (kJ/kg),

H₂—hydrogen content of the sample (db-%),

A_d—ash content on a dry basis (db-%),

M—moisture content of the sample (wb-%).

The energy of vaporization of water at 25 °C is 41.53 kJ/mol, corresponding to 206 kJ/kg per 1% (m/m) of hydrogen in the fuel sample, or 23 kJ/kg per 1% (m/m) of moisture, as defined by the EN 14918 [45] standard. For the purposes of this study, the hydrogen content (H₂) was not determined experimentally; instead, a literature value of 5.8% was adopted for lavender biomass [28].

2.5. Chemical Characterization of Lavender Pellets for Soil Amendments

To assess the potential of lavender post-distillation residues in pellet form as a soil amendment, a comprehensive chemical characterization was conducted. The analysis targeted key parameters related to soil fertility and environmental safety, including pH, moisture, ash content, organic matter, total and organic carbon, macro- and micronutrients, and potentially toxic heavy metals, which were found to be well within safety limits for agricultural application in accordance with Regulation (EU) 2019/1009.

Organic matter was calculated as the loss on ignition (LOI) at 550 °C, according to the EN 13039 standard [46]. Total nitrogen (N) and carbon (C) contents were determined through the total combustion method using a CNS elemental analyzer (DM 8/1-3-091), which simultaneously quantifies carbon, nitrogen, and sulfur in solid samples. Total organic carbon (TOC) was determined in accordance with ISO 10694. Macro- (P, K, Ca, Mg) and micronutrients (Al, B, Cu, Fe, Na, Mn, Zn) were analyzed after microwave-assisted acid digestion of the samples, following US EPA Method 3051A. Elemental concentrations were quantified using inductively coupled plasma optical emission spectroscopy (ICP-OES). Heavy metals (Cd, Cr, Ni, Pb) were also determined using ICP-OES after acid digestion, in accordance with the EN 16963 standard for fertilizers and soil improvers. Total mercury (Hg) was quantified using a direct mercury analyzer (DMA-80, Milestone) based on thermal decomposition, gold amalgamation, and atomic absorption spectrometry, following US EPA Method 7473. Values below the limit of detection (LOD) are reported as <LOD and were determined based on the analytical performance of the applied methods and instrument-specific detection limits.

To ensure analytical accuracy, a reference sample of commercial mineral fertilizer (Yara Mila Cropcare 11:11:21) was used as a control for the determination of N, P, and K. For the validation of results related to secondary and trace elements, a certified reference material provided by BIPEA (Sample No. 8-3424-0079, PT: 24—mineral fertilizer) was included as part of the quality control protocol.

2.6. Chemical Characterization of Lavender Pellets for Recovery of Bioactive Compounds

2.6.1. Extract Preparations

Aqueous extracts (infusions and decoction) and ethanol extract (via maceration with 70% ethanol during 72 h) were prepared using a 1:10 (*w/w*) biomass:solvent ratio. Infusion preparation included the pouring of boiling water over the pellets and extraction for 15 min, while the decoction was prepared by boiling pellets with water for 30 min. After filtration and evaporation to dryness, the extraction yield (dry extract content—d.e.) was determined for each.

2.6.2. Chemical Characterization

The levels of ten polyphenolic compounds in lavender pellet extracts were determined using high-performance liquid chromatography (HPLC-DAD; Agilent Technologies 1100, Santa Clara, CA, USA) according to the previously developed and validated analytical method by our research group [47,48]. Samples were prepared in a mobile phase mixture and analyzed using a Nucleosil C18 column using a gradient elution with 1% formic acid and methanol. Flow rates and detection wavelengths were optimized for efficient separation and accurate quantification. Calibration curves were established using standard compounds, with detection carried out at 280, 330, and 350 nm depending on the analyte.

2.7. Evaluation of Microbiological and Nutritional Properties of Lavender Pellets

To evaluate the potential use of lavender pellets in animal nutrition, their microbiological and nutritive value were analyzed, along with their amino acid and fatty acid profiles.

2.7.1. Microbiological Safety Analysis

Microbiological safety analysis included the enumeration of total aerobic bacteria (ISO 4833-1), yeasts and molds (ISO 21527-2), Enterobacteriaceae (ISO 21528-2), and specific pathogenic indicators such as *Salmonella* spp. (ISO 6579-1), beta-glucuronidase-positive *Escherichia coli* (ISO 16649-2), coagulase-positive staphylococci (ISO 6888-1), and *Clostridium perfringens* (ISO 7937) [49–55]. Water activity (*aw*) in the samples was determined using a multifunction device, Lab Swift-*aw* (Novasiana AG, Lachen, Switzerland), to measure

aw values. The determination procedure included filling the measuring vessel to 2/3 of its height, which is placed in the measuring chamber of the device, and the measuring process is performed at a constant room temperature ($\approx 23\text{ }^{\circ}\text{C}$) until the measurement stability is established on the display. Water activity value tests were performed in triplicate.

2.7.2. Nutritional Composition

Cellulose content was determined according to the ISO 6865 method [56]. Fat content was determined through Soxhlet extraction with prior acid hydrolysis, following ISO 6492. Protein content was assessed through the Kjeldahl method according to ISO 5983-1 [57], using a nitrogen-to-protein conversion factor of 6.25.

2.7.3. Determination of Amino Acid Composition

Amino acid analyses of the lavender pellets were performed through ion exchange chromatography using an Automatic Amino Acid Analyzer Biochrom 30+ (Biochrom, Cambridge, UK) [58]. The technique was based on amino acid separation using strong cation exchange chromatography, followed by the ninhydrin color reaction and photometric detection at 570 nm, except for proline, which was detected at 440 nm. Samples were previously hydrolyzed in 6 M HCl (Merck, Germany) at $110\text{ }^{\circ}\text{C}$ for 24 h. After hydrolysis, samples were cooled to room temperature and dissolved in 25 mL of Loading buffer (pH 2.2) (Biochrom, Cambridge, UK). Subsequently, the prepared samples were filtered through a $0.22\text{ }\mu\text{m}$ pore size PTFE filter (Plano, TX, USA), and the filtrate was transferred into a vial (Agilent Technologies, Santa Clara, CA, USA) and stored in a refrigerator prior to analysis. The amino acid peaks were identified through a comparison of retention times with the retention times of an amino acid standard purchased from Sigma Aldrich (Amino Acid Standard Solution (Sigma-Aldrich, St. Louis, MO, USA)). The results were expressed as mass of amino acid (g) in 100 g of sample.

2.7.4. Determination of Fatty Acid Composition

Lipids were extracted from the sample using a cold extraction method with a chloroform:methanol mixture (2:1, *v/v*) by shaking for 2.5 h. The extracted lipids were then transesterified into fatty acid methyl esters (FAMES) following the ISO 12966-2 standard method. The resulting FAMES were analyzed using an Agilent 7890A gas chromatograph equipped with a flame ionization detector (Agilent Technologies, Santa Clara, CA, USA). Separation was performed on an SP-2560 fused silica capillary column ($100\text{ m} \times 0.25\text{ mm}$ i.d., film thickness $0.20\text{ }\mu\text{m}$; Supelco, Bellefonte, PA, USA). The injector and detector temperatures were set to $250\text{ }^{\circ}\text{C}$. The column oven temperature was initially held at $140\text{ }^{\circ}\text{C}$ for 3 min, then increased to $220\text{ }^{\circ}\text{C}$ at a rate of $3\text{ }^{\circ}\text{C}/\text{min}$ and held for 5 min. Subsequently, the temperature was raised to $240\text{ }^{\circ}\text{C}$ at a rate of $2\text{ }^{\circ}\text{C}/\text{min}$ and maintained for 10 min. FAME identification was performed by comparing retention times with those of a standard reference mixture (Supelco 37 Component FAME Mix, Sigma-Aldrich, St. Louis, MI, USA). The results were expressed as grams of each identified fatty acid per 100 g of total FAMES.

2.8. Statistical Analysis

All measurements of the investigated parameters were performed in triplicate, and the results are presented as mean $\pm$ SD.

3. Results

3.1. Moisture and Ash Content

Moisture and ash content analyses are crucial parameters for assessing the water and inorganic mineral fractions in a sample and are widely used to evaluate fuel, material,

and food quality, safety, and nutritional value. In this study, the use of different standards reflects the multifunctional potential of lavender solid residues, enabling their evaluation across bioenergy, soil-related, and animal feed applications within a circular economy framework. The results for moisture and ash content are presented in Table 1. The moisture content of lavender pellets varied slightly depending on the standard applied and the intended application (4.53–5.78%). These results indicate that lavender pellets have a low moisture content across all applications, which is favorable for storage stability and suitability as a biofuel, as a high moisture content can reduce combustion efficiency and promote microbial degradation. Ash content, expressed on a dry matter basis, varied between 10.23% and 12.60%. Overall, these analyses confirm that lavender solid residues possess properties suitable for multiple valorization routes. The small variations observed among different standards reflect the multifunctional potential of these residues, supporting their integration into a circular economy framework, where the same biomass can serve as a fuel, soil amendment, or feed resource.

Table 1. Evaluation of lavender pellets according to different standards for biofuels, solid fertilizers, and animal feeding stuffs; (mean $\pm$ SD, %).

Parameter	Value		
	For Biofuels ¹	For Solid Fertilizers ²	For Animal Feeding Stuffs ³
Moisture content	5.51 $\pm$ 0.10	5.78 $\pm$ 0.15	4.53 $\pm$ 0.02
Ash content	12.64 $\pm$ 0.55	10.23 $\pm$ 0.12	10.30 $\pm$ 0.04

¹ According to EN 14774-2/EN 14775 [39,42]; ² according to EN 12048/EN 13040 [40,43]; ³ ISO 6496/ISO 5984 [41,44].

3.2. Properties of Lavender Pellets as Solid Fuel

Table 2 presents the results of the energy characterization of lavender pellets. The HHV of the pellets was measured at 18,900 kJ/kg, while the LHV on a wet basis, representing the usable energy content of the fuel, was calculated to be 16,603 kJ/kg, equivalent to approximately 4.6 kWh/kg. For context, the LHV of 16.6 MJ/kg (wet basis) is comparable to that of conventional wood pellets, which typically exhibit around 17 MJ/kg at an 8% moisture content, and exceeds that of corn cob pellets, which have about 15 MJ/kg at 9% moisture [59,60]. These results indicate that lavender pellets can be considered a high-quality solid biofuel rather than a lower-grade alternative.

Table 2. Energy properties of lavender pellets as a solid fuel (mean $\pm$ SD, kJ/kg).

Parameter	Value
Higher heating value on a dry basis (HHV db)	18,900 $\pm$ 204
Lower heating value on a dry basis (LHV db) *	17,705
Lower heating value on an ash free basis (LHV af) *	20,267
Lower heating value on a wet basis (LHV wb) *	16,603

* LHV (db, af, and wb) was calculated from the HHV according to Formulas (1)–(3).

3.3. Soil Amendments Potential of Pelleted Lavender Residue

The chemical composition of the lavender pellets indicates their potential as a soil amendment (Table 3). The material appeared olive-brown in color, with a slightly acidic pH (5.69). The organic matter content in the examined fertilizer was very high (87%), which is particularly beneficial for soils with a low water-holding capacity. Organic matter enhances the soil's ability to retain moisture, making this characteristic especially valuable. Additionally, the lavender post-distillation solid residue pellets demonstrated a favorable macronutrient profile, with a total nitrogen (N) content of 1.30%, phosphorus as P₂O₅ at 0.39%, and potassium as K₂O at 1.13%. These values are consistent with the ranges reported

for organic fertilizers, such as composts and manures. In addition to macronutrients, the lavender pellets also contain significant levels of secondary nutrients and micronutrients essential for plant growth.

Table 3. Main chemical parameters of lavender pellets (mean $\pm$ SD).

Parameter	Value
pH (H ₂ O)	5.69 $\pm$ 0.02
N (%)	1.30 $\pm$ 0.06
P ₂ O ₅ (%)	0.39 $\pm$ 0.02
K ₂ O (%)	1.13 $\pm$ 0.05
Total C (%)	43.74 $\pm$ 0.32
Organic C (%)	41.93 $\pm$ 0.29
Organic matter (%)	83.99 $\pm$ 0.22
Ca (mg/kg)	9681.5 $\pm$ 302.0
Mg (mg/kg)	2921 $\pm$ 164
Na (mg/kg)	1159 $\pm$ 86
Al (mg/kg)	1527 $\pm$ 74
B (mg/kg)	29.36 $\pm$ 1.00
Cu (mg/kg)	9.42 $\pm$ 0.60
Fe (mg/kg)	2136 $\pm$ 126
Mn (mg/kg)	43.33 $\pm$ 2.00
Zn (mg/kg)	32.43 $\pm$ 2.50
Cd (mg/kg)	<LOD (1.5)
Cr (mg/kg)	12.01 $\pm$ 0.35
Ni (mg/kg)	<LOD (2.0)
Pb (mg/kg)	<LOD (2.0)
Hg (mg/kg)	0.0081 $\pm$ 0.0005

LOD—limit of detection.

Micronutrient concentrations in the lavender pellets were also favorable. Iron (Fe: 2136 mg/kg) and zinc (Zn: 32.43 mg/kg) were within agronomically beneficial ranges, while copper (Cu: 9.42 mg/kg) and manganese (Mn: 43.33 mg/kg) contribute to an adequate micronutrient supply for most crops. Boron (B: 29.36 mg/kg) was present in relatively high concentrations compared to typical composts. This is particularly advantageous in calcareous soils, where a high pH and carbonate content often limit B availability through precipitation and adsorption processes. However, excessive boron levels may cause phytotoxic effects in sensitive crops; therefore, application rates should be carefully adjusted according to soil properties and crop requirements.

Importantly, concentrations of heavy metals in the pellets were well below national and EU regulatory limits for organic fertilizers. Cadmium (Cd), nickel (Ni), and lead (Pb) were below detection limits (<1.5, <2.0, and <2.0 mg/kg, respectively), while mercury (Hg) was detected at only 0.0081 mg/kg. Only chromium (Cr) was quantified at 12.01 mg/kg, still far below the commonly accepted threshold of 100 mg/kg.

3.4. Lavender Pellets for Recovery of Bioactive Compounds

The application of ethanol (70%, *v/v*) for extraction resulted in an extract yield of 13.04%, whereas for water-based extractions the yield was slightly higher, with 15.60% for decoction and 21.66% for infusion (Table 4). It can be assumed that the higher yields of aqueous extracts are the result of a higher water affinity toward compounds such as polysaccharides, especially pectin-type. As can be seen from the table, infusion and decoction generally produced lower gallic acid but higher levels of chlorogenic acid and rosmarinic acid compared to ethanol extraction. Decoction, in particular, showed the highest levels of chlorogenic acid (8.53 mg/g d.e.) and rosmarinic acid (8.21 mg/g d.e.). Other flavonoids, such as quercetin, rutin, and quercitrin, were mainly detected in water ex-

tracts, with quercetin being the highest in decoction (1.42 mg/g d.e.). Overall, water-based extraction (infusion or decoction) was more effective in extracting bioactive polyphenols such as rosmarinic and chlorogenic acids, whereas ethanol favored gallic acid extraction. These results suggest that the choice of extraction method strongly influences the profile of bioactive compounds obtained from lavender pellets. The residual compounds in the plant material, including phenolics and flavonoids, remain stable during pelletization, as they have already been exposed to high temperatures during the distillation process, preserving their extractability for subsequent applications.

Table 4. Comparison of polyphenol profiles of lavender pellets using different extraction methods (mean $\pm$ U, mg/g of dry extract).

Compound	Maceration with 70% Ethanol (72 h)	Infusion	Decoction
<i>Trans</i> -cinnamic acid	<LOD	<LOD	<LOD
Caffeic acid	<LOD	0.49 $\pm$ 0.02	0.26 $\pm$ 0.01
<i>p</i> -coumaric acid	<LOD	<LOD	<LOD
Quercetin	<LOD	0.19 $\pm$ 0.01	1.42 $\pm$ 0.10
Chlorogenic acid	0.44 $\pm$ 0.02	4.13 $\pm$ 0.21	8.53 $\pm$ 0.43
Rosmarinic acid	0.24 $\pm$ 0.01	6.73 $\pm$ 0.40	8.21 $\pm$ 0.49
Ferulic acid	0.30 $\pm$ 0.02	0.19 $\pm$ 0.01	0.83 $\pm$ 0.05
Gallic acid	6.11 $\pm$ 0.92	0.06 $\pm$ 0.01	0.05 $\pm$ 0.01
Rutin	<LOD	3.55 $\pm$ 0.28	0.85 $\pm$ 0.07
Quercitrin	<LOD	0.89 $\pm$ 0.04	0.18 $\pm$ 0.01
Extraction yield (%)	13.04	21.66	15.60

LOD—limit of detection; U—expanded measurement uncertainty with 95% confidence level ($k = 2$).

3.5. Characterization of Lavender Pellets for Nutritional Properties and Feed Application

The utilization of lavender solid post-distillation residues processed into pellets represents a promising strategy within the framework of the circular economy, particularly regarding their potential application in animal nutrition. However, their suitability as a functional feed ingredient or dietary supplement requires comprehensive characterization in terms of safety and nutritional quality. From a safety perspective, feed materials must comply with established microbiological criteria, as microbial contamination can adversely affect animal health and feed stability. In this context, water activity (a_w) is a critical parameter, as it directly reflects the inherent resistance of the material to microbial spoilage. The measured a_w of 0.437 is well below the thresholds for mold growth (>0.60) and bacterial growth (>0.85), confirming that the pellets are intrinsically stable. Therefore, the assessment of microbial load, expressed as colony-forming units per gram (CFU/g), is a fundamental parameter for evaluating the hygienic quality of lavender pellets. The determination of total aerobic mesophilic bacteria, yeasts and molds, as well as the absence or acceptable limits of pathogenic microorganisms, is essential to ensure the safe inclusion of lavender pellets in animal diets.

The results are presented in Table 5. As shown in this table, the microbiological quality of lavender pellets was assessed by enumerating total aerobic bacteria, yeasts and molds, Enterobacteriaceae, *Salmonella* spp., β -glucuronidase-positive *Escherichia coli*, coagulase-positive staphylococci, and *Clostridium perfringens*. All tested parameters were within safe limits, and no pathogenic microorganisms were detected, further confirming the high inherent storage stability of the pellets.

The nutritive value of lavender pellets, including crude proteins, cellulose, and fats, is crucial for their feed potential, influencing digestibility and energy contribution. These values are presented in Table 6. The protein content, averaging 9.38%, suggests that lavender pellets are not suitable as a primary protein source; however, they can serve as

a complementary protein contributor when included in balanced feed formulations. The cellulose content was high (33.38%), reflecting the fibrous nature of lavender biomass. Such a level of structural carbohydrates may limit energy availability, particularly in monogastric species, but can be beneficial in ruminant nutrition. In ruminants, higher fiber fractions stimulate rumen fermentation, enhance chewing activity, and support gut health. Therefore, lavender pellets are best positioned as a fiber supplement rather than as an energy- or protein-rich feed component. Crude fat content was low (2.18%), which is consistent with the expectations for plant residues. Although fat improves energy density and palatability, the observed values indicate that lavender pellets cannot be regarded as energy-dense feedstuff. Nonetheless, the quality and profile of fatty acids, rather than their quantity alone, may be of particular interest and warrant further investigation.

Table 5. Safety parameters of lavender pellets (mean $\pm$ SD, CFU/g).

Parameter	Content
Total viable count	200
Total count of yeast and molds	<10
Enterobacteriaceae	<10
<i>Salmonella</i> spp.	n.d.
<i>E. coli</i>	<10
Coagulase-positive staphylococci	<100
<i>Clostridium perfringens</i>	<10
Water activity (aw)	0.437 $\pm$ 0.009

n.d.—not detected.

Table 6. Protein, cellulose, and fat content of lavender pellets (mean $\pm$ SD, %).

Parameter	Content
Proteins	9.38 $\pm$ 0.15
Cellulose	33.38 $\pm$ 0.11
Fats	2.18 $\pm$ 0.02

Protein content is of particular importance; however, protein quality, i.e., the amino acid composition, is a critical determinant of nutritional value, as it defines the availability of essential amino acids required for growth, maintenance, and metabolic functions in animals. The amino acid composition of lavender pellets is presented in Table 7. The results showed that the total amino acid content reached 8.91 g/100 g and exhibited a favorable profile, particularly with regard to lysine, which is the limiting amino acid in many plant-based proteins. The sum of essential amino acids (TEAAs), including threonine, valine, methionine, isoleucine, leucine, phenylalanine, histidine, and lysine, was 3.27 g/100 g, accounting for 36.70% of the total amino acids (TAAs). Leucine was the most abundant essential amino acid, while methionine, typically low in plant proteins, was present at the lowest level. Among the non-essential amino acids, aspartic and glutamic acids together accounted for the largest portion, representing 48.76% of non-essential amino acids (TNAAs) and 30.86% of total amino acids (TAAs).

Although the total fat content of the lavender pellet is relatively low, its fatty acid profile is highly favorable (Table 8). In the pellet, saturated fatty acids (SFAs) accounted for 35.20% of the total fatty acids, with palmitic acid being the most predominant, comprising 23.91%. Other SFAs, including myristic, stearic, arachidic, and behenic acid, were present in smaller proportions. Monounsaturated fatty acids (MUFAs) made up 28.58% of the total, with oleic acid being the dominant MUFA at 27.39%. Polyunsaturated fatty acids (PUFAs) represented the largest group, contributing 36.22% to the overall fatty acid content. Among the PUFAs, linoleic acid and α -linolenic acid were the most abundant, comprising 16.24%

and 17.87%, respectively. The resulting ω -6/ ω -3 ratio of 1.03 (corresponding to an ω -3/ ω -6 ratio of 0.97) highlights the nutritional value of the pellets for functional livestock diets.

Table 7. Total amino acid composition of the lavender pellets (mean $\pm$ SD, g/100 g of sample).

Amino Acids	Content
Aspartic acid	1.24 $\pm$ 0.02
Threonine *	0.49 $\pm$ 0.01
Serine	0.56 $\pm$ 0.01
Glutamic acid	1.51 $\pm$ 0.01
Proline	0.35 $\pm$ 0.01
Glycine	0.58 $\pm$ 0.00
Alanine	0.65 $\pm$ 0.01
Cystine	n.d.
Valine *	0.64 $\pm$ 0.01
Methionine *	0.03 $\pm$ 0.00
Isoleucine *	0.40 $\pm$ 0.01
Leucine *	0.73 $\pm$ 0.02
Tyrosine	0.33 $\pm$ 0.00
Phenylalanine *	0.49 $\pm$ 0.01
Histidine *	0.14 $\pm$ 0.00
Lysine *	0.35 $\pm$ 0.01
Arginine	0.42 $\pm$ 0.02
Total essential amino acids (TEAAs)	3.27 $\pm$ 0.07
Total non-essential amino acids (TNEAAs)	5.64 $\pm$ 0.08
Total amino acids (TAAs)	8.91 $\pm$ 0.15

n.d.—not detected; *—essential amino acids.

Table 8. Total fatty acid composition of lavender pellets (mean $\pm$ SD, g/100 g of sample).

Fatty Acid	Content
Myristic (C14:0)	1.28 $\pm$ 0.06
Palmitic acid (C16:0)	23.91 $\pm$ 0.04
Stearic (C18:0)	4.30 $\pm$ 0.03
Arachidic (C20:0)	2.76 $\pm$ 0.01
Behenic acid (C22:0)	2.95 $\pm$ 0.02
Σ SFA	35.20 $\pm$ 0.16
Palmitoleic acid (C16:1)	1.18 $\pm$ 0.01
Oleic acid (C18:1n9c)	27.39 $\pm$ 0.04
Σ MUFA	28.58 $\pm$ 0.05
Linoleic acid (C18:2n6c)	16.24 $\pm$ 0.04
α -linolenic acid (C18:3n3)	17.87 $\pm$ 0.06
Eicosadienoic acid (C20:2n6)	1.27 $\pm$ 0.02
Arachidonic acid (C20:4n6)	0.84 $\pm$ 0.01
Σ PUFA	36.22 $\pm$ 0.13
ω -3 PUFA	17.87 $\pm$ 0.03
ω -6 PUFA	18.35 $\pm$ 0.02
ω -6/ ω -3	1.03 $\pm$ 0.02
ω -3/ ω -6	0.97 $\pm$ 0.02

SFA—saturated fatty acid; MUFA—monounsaturated fatty acid; PUFA—polyunsaturated fatty acid.

4. Discussion

4.1. Proximate Composition

In this study, the analyses showed that lavender pellets are low in moisture (4.53–5.78%), indicating their excellent storage stability. The literature indicated that the moisture content in post-distillation lavender and lavandin straw ranged from 6.65 to 7.6%, depending on the plant part (stem or flower) [26], while that of lavender pellets

was 5.14% [36]. By contrast, the results from this study indicated that lavender pellets are rich in minerals (ash content 10.23–12.60%), while the results from the literature indicated that the ash content of lavender post-distillation residues varied between 5.41 and 8.56% [15,20,28,36]. The higher ash content in this study likely reflects the influence of cultivar, local soil conditions, or a higher proportion of woody stems. The high mineral value indicated its potential use as a soil amendment or food and feed additive, as well as an impact on combustion when used as fuel.

4.2. Solid Fuels

The LHV on a wet basis of the lavender pellets exceeded 4.0 kWh/kg, meeting the minimum energy requirement of the ISO 17225-6 standard [61] for non-woody pellets. This performance is largely attributed to the low moisture content (>10%) exceeding the maximum limits for both Class A ($\leq 6\%$) and Class B ($\leq 10\%$) pellets, preventing classification within these standard categories. Thus, while the pellets exhibit adequate energy potential, the high ash content may limit their suitability as a solid biofuel. On a dry basis, the LHV is compared with other agricultural residues such as corn cobs or straw, indicating a competitive energy content among non-woody biomass sources [59,60]. Lavender post-distillation residues can be efficiently converted into high-durability biomass pellets with stable combustion, moderate ash content (8.56%), and a high calorific value (4325 kcal/kg), making them suitable for renewable energy production in both industrial and household systems [36]. To maintain ash content within the acceptable range for residential-quality pellets, lavender residues were co-pelletized with fir (*Abies alba*) or pine (*Pinus nigra* and *P. brutia*) wood [37,38]. Lavender biomass alone shows a relatively high ash content (5.93%), necessitating blending with woody biomass [37]. Increasing the lavender content slightly raised the moisture levels, which positively influenced mechanical durability, and pellets with higher lavender participation exhibited improved mechanical strength. Although lavender slightly reduces calorific value compared to fir, its incorporation in mixed pellets remains suitable for residential biofuel applications. Studies indicate that lavender waste can be used up to 15% in combination with pine wood to produce high-quality residential pellets [38]. Its inclusion enhances mechanical strength, dimensional stability, hydrophobicity, and bulk density, with only a minor, non-significant decrease in calorific value. Overall, lavender lignocellulosic residues are appropriate for producing high-performance residential pellets when limited to 15% of the feedstock.

4.3. Soil Amendment

Post-distillation lavender solid residues contain 91.91% organic matter [13], whereas our study reported a lower concentration of 83.99%. Moreover, lavender post-distillation residues are characterized by a high carbon content, generally ranging from approximately 41 to 51% of dry matter, as consistently reported across multiple studies [11,13,28,29,31,36]. In line with these findings, our results indicate a carbon content of 43.74%, which is in full agreement with the reported values. By comparison, high-quality composts typically contain lower levels of organic matter, rarely exceeding 50% of dry matter [62,63]. Moreover, the high organic carbon content (over 41%) is comparable to that of manure and considerably higher than in most composts [64]. This supports the potential of these residues to improve soil physical properties and water retention, particularly in degraded or sandy soils.

The nitrogen content in lavender post-distillation residues is relatively low, generally ranging from about 1.2 to 1.6%, as reported across several studies [11,13,28,29,31,36]. In agreement with these reports, the nitrogen content determined in this study was 1.3%. By comparison, the nitrogen content in high-quality composts typically ranges from 0.6% to

1.5%, depending on the feedstock and maturity, with animal manure composts reaching the upper end of this range [65]. The phosphorus content (0.39% P_2O_5) falls within typical compost ranges of 0.3–0.6% [64], while the potassium content (1.13% K_2O) aligns with values reported for green biomass and manure composts [62,66]. Overall, the NPK composition indicates that lavender pellets can effectively contribute to nutrient supply in agricultural soils, comparable to traditional organic amendments. Furthermore, the application of lavender post-distillation solid residues at rates of 2% and above (up to 8%) has been shown to significantly increase soil electrical conductivity, organic carbon, total nitrogen, C/N ratio, and the availability of P, K, B, Cu, and Mn [12]. Due to the relatively high C/N ratio, the application of lavender pellets may induce temporary nitrogen immobilization during microbial decomposition, potentially reducing nitrogen availability to plants in the short term, as commonly observed for organic amendments with a high carbon content [65]. Therefore, their use is more suitable as a long-term soil conditioner rather than a rapid nutrient source. To mitigate this effect, co-application with nitrogen-rich materials (e.g., manure or mineral fertilizers) can be recommended.

Among secondary elements, lavender post-distillation solid residues in this study contained considerable amounts of calcium (9681.5 mg/kg) and magnesium (2921.0 mg/kg), which are comparable to those in cattle manure and mixed organic composts [62,65]. The elemental composition of lavender post-distillation solid waste was Ca 1.2057 wt.%, K 0.9593 wt.%, and Mg 0.3718 wt.%, with Cr, Na, Zn, Cu, and Mn also present [34]. Heavy metals in lavender pellets in this study were well below regulatory limits, with Cr at 12.01 mg/kg and all others at or below detection limits [65,67].

Lavandin post-distillation solid waste has been reported to exert allelopathic and phytotoxic effects on seed germination and seedling growth, particularly in monocot crops such as wheat and barley, largely due to the presence of lysophosphatidylcholine, indicating that caution is needed when considering its direct application to agricultural soils [25]. In contrast, the vermicomposting of lavender waste resulted in compost with a germination index above 100, suggesting the absence of phytotoxicity and its suitability as a soil amendment after proper treatment, although this process involved co-composting lavender residues with horse manure and *Eisenia andrei* under controlled laboratory conditions [14].

Considering that the pH of lavender post-distillation solid residues is slightly acidic, this material is regarded as advantageous for use as a fertilizer in alkaline soils in Mediterranean regions [12], as well as in the Vojvodina province [68]. The relatively high concentration of boron in lavender pellets can help alleviate boron deficiency, which is common in alkaline soils [69,70]. Overall, the nutrient and micronutrient profile of lavender pellets reflects a well-balanced organic amendment. These results confirm that the material poses no environmental risk from heavy metals and complies with the compost quality standards established for sustainable agricultural practices. Their use can improve soil fertility by increasing organic carbon and phosphorus and potassium availability, although it may also reduce available nitrogen and significantly increase manganese levels and electrical conductivity, potentially leading to nutrient imbalance and phytotoxicity at high application rates [12].

4.4. Recovery Bioactive Compounds

The results indicated that Spanish lavender post-distillation solid residue still contains important amounts of different polyphenolic compounds [21]. The qualitative analysis using HPLC-ESI-MS revealed that both true lavender and lavandin post-distillation solid residues were rich in phenolic acids and glycosylated flavonoids [19]. Dried and ground lavender residues were extracted with aqueous ethanol under varying conditions, and the purified extracts were chemically characterized through UHPLC-Q-Orbitrap-HRMS, reveal-

ing 42 compounds dominated by phenolic acids, flavonoids (including O-glycosylated luteolin derivatives), and other bioactive compounds such as organic acids, phenylpropanoids, aldehydes, alcohols, and ketones [22]. The extraction of bioactive compounds from post-distillation lavender residues using a non-ionic surfactant showed, via HPLC analysis, that isoferulic acid (33.97%) and p-coumaric acid (15.30%) were the main phenolic compounds, while kaempferol (6.48%) and rutin (6.17%) were the predominant flavonoids, followed by luteolin and quercetin [24]. The 70% ethanol extract of lavender post-distillation residues contains major phenolic acids, including ferulic (196.94–298.06 µg/mL) and rosmarinic (156.48–194.55 µg/mL) acids, as well as other phenolics (salicylic, p-coumaric, syringic, and protocatechuic acids) and flavonoids such as epicatechin (699.91–1258.14 µg/mL), rutin (176.66–208.79 µg/mL), catechin, hesperidin, and quercetin [20]. Steam-distilled lavender straw contained phenolic acids, including 3,4-dihydroxybenzoic (0.51 g/100 g), gallic (0.29 g/100 g), neochlorogenic (0.16 g/100 g), ferulic (0.16 g/100 g), and rosmarinic (0.13 g/100 g) acids, as well as flavonoids such as catechin (0.33 g/100 g), epicatechin (0.25 g/100 g), kaempferol, myricetin, quercetin-3-β-glucoside, and quercetin [15]. Phenolic compounds of industrial interest include rosmarinic acid, which is mainly found in flowers (67–78 mg/100 g, depending on whether it is lavender or lavandin), while its content in stalks is negligible, up to 4 mg/100 g [26].

4.5. Nutritional Properties and Feed Application

Although some authors highlight the potential of post-distillation lavender solid residues for reuse in the food and pharmaceutical fields [19,22], there are no available data on the microbiological safety of the raw material. However, several studies report antimicrobial activity [23,24], which may be associated with the microbiological safety of lavender post-distillation raw material. Moreover, the chemical analysis of the lavender pellets showed a low moisture content of 4.53%, which is highly favorable for storage stability and prolonging shelf life. Low moisture levels limit microbial growth and nutrient degradation, ensuring safe handling and extended usability in feeding systems. This observation is supported by the measured water activity (*a_w*) values, which were below 0.5 (0.437), as shown in Table 5. Water activity is a key indicator of the availability of free water for microbial growth and metabolic activity. At the recorded *a_w* level, the value is below the safety threshold where the growth of common food and feed bacteria is inhibited. Therefore, both the low moisture content and the reduced water activity suggest that the microbiological quality of the lavender pellets is likely to remain stable during storage, minimizing the risk of spoilage and maintaining the overall safety and integrity of the product.

Similar results were reported for lavender post-distillation waste material generated in Bulgaria, which contained 39.1% cellulose and 2.6% fats but a significantly lower protein content of only 1.2% [36]. Other results also indicated a high content of cellulose in lavender residues: 48.13 [29] and 38.16 g/100 g [15]. Post-distillation lavender solid residues contain 6.72–8.15% proteins [20]. Moreover, post-distillation lavender residues contained 5.95% acid-soluble polysaccharides, which were primarily composed of galacturonic acid (619.17 µg/mg) [27].

These findings are comparable to those of some forage-based feeds but remain considerably lower than protein-rich sources such as soybean meal or alfalfa [71,72]. Additionally, an analysis of the chemical composition of black pod by-products from the tree bean (*Parkia timoriana*) reported a cellulose content of 26.05% in large-type by-products [73]. The study highlighted that, although high fiber levels, including cellulose, may limit digestibility in monogastric species, they are beneficial for ruminants as they promote rumen fermentation and support overall gut health.

Overall, while previous studies reported the presence of individual amino acids in lavender post-distillation waste at trace levels, namely valine (0.42–0.76 µg/g), nor-valine (0.58–0.96 µg/g), leucine (0.60–1.18 µg/g), isoleucine (0.50–1.78 µg/g), proline (2.56–2.72 µg/g), glycine (1.91–2.28 µg/g), serine (0.17–0.23 µg/g), threonine (0.84–2.14 µg/g), aspartic acid (0.35–0.83 µg/g), phenylalanine (0.59–0.66 µg/g) and lysine (0.53–0.68 µg/g) [20], the present findings demonstrate a substantially higher total amino acid content and a more nutritionally relevant essential amino acid profile in lavender pellets, indicating an improved protein quality after processing. Although lavender pellets in animal feed are primarily valued for their essential oil content and associated calming and health-promoting effects, their contribution of protein and specific amino acids may support a more balanced diet, particularly when supplemented with limiting amino acids such as lysine and methionine. Protein quality is closely linked to amino acid composition, especially the presence of essential amino acids, which are crucial for growth, tissue repair and metabolic processes [58,74]. Overall, these results suggest that lavender pellets can contribute to improving the dietary amino acid profile, while combining different plant protein sources represents an effective strategy for achieving nutritionally balanced protein formulations and may offer a partial alternative to animal-derived proteins.

Previous reports indicate that four fatty acids were identified in lavender post-distillation solid residues, including two saturated acids, palmitic (0.84–4.82 µg/g) and stearic (0.45–0.58 µg/g), and two unsaturated acids, linoleic (0.26–0.50 µg/g) and α -linolenic (0.75–1.32 µg/g) [20]. In the current study, lavender pellets contained linoleic acid levels comparable to linseed cake and a relatively high α -linolenic acid content, exceeding that of rapeseed and sunflower cakes and similar to hempseed cake, indicating their potential as a PUFA source in animal feed [75]. Linoleic acid, an ω -6 PUFA, and α -linolenic acid, an ω -3 PUFA, are both classified as essential fatty acids. Because both humans and animals cannot synthesize these fatty acids endogenously, they must be consumed through diets. These fatty acids play fundamental roles in maintaining physiological health by preserving the cell membrane structure, modulating inflammatory and immune responses, and supporting metabolic functions [76]. The high α -linolenic acid content in lavender pellets suggests that their inclusion in animal feed could provide significant health benefits and support animal performance. Given the essential physiological roles of ω -3 fatty acids, ensuring adequate dietary intake through rich natural sources is crucial. The content of total ω -3 PUFAs in lavender pellets was 17.87 g/100 g, while the content of ω -6 PUFAs was 18.35 g/100 g. While both ω -6 and ω -3 PUFAs are essential, maintaining an appropriate balance between them is particularly important. An optimal dietary ratio of ω -6/ ω -3, generally considered to be 3:1 or lower, is associated with improved health outcomes and a reduced risk of inflammation-related conditions. In this study, the ratio was found to be 1.03, indicating an ideal balance. This ratio was found to be similar to that in camelina cake, while slightly lower than in linseed cake [75]. Regarding its fatty acid profile, the inclusion of lavender pellets in animal diets may help modulate the quality of animal-derived products such as eggs, meat, and milk, thereby supporting the production of functional foods with enhanced nutritional value. Moreover, a 1:1 ratio of ω -6/ ω -3 is widely considered an optimal target for functional livestock, as it directly reduces systemic inflammation, unlike simple protein or fat percentages. This ideal balance, often achievable through targeted supplementation, improves metabolic health, enhances product quality, and reduces chronic inflammatory disorders compared to high-grain diets [77].

4.6. Circular Bioeconomy Potential of Lavender Pellets

Overall, lavender post-distillation residues can be effectively converted into permanent biomass pellets with highly favorable properties. When used as fuel, they exhibit

stable combustion, moderate ash content, and a high calorific value, making them a high-quality raw material for biopellet production. In addition, they can serve as a nutrient-rich soil amendment, effectively improving soil fertility and its characteristics. Pellets are also a significant source of bioactive compounds, such as phenols and flavonoids (non-volatile fraction), which are of considerable industrial relevance. Furthermore, our research confirmed that lavender pellets can be used as a feed supplement for animals.

This multifunctional valorization highlights the potential of post-distillation residues to support circular bioeconomy strategies, offering simultaneous benefits in renewable energy production, agricultural sustainability, industrial extraction, and animal feed applications. The limitations of the study include the use of a single plant species from a single location and the potential variability in residue composition due to chemotype and distillation conditions. Future research should explore the optimization of pellet production, long-term soil improvement effects, in vivo feeding trials, and multi-cultivar and multi-environment studies to enhance the generalizability and practical applicability of these findings. These results also demonstrate that lavender pellets can be efficiently valorized using a cascade approach, allowing for sequential extraction followed by use for energy, soil improvement, or feed applications without a significant loss of functionality.

5. Conclusions

Lavender post-distillation solid residue is rich in organic matter (87%), including cellulose (33.38%), protein (9.38%), essential macronutrients (N 1.30%, P₂O₅ 0.39%, K₂O 1.13%), and micronutrients (Fe 2136 mg/kg, Zn 32.43 mg/kg, Cu 9.42 mg/kg, Mn 43.33 mg/kg, B 29.36 mg/kg), as well as amino acids (8.91 g/100 g), fatty acids (2.18%), phenolic acids (chlorogenic and rosmarinic), and flavonoids (quercetin, rutin, and quercitrin), while also exhibiting a high calorific value (HHV 18,900 kJ/kg). These characteristics indicate that pellets derived from lavender post-distillation residues can serve as a solid fuel, a soil amendment supporting fertility and moisture retention, a raw material for bioactive compound recovery, and a feed additive with a favorable fatty acid profile rich in polyunsaturated fractions. Microbiological and heavy metal analyses confirm their safety, highlighting the multifunctional valorization potential of lavender residues and their contribution to circular economy strategies.

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Abbreviations

The following abbreviations are used in this manuscript:

d.e.	Dry extract
HHV	Higher heating value
LHV	Lower heating value
LOD	Limit of detection
MUFA	Monounsaturated fatty acid
PUFA	Polyunsaturated fatty acid
SFA	Saturated fatty acid

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