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Characterization of Spent Mushroom Compost and Evaluation of Its Potential for Thermochemical Valorization through Ash Reduction Treatments

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Abstract: This study focuses on applying ash reduction treatments in order to explore the potential for industrial-scale thermochemical utilization of Spent Mushroom Compost (SMC). SMC is a waste byproduct generated by the mushroom industry. Typically, for every kilogram of produced mushrooms, five kilograms of SMC are discarded, with current disposal methods involving landfills or incineration, causing environmental problems. Utilizing SMC effectively presents challenges due to the inherent properties of this biomass type, characterized by high moisture and ash content, low fixed carbon content, and material heterogeneity. These attributes create difficulties when employing a thermochemical valorization route due to the low carbon content and mineral treatments involved. The results have unveiled the heterogeneous nature of the material and its individual components when physically separated. Among the three identified fractions (agglomerated, woody, and fines), the woody fraction showed the highest potential for thermochemical utilization. Notably, when subjected to washing with distilled water and citric acid treatments, it resulted in up to 66% ash reduction, a significant outcome. Other fractions of the material may find potential applications in agriculture. The effective utilization of such high-volume waste biomasses demands diverse and innovative approaches, underlining the urgency and complexity of the problem and the need to employ the principles of a circular economy.

Keywords: spent mushroom compost (SMC); residual biomass; ash reduction; thermochemical process; water pretreatment; citric acid

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1. Introduction

The increasing demand for mushrooms has driven significant growth in the industry, with an estimated global revenue of approximately 42.7 billion dollars between the years 2000 and 2020 [1]. However, the production of 1 kg of mushrooms results in 5 kg of post-industrial waste, predominantly in the form of spent mushroom compost (SMC) from cultivation beds after harvest [2]. The improper disposal of SMC, often through open field dumping or incineration [3], has been associated with extensive adverse effects on soil, water, and air quality [4]. This poses a notable environmental challenge for mushroom-producing industries [5,6]. Despite the potential for various applications, the effective integration and use of the volume of SMC produced during the production process, estimated to reach 104 million tons by 2026, are currently lacking [7].

Considering the volume of SMC generated from the production processes, various utilization alternatives have been studied, primarily at a laboratory scale. Jasínska et al. conducted studies on the use of SMC within the same mushroom cultivation process.

However, the results indicated that the enrichment of this residue is necessary due to nutrient losses for a new crop, leading to additional production costs. Furthermore, it is likely that the residue cannot be used for the same species from which it was extracted [8].

Its use as a type of fertilizer, compost, or organic amendment has also been the subject of research, with various authors reporting benefits related to the controlled application of the residue [9]. However, a commercially available product derived from SMC has not been developed due to its short shelf life resulting from its moisture content and microbial population.

On the other hand, studies conducted by Van Wik [10] aimed to evaluate this biomass as a dietary supplement for cattle, focusing on leveraging the nutritional properties of the residue for this species. The results indicated that, although there is potential for use, the high variability in nutritional content and neutral detergent fiber (NDF) necessitates further research in this area, as well as economic studies on the transformation of the residue into pellets for conservation and transport purposes.

A well-known but still developing avenue for biomass utilization is the thermochemical route, aimed at extracting both value-added products depending on the process and materials for energy applications. The recovery of biomasses such as SMC often involves utilizing thermochemical processes, including torrefaction and pyrolysis, to modify their properties. Typically, these methods subject the material to temperatures ranging between 200 and 1000 °C, reducing moisture and increasing fixed carbon and calorific values [11,12]. However, the properties of the SMC, such as high moisture content (over 40%), ash content (over 30%), low fixed carbon (less than 10%), and material heterogeneity, pose significant challenges [13,14]. As a result, thermochemical processes are characterized by low efficiency, poor mass and energy yields, and high operational costs [14,15].

To address these challenges in thermochemical valorization, treating the material to reduce ash content is essential, with techniques like washing and acid digestion being particularly prominent. However, it is crucial to first characterize the material to differentiate its identifiable fractions and determine their suitability for thermochemical processes or for alternative applications, such as organic fertilizers.

Research has been conducted on the application of treatments to biomasses such as rice husks, sugarcane bagasse, and SMC. Studies by Toor et al. and Tabish et al. [16,17] demonstrated the use of organic acids for digestion processes, resulting in an ash reduction of up to 66.9%. However, there is limited research on how the heterogeneity of SMC can impact its potential uses and the challenges it poses to characterization techniques for carbonaceous materials. Furthermore, the benefits of this heterogeneity in applications like thermochemical processes have not been thoroughly explored. Consequently, the objective of this study was to evaluate the potential of utilizing thermochemical processes for this biomass by examining the impact of water washing and acid digestion treatments, while considering the complex characteristics of this biomass.

2. Methodology

2.1. Quartering, Separation, and Selection of Samples

The SMC used in this study was obtained from the production process of Setas Colombianas S.A. in Llanos de Cuivá, Antioquia. A total of 20 kg of samples were randomly collected from production batches when unloading the culture beds. These samples were carefully packed and sealed in high barrier bags with a PE/PA/EVOH structure, featuring an oxygen transmission rate (OTR) of 0.5 to 0.6 $cm^3/100\ in^2/day$ at 23 °C/1 atm. The maximum time between unloading the material and transport to the laboratory was two days. Upon arrival, the material underwent successive quartering following the ASTM E5717 and D2234 standards to ensure a representative sample was obtained for subsequent treatment and characterization [18,19]. Following the quartering process, the material was further selected for treatment. Table 1 describes the acronyms used for sample labeling.

Table 1. Sample labeling.

Acronym	Meaning
SMC_Complete	Complete biomass without any physical separation.
SMC_Woody	Fraction with woody appearance.
SMC_Agglomerated	Fraction of compacted SMC.
SMC_Fines	Fraction of SMC with visually small particle sizes.

2.2. Characterizations

2.2.1. Lignin, Cellulose, and Hemicellulose Content

The Van Soest method [20] was used to perform a series of digestions to determine the acid detergent fiber (ADF), neutral detergent fiber (NDF), and acid detergent lignin (ADL) contents. Following the analytical procedure used by Huang et al. [21], the percentages of lignin, cellulose, and hemicellulose of the SMC_complete were determined. The sample had to be dried at 105 °C for 24 h to conduct this analysis.

2.2.2. Physicochemical Analyses

The characterization of the SMC_complete was conducted according to the guidelines outlined in the Colombian Technical Standard NTC 5167 [22], focusing on physicochemical analyses. This process also involved determining the most suitable classification for the material and identifying the required enrichment for its agricultural applications.

Thermal stability and functional groups were determined using TGA (Thermogravimetric Analysis) and FTIR (Fourier Transform Infrared) analysis. A TGA SDT 5600 thermal analyzer (TA Instrument, New Castle, DE, USA) was used, and the operating conditions were based on the research of [23]. A heating ramp was defined in an inert atmosphere (N_2) at a rate of 15 °C/min from room temperature to 105 °C, followed by an 80 min isotherm, and then an increase at the same rate from 105 °C to 900 °C with a 30 min hold. Finally, in an oxidizing atmosphere (air), the isotherm time was extended for 10 min. A proximate analysis was performed to determine the moisture content, volatile materials (VM), fixed carbon (FC), and ash for the samples. For these analyses, the samples were dried at 105 °C for 24 h, ground, and sieved using standardized E11 No. 60 mesh (250 µm).

An FTIR analysis was carried out using the DRIFT (Diffuse Reflectance Infrared Fourier Transform) technique to determine the functional groups present in the SMC samples. A 95% KBr and 5% powdered sample, previously dried, ground, and sieved with standardized E11 No. 60 mesh (250 µm), was used for this analysis. An IRTracer-100 infrared spectrometer was used within a working range of 4000 to 400 cm^{-1}. The SMC morphology was visualized using a Jeol JSM-7100F scanning electron microscope (JEOL, Showima City, Tokyo, Japan) with a particular focus on its heterogeneity. Sample preparation entailed gold sputtering on copper tape. The SMC was dried and sieved under the same conditions as the previous characterizations.

2.3. Treatments for Ash Reduction

Two treatments were conducted to reduce the ash content in the SMC. The washing treatment (WT 1) followed the research of Bandara et al. and Singhal et al. [24–26]. The washing was performed at 80 °C for 30, 45, and 60 min with magnetic agitation at 800 rpm and an SMC to water ratio of 1:25, using a 1000 mL Erlenmeyer flask and a heating plate with temperature control. After the allotted time, the agitation was stopped, and the biomass and water mixture were left to rest for 30 min to facilitate decantation and filtration. The latter was conducted under vacuum using a pump with a vacuum level between 50–100 hPa and Advantec Grade 1 qualitative filters.

On the other hand, the treatment with citric acid (CAT 2) followed the methodology of [16,27]. A solution of 5% citric acid at 99.98% purity was used for the digestion process. The digestion treatment was conducted at room temperature for 4 h using a magnetic stirring plate with an SMC to citric acid ratio of 1:15 by mass. After the digestion time, the material was left to rest for 30 min to facilitate decantation, followed by vacuum filtration under the same conditions as in treatment WT1. The material was then washed with 200 mL of distilled water, subjected to a second decantation, vacuum filtration, and further washed with distilled water until the effluent increased its pH to between 4 and 6.

One of the limitations of the methodology, independent of the washing type of acid digestion, was the inherent mass loss during the filtration process, as well as the time required for this process, which ranged from 2 to 3 h depending on the pore size of the filter and the granulometry of the woody SMC.

3. Results and Discussion

3.1. Characterization of SMC and Heterogeneity Phenomenon

The heterogeneity of this SMC biomass was observed during the quartering and separation of samples. Variations in appearance, specifically woody, agglomerated, and fine materials, were consistently visualized across different batches of mushroom production and cultivation bed discharges, as illustrated in Figure 1.

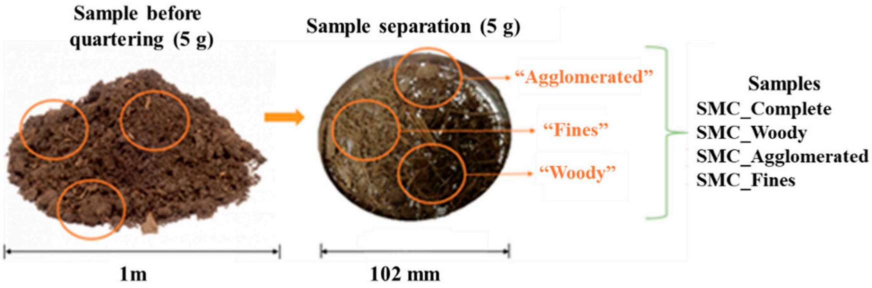

Figure 1. Visual inspection and fractions of SMC_Complete.

SEM microscopy revealed the great heterogeneity of the SMC_complete sample (Figure 2), observing structures in the form of fibers of variable lengths and diameters that did not present porosity on their surface. In addition, fine and agglomerated particles were found with great variability in shapes and particle diameters.

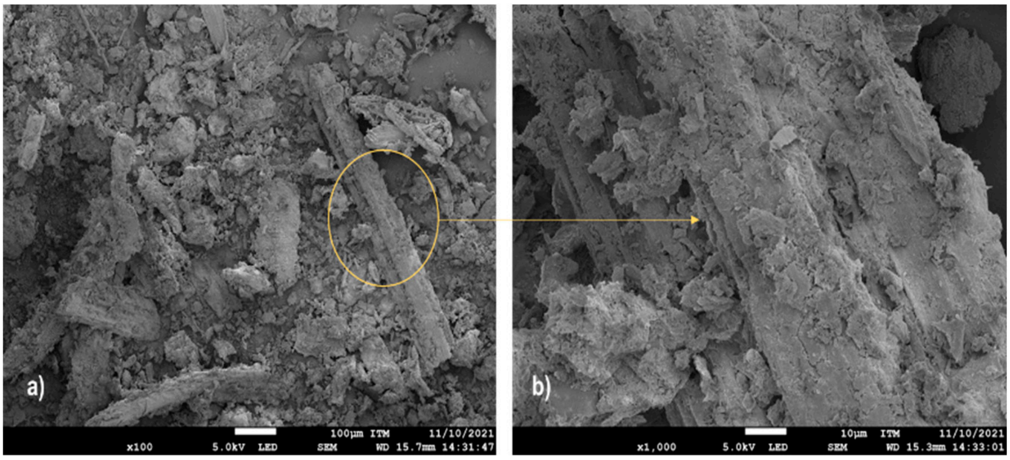

Figure 2. SEM micrograph: SMC_Complete: (**a**) 100 µm, (**b**) 10 µm.

According to various authors, SMC is produced through the mixture of different types of precursor biomasses, which primarily depend on availability and the country [28,29]. The most used biomasses in Colombia are rice chaff, sugarcane bagasse, coconut husk, and others [30,31]. Even after the composting and mixing processes, distinct fractions can be identified, resulting in different properties. This was evident during the preliminary material inspections and the sample selection processes, as depicted in Figure 1.

The reason for this heterogeneity within the same material lies in the preparation process of the cultivation bed and the previously mentioned raw materials. Since it undergoes various mixing processes and different timings for the addition of precursor biomasses, once the fruiting bodies begin to grow, material compaction occurs along with free spaces for growth. After the harvesting process and the cultivation bed is emptied, these characteristics persist in the SMC, as well as potential differentials in physicochemical composition.

Moreover, this heterogeneity is not only evident visually. A detailed analysis of the material fractions showed differences in composition. Woody material, for example, is suitable for thermochemical processes due to its lower ash content. Notably, no previous studies have isolated SMC for different types of use.

Table 2 presents the primary findings of the physicochemical characterization of the SMC_Complete material in accordance with the TGA, The Van Soest method, and NTC 5167 standard guidelines. The analysis indicated that the sample exhibited a pronouncedly high ash and volatile matter content but possessed a low fixed carbon percentage. The notably high ash content restricted its application in thermal processes such as pyrolysis, gasification, and combustion, necessitating implementing processes to mitigate this limitation. Furthermore, the examination of NDF (neutral detergent fiber), ADF (acid detergent fiber), and ADL (acid detergent lignin) enabled the determination of lignin, cellulose, and hemicellulose percentages in the complete SMC. NDF and FDA values of 52.4% and 42.6%, respectively, facilitated the calculation of the hemicellulose content at 9.8% through the difference. Additionally, the LDA value representing lignin was determined to be 34.3%. By computing the variance between the FDA and LDA, the cellulose percentage was identified as 8.3%.

Table 2. SMC_complete physicochemical characterization.

Analysis	Parameter	Symbol or Acronym	Result
Proximate analysis [a]	Moisture	M	6.9%
	Volatile matter	VM	41.7%
	Fixed carbon	FC	6.8%
	Ash	Ash	44.5%
Lignocellulosic components	Hemicellulose	n/a	9.8%
	Cellulose	n/a	8.3%
	Lignin	n/a	34.3%
Inorganics	Cadmium	Cd	<0.10 ppm
	Chrome	Cr	<1.00 ppm
	Nickel	Ni	<0.20 ppm
	Lead	Pb	<0.50 ppm
	Mercury	Hg	<0.10 ppm
	Arsenic	As	<0.10 ppm
	Calcium	CaO	12.68%
	Magnesium	MgO	0.82%
	Potassium	K_2O	2.31%
	Sodium	Na	0.11%
	Zinc	Zn	0.007%
Organics	Oxidizable organic carbon	n/a	42.60%
	Phosphorus oxide	P_2O_5	0.61%
	Organic nitrogen	Total N	2.88%
	C/N ratio	n/a	14.80
Physical analysis	pH	n/a	5.52
	WHC [b]	n/a	177.80%
	Moisture	n/a	45.30%
	CEC [c]	n/a	41.60 meq/100 g
	Electrical conductivity	n/a	1.09 dS/m
	Density	n/a	0.24 g/cm^3

[a] Samples previously dried, [b] water holding capacity, [c] cation exchange capacity.

The data obtained from the analysis conducted with the NTC 5167 focused on examining the presence of heavy metals in the material, assessing potential risks to soils, and identifying essential elements for plant growth and soil bioremediation. The current SMC values indicated that the levels of heavy metals were within acceptable limits in parts per million (ppm), posing no significant risk. Notably, the analysis highlighted elements crucial for soil application, including potassium, calcium, and magnesium, which are present in the mineral matter and serve important functions in this context. There is potential for market utilization if these elements are enriched. The presence of organic carbon and nitrogen is noteworthy regarding the organic chemical analysis. However, the nitrogen levels are at the minimum limit for fertilizer applications, indicating a need for enrichment for this specific purpose. The initial moisture content before the drying processes was 45.6%, a value similar to that reported in the literature [15,16].

The determined moisture content of 45% and the presence of key elements such as nitrogen (N), potassium (K), and phosphorus (P) indicate that SMC can be categorized as a form of mineral organic fertilizer. However, to further fulfill this classification, it is important to lower the moisture content to between 15% and 20% and enhance the material with N, K, and P contents. On the other hand, the characterization of the structural components (lignin, cellulose, and hemicellulose) in comparison with results by the same method in the literature [32], give reason to think that the mixture of precursor biomasses and the fraction taken for the realization of the method impact the results, where for this case the percentage of hemicellulose was 9%, and the literature reports indicate a presence in this component of around 2 to 6%, especially in SMC rich in cotton chain residues.

The results in Figure 3 display the findings from the proximate TGA analysis of the various SMC fractions. All three SMC fractions showed high levels of ash and volatile materials and low levels of fixed carbon. Specific data from the proximate analysis can be found in Table 3, revealing differences, especially in the ash content, ranging from 44.5% for SMC_Complete to 38.9% for the SMC_woody sample. Through the application of physical separation methods, an increase in the content of volatile material and fixed carbon was achieved for SMC_woody and SMC_fines. This suggests that it is possible to obtain a biomass with a higher carbon content, which would positively impact thermal processes by increasing the fraction susceptible to chemical reactions.

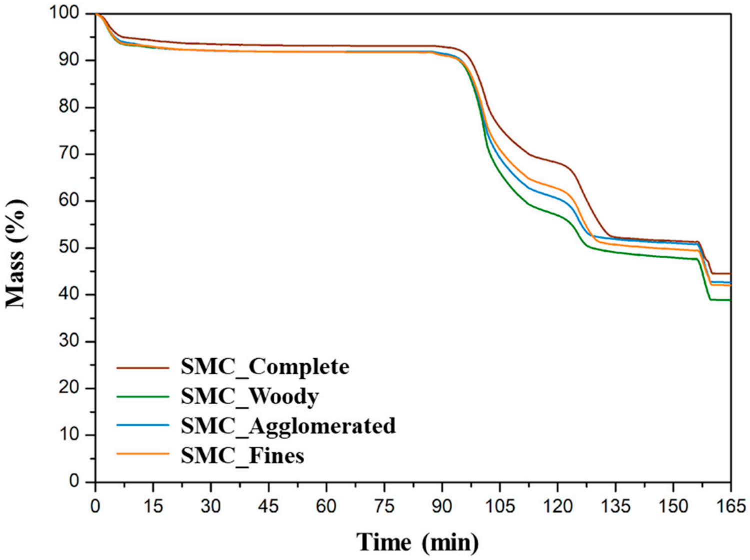

Figure 3. Thermogravimetric analysis of SMC fractions.

Table 3. Proximate analysis of SMC fractions.

Sample	Moisture (%)	Volatile Matter (%)	Fixed Carbon (%)	Ash (%)
SMC_Complete	6.9 ± 0.1	41.7 ± 0.8	6.8 ± 0.1	44.5 ± 0.9
SMC_ Woody	8.2 ± 0.2	44.9 ± 0.9	7.7 ± 0.1	38.9 ± 0.8
SMC_Agglomerated	8.1 ± 0.2	41.1 ± 0.8	8.0 ± 0.2	42.6 ± 0.9
SMC_Fines	8.3 ± 0.2	42.2 ± 0.8	7.3 ± 0.1	42.1 ± 0.8

In Figure 4, the FTIR spectra of the samples show the presence of various functional groups associated with the major components of the biomass, namely cellulose, hemicellulose, and lignin. Therefore, the spectra were very similar. The observed bands included hydrogen-bonded stretching bands of OH groups (3000–3600 cm^{-1}), C-H bands (2960–2850 cm $^{-1}$), C=O bands (1800 cm $^{-1}$), C=C groups (1650 cm^{-1}), and C-O bands (1080 cm^{-1}). Additionally, peaks corresponding to C-H and inorganic groups were evident in the far spectrum (below 1000 cm^{-1}), indicating the presence of inorganic groups in the sample, which aligns with the proximate analysis results. The region that showed the most significant changes in functional groups, often called the fingerprint region, was found between 1000 cm^{-1} and 500 cm^{-1}. Within this range are two noticeable peaks at 876 cm^{-1} and 713 cm^{-1} in the SMC_fines and SMC_agglomerated, and to a lesser extent in the SMC_complete, indicative of characteristic calcite features.

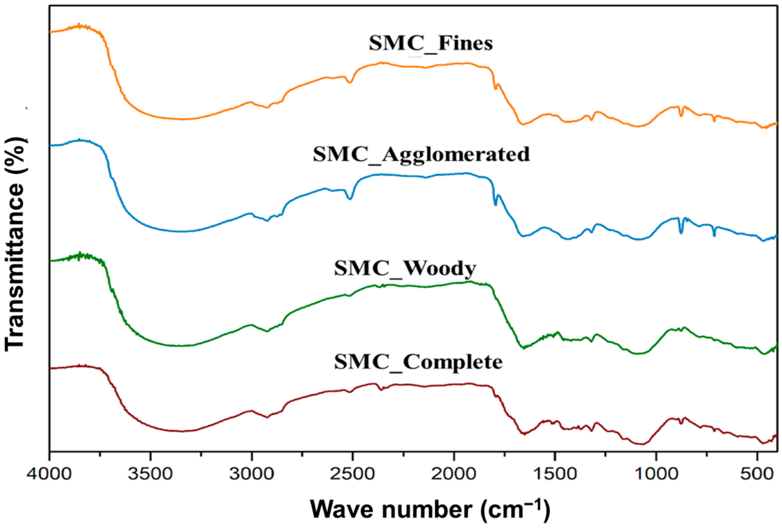

Figure 4. FTIR analysis of SMC biomass fractions.

Based on the FTIR results, the spectrum obtained resembles the findings of Liu et al. [33] and displays the typical spectra of lignocellulosic materials. Variations in peak intensities may be attributed to differences in sample composition, specifically the varying presence of precursor biomasses. This characteristic categorizes SMC as a type of lignocellulosic biomass and suggests similar behavior to other biomasses during thermochemical processes.

3.2. *Effect of Ash Reduction Treatments on the Thermal Behavior of Biomasses*

Figure 5 illustrates the outcomes of the TGA conducted on two treatments, one with water (WT1) and the other with citric acid (CAT2). The mass versus time curve revealed distinct stages: initial moisture loss, the subsequent evolution of volatile matter between 90 and 160 min, and finally, oxidation of the fixed carbon after 170 min. The data illustrated a significant enhancement in this parameter using citric acid, establishing it as the preferred treatment for reducing ash content. This conclusion is further supported by Table 4, which demonstrates the composition changes in the biomass through proximate analysis. It shows a decrease in ash content and an increase in fixed carbon and volatile materials.

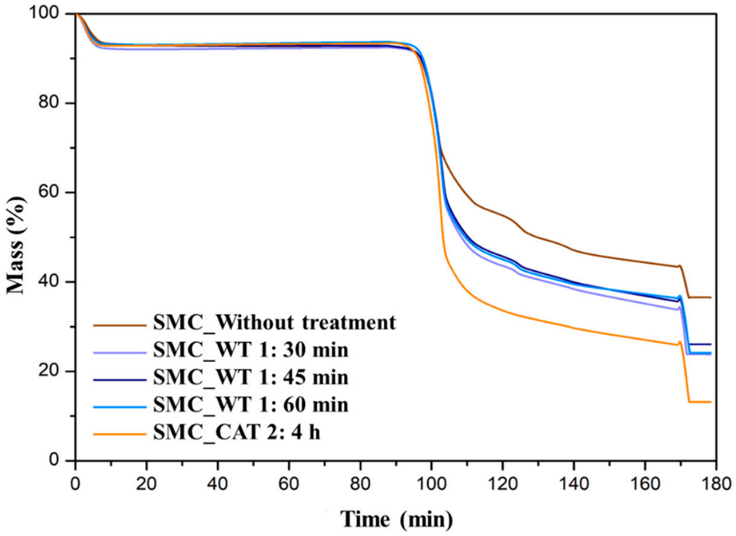

Figure 5. Thermogravimetric analysis of SMC after water (WT) or citric acid (CAT) treatments.

Table 4. Proximate analysis of SMC after water (WT) or citric acid (CAT) treatments.

Sample	Moisture (%)	Volatile Matter (%)	Fixed Carbon (%)	Ash (%)
SMC_ WT 1: 30 min	7.57 ± 0.15	58.08 ± 1.16	10.51 ± 0.21	23.80 ± 0.47
SMC_ WT 1: 45 min	7.13 ± 0.14	56.72 ± 1.13	9.66 ± 0.19	26.04 ± 0.52
SMC_ WT 1: 60 min	6.32 ± 0.13	56.78 ± 1.14	12.74 ± 0.25	24.12 ± 0.48
SMC_ CAT 2: 4 h	6.63 ± 0.13	66.75 ± 1.34	13.27 ± 0.26	13.15 ± 0.26

When using distilled water for washing, there was a consistent trend of decreasing ash content and increasing fixed carbon for the three residence times. The reduction in ash content was most pronounced at 30 min. However, for longer residence times, it was possible that some metals and oxides may have started to precipitate in the solid phase, so the trend of residence time was not clear. Alternatively, when using citric acid digestion following the method described by Toor et al. [16], similar results in ash reduction were obtained compared to those in previous studies by various authors [17,27]. In this case, 13.15% ash content was achieved, indicating a 64% reduction.

Previous research [34] also indicated that a biomass treated with citric acid at different concentrations (1% and 5%) experiences an increase in volatile materials and calorific values, improving the fuel properties and potential for utilization in gasification or combustion processes. A lower mineral content, particularly in alkaline and alkaline earth oxides, has logistical benefits in reducing material accumulation on the walls of combustion and gasification chambers and pipes. This leads to lower maintenance requirements. Additionally, the reduction in ash decreases post-treatment costs, such as those associated with bag filters or electrostatic filters. On the other hand, in the process of fast pyrolysis, alkaline and alkaline earth elements act as catalysts and have the potential to significantly reduce bio-oil yield and adversely affect its composition. Moreover, these inorganic substances present in residues may lead to diminished bio-oil stability, increasing the likelihood of quality degradation during long-term storage. This emphasizes the necessity of pretreating biomasses prior to the thermal process to minimize the ash content [27]. Washes conducted with distilled water at 80 °C exhibited inferior performance, but still higher ash reduction compared to that of acid treatment.

Hemicellulose degradation occurs within a temperature range of 200 to 300 °C in an inert atmosphere, while cellulose degrades between temperatures of 250 and 380 °C, exhibiting a distinct peak after 300 °C. Lignin, characterized by its intricate structure, undergoes degradation within the temperature range of 200 to 500 °C, with heightened significance at around 400 °C, potentially overlapping with the end of cellulose degradation [35,36]. Figure 6 depicts the DTG curves of the SMC and treated SMC with water or citric acid. Higher signal intensities were observed for the SMC treated with water or citric acid compared to the untreated SMC. This phenomenon can be attributed to a mass compensation effect, wherein a reduction in the ash fraction caused by the pretreatment increases the presence of lignocellulosic components.

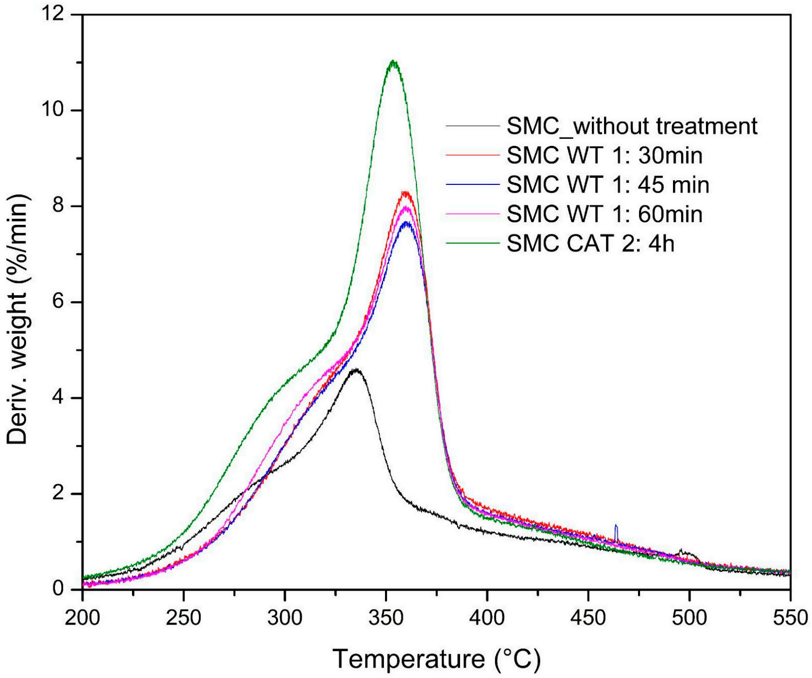

Figure 6. DTG analysis of SMC after water (WT) or citric acid (CAT) treatments.

The treatment involving citric acid exhibited increased intensity in the signals associated with the hemicellulosic and cellulosic components, occurring within the temperature ranges of 200–300 °C and 250–380 °C, respectively, in comparison to the water treatments. This heightened intensity may be attributed to the mass compensation effect, as this treatment demonstrated the most significant reduction in ash content. Regarding the lignin component, the characteristic signal in the DTG curve above 400 °C was quite similar between all treatments.

The presence of citric acid in the treatments with biomasses was found to exhibit chelating properties and weak tryptonic acid behavior. Acting as a chelating agent, citric acid diminishes the concentration of alkali and alkaline earth metals due to its three pi bonds (C=O) facilitating the electrostatic attraction between the oxygen ion of the hydroxyl group and the deprotonated metal ions [27]. The reduction of these metals in the pretreatment process elevates the temperature of cellulose decomposition, as depicted in Figure 6, attributed to the decreased activation energy resulting from the presence of alkali and alkaline earth metals.

Furthermore, as a weak acid, citric acid has the potential to induce dehydration and hydrolysis reactions, particularly in hemicellulose and cellulose constituents. Nevertheless, this study demonstrated an increase in these components during treatment with citric acid, suggesting that the impact of these reactions is not evident in the DTG curves, likely due to the mass compensation effects previously mentioned.

On this point of comparison, it is important to highlight aspects beyond the results mentioned here. Clearly, in relation to the objective, the treatments with acid significantly reduced the ash content in the woody fraction of the SMC, but environmental and operational aspects must also be considered. Given the amount of SMC available for utilization, a key strategy involves extracting various value-added products from the same biomass and, importantly, evaluating processes at a larger scale. Therefore, it is crucial to discuss the environmental impacts of each treatment, considering the growing and necessary transition from a linear economy to a circular economy, where the best waste is either that which does not exist or that which can be reintegrated into the same or another supply chain.

For each of the treatments, the goal concerning thermochemical utilization is the use of the resulting solid. However, the liquid streams will have specific physicochemical characteristics that need to be managed. On this point, a less demanding treatment in terms of management, with potential for future study, was the one resulting from treatments with distilled water at 80 °C for various durations. In comparison to citric acid, life cycle assessment studies have revealed its impact from the production process itself, through biomass washing treatments, and how these liquid streams require more management, treatment, and pose greater challenges for disposal [27].

Possible directions for future work in this area could focus on analyzing the liquid streams resulting from both treatments, particularly those involving distilled water. The aim would be to determine the inorganic species solubilized during the washes and assess how these liquid mixtures could be potential candidates for applications such as fertilizers, considering the state of the art surrounding SMC.

4. Conclusions

The article details original research findings related to the characterization of a biomass derived from mushroom production, focusing on the various fractions of this biomass. The study specifically compared two methods for reducing the ash content while also examining the physicochemical properties of the SMC. The objective was to decrease its ash content and increase its carbon content, making it suitable for thermochemical applications. The following conclusions can be drawn:

The examined treatments intended to reduce ash content and increase fixed carbon demonstrated effectiveness, particularly the application of 5% citric acid, with an ash reduction of up to 66%. An elevated reduction in ash content has the potential to enhance the thermal efficiency of thermochemical processes and reduce the post-treatment costs associated with combustion gasses, thereby improving the applicability of materials for thermochemical processes such as combustion, gasification, or pyrolysis. This presents an alternative method for utilizing this biomass in Setas Colombianas S.A., the largest mushroom producer in Colombia and one of the most significant exporters in the Latin American region through co-combustion processes in biomass boilers, using the modified residue as a result of the treatments evaluated in this research. This approach aims to mitigate the environmental impacts of mushroom production, addressing environmental concerns through cleaner production and energy generation from renewable resources.

SMC heterogeneity represents the distinct characteristic of a residual biomass, influencing analytical techniques at severe scales due to diverse material fractions present in samples, even after grinding and sieving processes. The analysis of the material fractions revealed variations in composition. For instance, wood material is appropriate for thermochemical processes because it has a lower ash content. It is noteworthy that there are no existing studies in the literature at an industrial-scale that have specifically identified SMC fractions for various types of use.

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