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Evaluation of Biochar as an Additive in the Co-Composting of Green Waste and Food Waste

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Abstract: Green waste (GW) represents 11% of municipal solid waste. Managing this waste is challenging due to its physicochemical variability, low density, and presence of hard-to-degrade lignocellulosic compounds. Composting is an alternative for GW transformation and valorization. However, due to the substrate characteristics, processing times are long, and the end product typically does not meet quality standards. Incorporating additives and co-substrates are operational strategies that contribute to overcoming these challenges. An essential step is the determination of a mixture's composition that ensures synergistic effects on the process and end-product quality. This research assessed the effect of adding biochar (Bch) in the co-composting of GW and food waste (FW). A previously studied co-composting mixture (M) of GW, raw and processed FW, sawdust (Sd), and phosphoric rock (Pr) with four treatments by duplicate were assessed at the pilot scale: T_1: 100% GW, T_2: M_1, T_3: M_2 + 2% Bch, y T_4: M_3 + 5% Bch. The results show that Bch treatments maintained the range of thermophilic temperatures for longer than the other two treatments (between four and five additional days), showing greater biological activity and better end-product hygienization. Likewise, in the Bch treatments, the hemicellulose and cellulose degradation improved compared to treatments without Bch by 33.9% and 23.3%, respectively, and nitrogen losses were reduced by up to 70%. Regarding the end product, adding a 2% dose of Bch allowed the highest fertility index compared to the other three treatments, showing its potential for agricultural use. This work demonstrates that adding biochar to FW and GW co-composting improves organic matter degradation rates, lignocellulosic degradation, and end-product quality.

Keywords: biochar; co-composting; compost; end-product quality; green waste; food waste

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1. Introduction

Green waste (GW) makes up a considerable portion of municipal solid waste (MSW)—around 11%. The management of this waste is challenging since the production of MSW is increasing. For instance, the production of MSW increased between 2012 and 2017 from 1300 million tons [1] to 2000 million tons, and it is expected that by 2050, it will reach 3400 million tons [2]. On the other hand, GW is characterized by a relatively high content of lignocellulosic substances with a complex and biologically hard-to-degrade structure [3] (27% to 57% cellulose, 11% to 55% hemicellulose and 3% to 22% of lignin—dry weight [4]).

Composting is a prominent alternative for GW treatment [5]. However, this alternative has limitations, such as an extended processing time and deficiencies in the end-product

quality due to lignocellulosic compounds [6]. Previous studies have showed that GW composting could be improved using strategies such as (i) co-composting with other substrates such as food waste (FW) and manure; (ii) additives such as zeolite and phosphoric rock; (iii) microbial inoculants [6–10]; or (iv) operational changes such as two-stage composting [11]. These strategies have increased lignocellulose degradation [6], reduced processing times by between 50% and 73% [6,7,12], and improved end-product quality, especially in terms of nitrogen and carbon availability [9,13]. Previous research on the co-composting of GW and FW together with sawdust (Sd) and phosphoric rock (Pr) improved the structure and nutritional content of the end-products and accelerated the transformation process of the substrates [14,15]. However, challenges remain regarding the reduction of nitrogen losses and the increase in the degradation rates [9].

Biochar (Bch) is one of the additives with a potential for GW degradation through composting. Bch is a porous material with an important surface area that provides an environment for microbial growth and diversity and boosts its biological activity [16]. Thus, during the composting process, the Bch promotes the slow release of nutrients, which contributes to the organic matter's degradation in substrates, increasing humification and reducing greenhouse gases [17]. Likewise, Bch can reduce nitrogen loss due to its high adsorption capacity, which allows nitrifying bacteria to transform ammonia into nitrate, thus reducing volatilization and denitrification [13]. Concerning the end product, Bch contributes to the immobilization of heavy metals in soils and, thus, reduces their absorption by plants [18,19]. Applying a compost mixture that includes Bch to the soils improves their physical characteristics and increases crop productivity [20,21].

Research that assessed Bch addition in composting processes has studied organic waste such as FW and animal manure in processes extending from 28 to 210 days, varying according to the type of waste and Bch doses [22–26]. For instance, Awasthi et al. [27] assessed the effect of Bch with doses of 2% to 10% during the composting of chicken manure and found benefits in the reduction of nitrogen emissions. On the other hand, Liu et al. [28] studied the effect of Bch in doses of 1% to 7% in the composting of sludge from wastewater treatment plants and found reductions in nitrogen losses and phytotoxicity. Wang et al. [29] addressed the effect of Bch in doses of 5% to 20% in the composting process of grain distillation wastes, wherein Bch reduced nitrogen losses. Malinowski et al. [30] investigated the effect of Bch (doses of 1.5%, 3%, and 5%) in the composting of the organic fraction of the MSW at real scale and found a positive impact on the compost quality and nitrogen loss reduction. These studies show a promising use of Bch as an additive for composting organic waste.

This research assessed the use of Bch as an additive in the co-composting of FW, GW, Pr, and Sd and assessed its effect on reducing process time (i.e., thermophilic and cooling phase) and end-product quality. Although research has addressed the use of Bch in the co-composting process of different materials, to the authors' knowledge, no research has reported the use of Bch in the co-composting of GW with FW as amendment material. This study increases the knowledge of strategies for improving the co-composting of hard-to-degrade materials such as GW.

2. Materials and Methods

2.1. Substrates, Additives, and Biochar

The substrates used for the co-composting process were GW and FW (raw and processed). GW was obtained from pruning and cutting green areas from the main campus of Universidad Industrial de Santander (UIS). This GW comprised leaves (35.1%), grass clippings (26.5%), soil extract (20.5%), tree branches (8.7%), fruits (3.02%), roots (0.36%), leftover material (0.26%), among others (5.62%) [31,32]. FW was collected in the student restaurants from UIS. Raw FW was made from fruit peels (33.7%), lettuce (17.9%), onion (17.5%), potato (16.7%), cassava (8.1%), banana (4.5%) and carrot (1.6%), while processed FW was 2.5% and was made from leftovers from lunches delivered daily.

Before the start of the experiments, FW and GW were stored for three days and one day, respectively. These storage periods allowed for achieving the amount of the required substrates in each treatment without a relevant alteration of the physicochemical characteristics of the substrates. In addition, these periods could simulate the operational conditions of the FW and GW collection services [6,12]. These wastes were manually shredded to achieve a particle size of between 30 and 50 mm [13]. Sd was added as a bulking material with 54.3% total organic carbon (TOC) and Pr with 28% P_2O_5 to increase the phosphorus content in the substrates and contribute to the reduction of the nitrogen volatilization [6,15,32]. Pr was obtained from a commercial establishment that had TOC (1%), CaO (38%), Al_2O_3 (0.5%), Fe_2O_3 (0.4%), MgO (0.1%), and K_2O (0.1%). A commercial Bch was used. This Bch was obtained from the mixture of pruning and agricultural waste (mainly sugarcane and corn) under pyrolysis conditions at a temperature of 650 °C for 2 h in a tube furnace in a nitrogen medium (99.9% purity) to ensure an oxygen-free environment. The pyrolysis temperature was higher than 600 °C because the Bch underwent a slow pyrolysis process (i.e., the temperature ranged between 300 and 700 °C and had a long residence time—hours) which generally results in higher Bch yield and better homogeneity. The pyrolysis reactor was of the externally heated tubular worm type divided into four individual heating zones with a temperature profile of 300 to 800 °C.

2.2. Experimental Setup

A pilot-scale setup was prepared in 250 L reactors with a treatment capacity of 40 kg, like a home-composting unit. Eight reactors were prepared to achieve four treatments running in duplicate. The reactors were of high-density polyethylene with a conical shape, a height of 0.85 m, and a radius of 0.3 m. These reactors were drilled with holes 2 cm in diameter, located at equal distances (15 cm) on the reactor's perimeter as a passive aeration mechanism, as proposed by Hernández-Gómez et al. [12]. In addition, the reactors were covered with a thermally insulated jacket to avoid heat loss during the substrate degradation process (Figure 1).

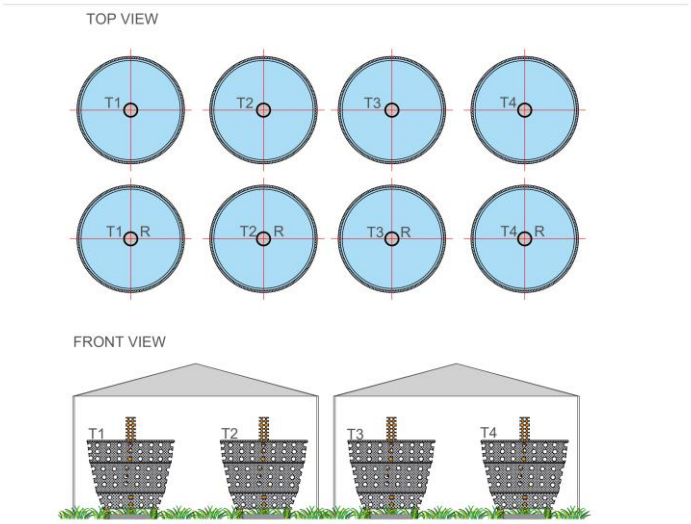

Figure 1. Experimental setup for the co-composting process. T1: GW, T2: FW + GW + Sd + Pr, T3: FW + GW + Sd+ Pr + Bch (2% dose), and T4: FW + GW + Sd + Pr + Bch (5% dose). The treatments with R correspond to the replicates.

Four treatments were prepared: T_1: GW, T_2: FW + GW + Sd + Pr, T_3: FW + GW + Sd+ Pr + Bch (2% dose), and T_4: FW + GW + Sd + Pr + Bch (5% dose). The Bch doses were established according to Malinowski et al. [30] and Nguyen et al. [22]. At the start of the experiment, substrates in each treatment were weighed and manually mixed with a shovel. Each experimental unit had a duplicate. Table 1 shows the proportion of the substrates

and additive mixtures defined based on the studies from Hernández-Gómez et al. [12] and Oviedo-Ocaña et al. [33].

Table 1. Composition of substrates, additives, and biochar in each experimental unit.

Treatment	Mixture Composition (*w*/*w*)	Mass
T_1	100% GW	40 kg
T_2	M1: 50% GW + 32.5% FW * + 2.5% FW ** + 13% Sd + 2% Pr	20 kg (GW) + 13 kg + (FW *) + 1 kg (FW **) + 5.2 kg (Sd) + 0.8 kg (Pr)
T_3	M2: (48% GW + 32.5%FW * + 2.5% FW ** + 13% Sd + 2% Pr) + 2% Bch	19.2 kg (GW) + 13 kg + (FW *) + 1 kg (FW **) + 5.2 kg (Sd) + 0.8 kg (Pr) + 0.8 kg (Bch)
T_4	M3: (45% GW + 32.5% FW * + 2.5% FW ** + 13% Sd + 2% Pr) + 5% Bch	18 kg (GW) + 13 kg + (FW *) + 1 kg (FW **) + 5.2 kg (Sd) + 0.8 kg (Pr) + 2 kg (Bch)

Notes: T: treatment; M: mixture; GW: green waste; FW: food waste; Sd: sawdust; Pr: phosphoric rock; Bch: biochar; * raw food waste; ** processed food waste.

2.3. Analytical Methods

Samples were taken at opposite points inside each reactor to obtain an integrated composite sample of 300 g for laboratory analyses. All measurements were performed in triplicate to obtain the standard deviation of the analyzed parameters. The analyzed parameters were selected according to APHA [34] and ICONTEC [35]: moisture (gravimetry after drying the sample at 105 °C), pH (potentiometric method immersing 10 g of solid sample in 50 mL of distilled water in a 1:10, w/v ratio), electrical conductivity (EC) (conductivity meter method immersing 10 g of solid sample in 50 mL of distilled water in a 1:10, w/v ratio), total organic carbon (TOC) (gravimetry at 550 °C), cation exchange capacity (CEC) (in an extract of 50 mL of distilled water and 10 g of sample), total nitrogen (TN) (Kjeldahl total nitrogen titrimetric method), and total phosphorus (TP) (spectrophotometric method). The total potassium (TK) and magnesium (Mg) content were determined by atomic absorption. Lignin (%-colorimetric method), cellulose (%-gravimetric method), and hemicellulose (%-gravimetric method) were determined according to recommendations from Soest [36]. The total reducing sugars content was conducted using the DNS technique (3,5-dinitro salicylic acid) [37].

The microbiological parameters selected were total coliforms (TC) and fecal coliforms (FC) (MPN in LMX Fluorocult Broth) and *Salmonella* spp. (biochemical tests and serological identification) according to recommendations from USEPA [38] and Boost and Poon [39]. The germination index (GI) was established using *Raphanus sativus* seeds sensitive to various compounds. One gram of solid sample was taken and diluted with distilled water at a ratio of 1:10 (w/v). At the end of the germination tests, characteristics related to the germinated seeds, roots, and leaves were assessed, and three indices were calculated: relative seed germination (RSG), relative root elongation (RRE), and germination index (GI) (see Equations (1)–(3)). Calculations were performed according to the methodology described by Issarakraisila et al. [40]:

$$\text{RSG} = \frac{\text{No. of seeds germinated in the dilution}}{\text{No. of seeds germinated in the blank}} \times 100 \quad (1)$$

$$\text{RRE} = \frac{\text{Average root length in the dilution (mm)}}{\text{Average root length in the blank (mm)}} \times 100 \quad (2)$$

$$\text{GI} = \frac{\text{RSG} \times \text{RRE}}{100} \quad (3)$$

The phytotoxicity levels were analyzed considering that (i) GI values $\leq$ 50% indicate a strong presence of phytotoxic substances, (ii) GI values between 50% and 80% indicate

moderate presence of phytotoxic substances, (iii) GI values exceeding 80% indicate a positive effect, and (iv) GI values exceeding 120% are evidence of biostimulation effects [40].

The Bch's surface morphology and chemical composition were determined using a scanning electron microscope with energy-dispersive X-ray spectroscopy (SEM-EDS, ZEISS-EVO18, Germany). The Bch's specific surface area, total pore volume, and pore size distribution were characterized by Brunauer–Emmett–Teller (BET) based on N_2 adsorption methods (Quantachrome Instruments model NOVA 1000 e, Quantachrome Instruments, Boynton Beach, FL, USA).

2.4. Process Monitoring

The co-composting process was monitored through temperature, pH, moisture, interstitial oxygen concentration, total reducing sugars (TRS), TOC, total nitrogen (TN), Mg, total potassium (TK), and content of hemicellulose, cellulose, and lignin. The temperature was measured daily using a 30 cm thermometer (Reotemp Thermometer, San Diego, CA, USA) in four points inside the reactor (center, at a depth of 25 cm, and at radial points at a depth of 25 cm).

The ambient temperature was measured daily with a fixed digital thermometer with a resolution of 0.1 °C. In addition, temperature stratification was determined each time turning was performed, using a thermographic camera (Luke® PTi120, Fluke Corporation, Everett, WA, USA). Interstitial oxygen concentration was estimated as the temperature (multichannel portable gas analyzer—CM37). Manual turning of each experimental unit was performed according to the temperature behavior (thermophilic phase) and oxygen concentration (<10%) and, in the cooling and maturation phases, to avoid compaction and lump formation and to homogenize the material. During process development, pH, EC, and moisture were quantified every three days. As moisture was monitored, water was added as required by each treatment. Finally, TN, Mg, TK, GI, and lignocellulose were measured during the main phases of the co-composting process (mesophilic—day 0, thermophilic—day 4, and cooling—day 30) and at the end product.

2.5. End-Product Quality

At the end of the co-composting process, the product was sieved, and samples were taken to be analyzed: pH, EC, moisture, TOC, TN, TP, TC and FC, enterobacteria, *Salmonella* sp., and enumeration of beneficial mesophilic microorganism. The CEC and water retention capacity (WRC) were established according to the Colombian technical standard on organic products used as fertilizers and soil conditioning amendments—NTC 5167 [35]. The GI was established with the previously described methodology. Stability was assessed through a self-heating test using 1.5 L Dewar glasses, according to Brinton et al. [41].

Another parameter used to measure end-product agricultural valorization was the fertility index (FI) proposed by Saha et al. [42]. This index was adapted considering the NTC 5167. Each criterion had a weighting factor ranging from 1 (least important) to 5 (most important), assigned according to its relative importance from an agricultural perspective [33]. After the end-product characterization, a score (Si) between 1 and 5 (only integers) at different ranges of values per agronomic quality parameter was assigned (more information in Saha et al. [40]). Each score was multiplied by the weighting factor assigned to the parameter [42], and then all products were added and divided by the sum of the weighting factors. FI was obtained for the end-product of each treatment using Equation (4). A higher FI indicates an end-product with a better agronomic value.

$$FI = \frac{\sum_{n}^{i=1}(S_i * W_i)}{\sum_{n}^{i=1} W_i} \quad (4)$$

where FI is the fertility index and Si is the score in a range of values according to the quality parameter. Wi is the weighting factor (range 1–5), while i is each parameter used to measure end-product quality (i = 1–7): EC, TOC, TN, C/N ratio, TP, TK, and GI.

2.6. Statistical Analyses

A one-way analysis of variance (ANOVA) was performed at a significance level of $\alpha = 0.05$ to determine the impact of the analyzed factors on the response parameters. Statistically significant differences among treatments were calculated via Fisher's LSD (least significant differences) [43]. Statistical analyses were performed using the free distribution software R version 3.5.1. The relationship between treatments and end-product quality was analyzed with multivariate techniques using principal component analysis (PCA). The PCA was intended to establish the correlation between the studied parameters and to identify the treatment with the best performance regarding end-product quality. Principal components were those with an eigenvalue higher than one and statistically significant according to the parsimony principle [44]. In addition, PCA validation demanded a Kaiser–Meyer–Olkin index higher than 0.5. The strength of the linear relationship between the end-product quality parameters was established through the Pearson coefficient (R) and a *p*-value at a significance level of 5%. This study considered a strong relationship for R equal to or higher than 80%. Thus, an R lower than 80% suggested a moderate to weak relationship. Finally, the agglomerative hierarchical method (Ward's method) was used to establish potential clusters between end-product quality parameters by looking at the minimum variance between clusters [45]. Data processing was carried out using SPSS® software.

3. Results and Discussion

3.1. Characterization of Substrates and Additive

Table 2 shows the physicochemical characterization of the substrates and the additive. The GW had a pH of around neutral and was higher than that of the FW, as reported in other studies [6,12]. The C/N ratio, TP, Mg, and TK were within ranges reported by Vandecasteele et al. [46] and Reyes-Torres et al. [9] for GW (i.e., 21.5–49.2, 0.12–0.21%, 0.17–0.35% and 0.43–1.44%, respectively). However, the moisture and TN were higher in the FW than in the GW. These values could be related to the variability of climate conditions and location, which influence the characteristics of the GW [9,47]. The cellulose and lignin were higher in the GW than in the FW, a typical behavior in these wastes [6,46].

Table 2. Physicochemical characterization of substrates and biochar.

Parameter	FW	GW	Bch *	T_2	T_3	T_4
pH	4.7 ± 0.2	7.5 ± 0.1	8.1 ± 0.2	6.2 ± 0.1	5.61 ± 0.3	5.62 ± 0.2
Moisture (%)	78 ± 1.5	63 ± 2.0	N.D	61 ± 3.2	62.1 ± 2.1	63.3 ± 1.4
Mg (%)	0.08 ± 0.01	0.17 ± 0.01	0.30 ± 0.01	0.20 ± 0.02	0.16 ± 0.01	0.15 ± 0.01
TK (%)	1.37 ± 0.3	0.62 ± 0.4	0.38 ± 0.02	0.9 ± 0.1	0.85 ± 0.1	0.88 ± 0.2
Hemicellulose (%)	74.80 ± 2.2	15.47 ± 3.5	N.D	23 ± 2.5	27.1 ± 2.0	18.4 ± 1.4
Cellulose (%)	3.07 ± 0.7	12.43 ± 2.4	N.D	21.9 ± 1.3	26.4 ± 1.7	28.1 ± 0.8
Lignin (%)	1.02 ± 0.3	40.80 ± 6.1	N.D	23.8 ± 3.7	35 ± 4.0	25.9 ± 1.3
TOC (%)	40.73 ± 4.2	29.87 ± 3.8	7.4 ± 0.5	39.1 ± 2.6	41.4 ± 3.1	39.1 ± 2.8
TN (%)	0.46 ± 0.03	0.65 ± 0.2	0.43 ± 0.02	0.53 ± 0.1	0.51 ± 0.1	0.45 ± 0.1
TP (%)	0.22 ± 0.12	0.25 ± 0.11	N.D	2.43 ± 0.21	1.34 ± 0.13	1.05 ± 0.12
C/N	88.54 ± 3.34	46.19 ± 4.43	17.21 ± 0.36	73.77 ± 3.52	81.18 ± 4.49	86.89 ± 4.29

Note: T_1: 100% GW; T_2: M_1; T_3: M2 + 2% Bch; T_4: M_2 + 5% Bch; * Bch: Al (%): 3.15; Si (%): 6.05; Ca (%): 18.94; Fe (%): 4.61; I (%): 0.97; Specific Surface Area (SSA) (m^2/g):567.28; Pore Volume (PV) (cm^3/g): 0.369; Pore Ratio (PR) (A°): 5.106. * SEM-EDS Analysis. N.D.: No data.

The FW had high moisture and a TOC that could favor the production of volatile fatty acids before the experimental setup (during the three days of storage), evidenced by an acidic pH (4.7). In addition, the FW had low TN, lower than in reports from Foronda-Zapata et al. [47] (1.5%) and Oviedo-Ocaña et al. [33] (1.56%), resulting in a high C/N ratio

at the start of the co-composting process. This relation indicates a low TN, which can affect biological activity. However, this limitation can be overcome by adding other co-substrates. Regarding the organic carbon content, hemicellulose predominated (78%) since this is present in a variety of fruits and vegetables [48]. On the other hand, the TP content was low, which is consistent with previous research developed in the study area [49]. In contrast, the TK was high, possibly due to the presence of plantain and banana peels [47,50]. Finally, Mg, which is an essential micronutrient in aerobic processes such as composting, was in the range reported by other authors (<1%) (e.g., [51]).

The mixture of GW and FW favored the substrate conditions at the start of the co-composting process (i.e., T_2, T_3, and T_4). This mixture improves pH neutrality, balances moisture content (around 65%), and benefits porosity. This mixture has been favorable for degrading the recalcitrant organic matter in GW in previous research by authors such as Hernández-Gómez et al. [12].

Bch had a pH slightly alkaline due to the presence of hydroxyl ions (OH^-) with values similar to those reported by Ravindran et al. [26], Awasthi et al. [27], and Castro-Herrera et al. [52]. The C/N ratio was lower than values from other authors (6.5 a 186) [22,26,53]. The concentration of micronutrients such as Al, Si, Ca, Fe, and I in Bch in this study was higher than in previous research [16,53], particularly regarding the concentration of I, which is beneficial for several plants, especially the halophytic. In addition, I contributes to metabolic and nutrient transport processes [54]. It must be emphasized that the variation of Bch's carbon, nitrogen, and micronutrients can change according to the substrate used and the operational conditions in which the Bch is obtained [17].

Concerning Bch structure, a specific surface area (SSA) of 567.28 m^2/g and a pore volume (PV) of 0.369 cm^3/g (see Figure 2) were found, which are indicators of a great capacity to adsorb nutrients such as nitrogen and enhance the consolidation of microbial consortia, due to the presence of functional groups such as hydroxyl, acyl, carboxyl, carbonyl, and ester. These characteristics allow the adsorption of heavy metals—in particular, those with an ionic radius proportional to pore size [55], which is essential in the co-composting process of MSW.

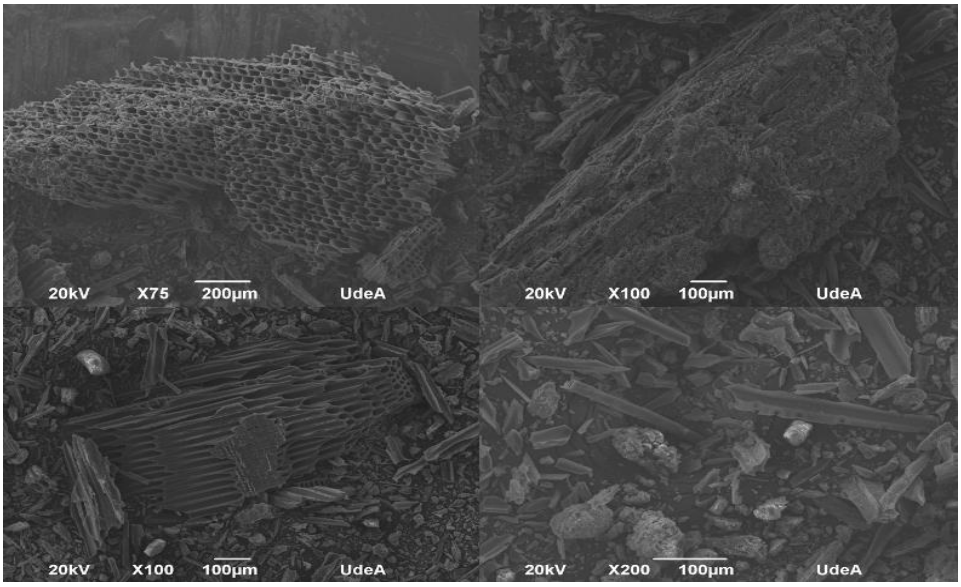

Figure 2. Scanning electron microscope with energy dispersive X-ray spectroscopy of Bch. Morphologic diversity of the used Bch.

In relation to the characteristics of the mixtures (T_2, T_3, and T_4), an increase in pH was observed due to the introduction of Bch and the content of cellulose and phosphorous due to the introduction of Sd (porosity improvement) and Pr (source of TP). In contrast, a major change in TOC, TN, or C/N ratio was not observed for the FW. Although the

treatments did not fulfill the initial C/N ratio (between 20:1 and 40:1 to ensure an adequate nutrient balance), values slightly outside this range could lead to successful results [52]. Godlewska et al. [56] suggest that this situation could be associated with hard-to-degrade carbon from the Bch or the lignin in the GW. However, authors such as Nguyen et al. [22] highlight that adding carbon from the Bch at the start of the process could improve oxygen availability and humification, accelerating the organic matter decomposition through faster microbial growth.

3.2. Co-Composting Process Monitoring

3.2.1. Monitoring of Operational Parameters

Figure 3 shows profiles of temperature, oxygen consumption (OC), pH, EC, and TRS. All treatments had a typical composting process behavior with sequential phases: mesophilic, thermophilic, cooling, and maturation. Likewise, treatments showed a positive correlation between the temperature with OC and TRS due to organic matter biodegradation and microbial activity [57].

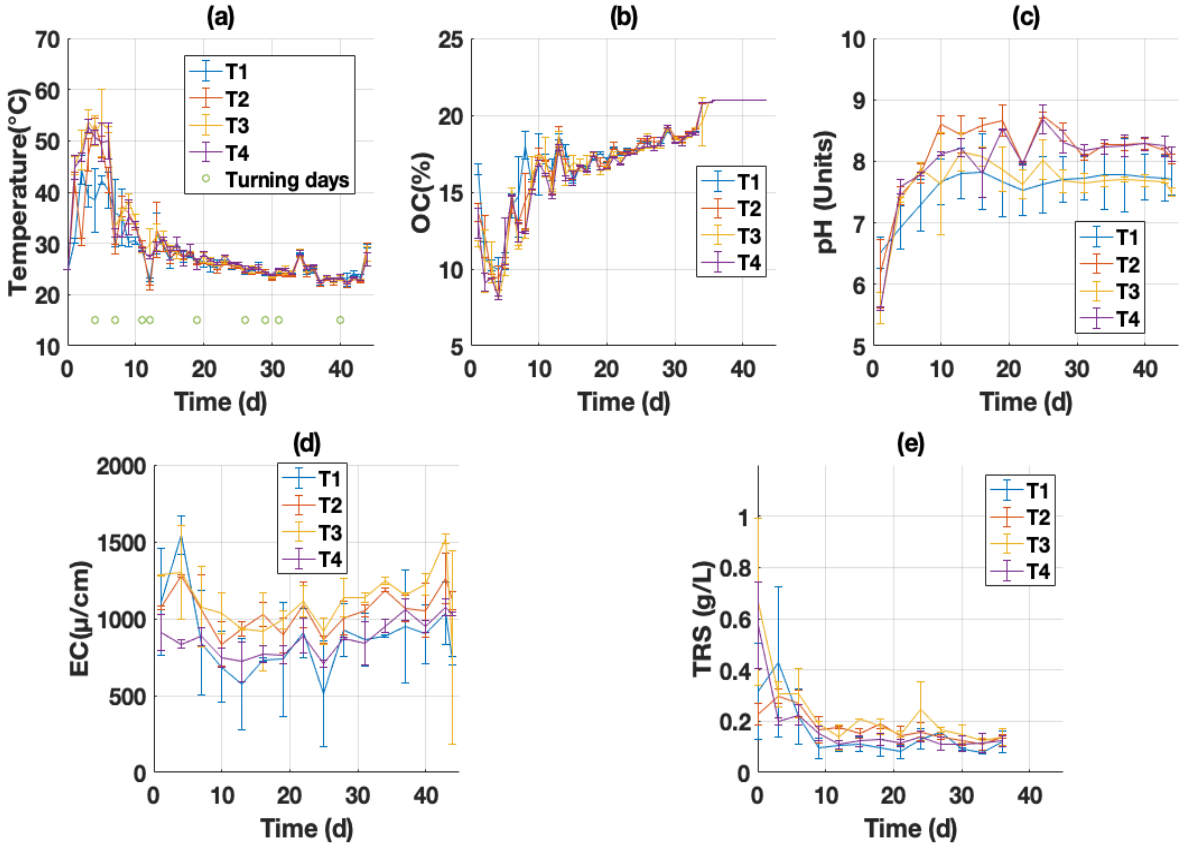

Figure 3. Behavior of the parameters monitored in the co-composting process according to treatment. (**a**) Temperature; (**b**) oxygen consumption; (**c**) pH; (**d**) electrical conductivity; (**e**) total reducing sugars. Source: Authors.

The temperature dynamics in each treatment (Figure 3a) show that in T_1, the maximum temperature was 44.3 °C (reached on day 3), indicating that the thermophilic condition was not achieved (T > 45 °C) [6]. T_2 reached the thermophilic range for a maximum temperature of 53.2 °C for three days. In contrast, treatments with Bch (T_3 and T_4) showed that this additive generated statistically significant temperature differences (p = 0.010) since these treatments were reached faster compared to treatments without Bch, which reached the thermophilic phase (day 3) with maximum temperatures of 52.8 °C and 53.6 °C, respectively (see Table 3).

Table 3. Behavior of average temperatures, added water, and pH in each treatment.

T	Added Water (L)	Initial pH	Start of the TPh (Days)	Maximum Temperature (°C)	Length of the TPh (Days)	Time to Reach Ambient Temperature (Days)
T_1	10	6.51	2	44.3	1	24
T_2	2	6.18	4	53.2	2	24
T_3	0.7	5.62	3	53.6	6	24
T_4	1.4	5.60	3	52.8	6	24

Note: T: treatment; TPh: thermophilic phase. Source: Authors.

The temperatures in the thermophilic range remained for six days for T_3 and T_4. Therefore, these treatments achieved hygienization conditions (T > 50 °C for three or more consecutive days [58]). This behavior is consistent with López-Cano et al. [59], who indicated that by adding Bch into the co-composting process, the temperature increases faster than in a process without Bch, and the thermophilic phase extends from one to six days, as in the present research. This phenomenon possibly occurs because Bch fills the free spaces between the particles of the composted raw material (as evidenced by the SSA and PV of the used Bch). This situation potentially leads to a reduction in heat loss during the process. Furthermore, Bch addition increases aeration since it prevents the formation of lumps or waste compaction and, thus, raises the number of microorganisms, accelerating transformations and increasing the amount of heat produced [56].

Regarding oxygen consumption (OC) and pH (Figure 3b,c), there were no statistically significant differences between the treatments for both parameters ($p > 0.05$). The reduction of the oxygen concentration occurred in the first five days of the process due to the biological activity. In addition, short-chain organic fatty acids were formed in these first days, affecting the process's alkalinity and pH. Then, a gradual increase in pH was observed, going from slightly acidic to alkaline (7.7–8.5 units). This increase could be attributed to the mineralization of TN-rich compounds (proteins, amino acids, and peptides) and ammonia nitrogen produced during the ammonia process [47,60]. Likewise, the high concentrations of TK (present in the FW) associated with water in the mixture could promote the formation of KOH, a strong base [47] that contributes to the pH increase. In addition, the Ca and Fe in Bch also form strong bases, such as $Fe(OH)_3$ and $Ca(OH)_2$, that also provide alkalinity.

The EC reflects the concentration of water-soluble inorganic ions in the processed material. The EC was higher (EC > 1000 µS/cm) at the start of the process in T_2, T_3, and T_4 with respect to T_1 (see Figure 3d), which is associated with the dominance of Sd, an additive with salts of sodium and calcium [15]. In these treatments, a generalized trend of a rise in EC was observed. According to Gong et al. [61], this rise is due to the microbial mineralization of organic matter and the release of mineral ions such as phosphates, ammonia, and potassium during the process. After day five, a slight decrease in EC coincided with the days in which treatments were moisturized, enhancing salts' lixiviation. Later, the EC gradually decreased, maintaining relatively low values of between 600 and 1200 µS/cm. At the end of the process, the EC values lacked statistically significant differences between treatments.

The TRS (Figure 3e) had statistically significant differences between treatments ($p = 0.010$). Treatments with Bch (T_3 and T_4) had an important solubilization from oligosaccharides to simple sugars, with concentrations between 0.57 and 0.67 g/L that, with process development, decreased to minimum values (0.11–0.140 g/L). This behavior could be attributed to microbial consortia with greater enzymatic capacity, possibly forming and consuming the lignocellulosic compounds and almost completely depleting the degradable fractions of cellulose and achieving organic matter stabilization. Authors such as Wang et al. [62] state that due to the Bch porosity, an indirect accelerating effect on the organic matter degradation occurs through the stimulation of the microbial and enzymatic activities that solubilize the organic matter. In contrast, in T_1 and T_2, these oligosaccharides were released from the vegetal organic matter and naturally accumulated. On the other hand, the oligosaccharides

could accumulate due to the absence of a microbial community that finishes hydrolyzation and consumes the released oligosaccharides. Wu et al. [63] indicated that bacteria that produce spores degrade the recalcitrant or lignocellulosic organic matter. The higher abundance of these bacteria generally occurs in extended thermophilic conditions, an aspect not present in these two treatments (Figure 3a).

3.2.2. Monitoring of the Lignocellulosic Fraction, Total Organic Carbon, Total Nitrogen, and Micronutrients through the Process Phases

Figure 4 shows the results of monitoring the lignocellulosic fraction, TOC, TN, Mg, TK, and GI through the phases of the co-composting process (MPh: Mesophilic; TPh: Thermophilic; and CPh: Cooling). Lignocellulose is a complex macromolecule made of three natural biopolymers that are strongly linked. Cellulose and hemicellulose are rapidly biodegradable and are primary carbon sources, while lignin is a hard-to-degrade biopolymer that acts as a physical barrier that delays the co-composting process [64].

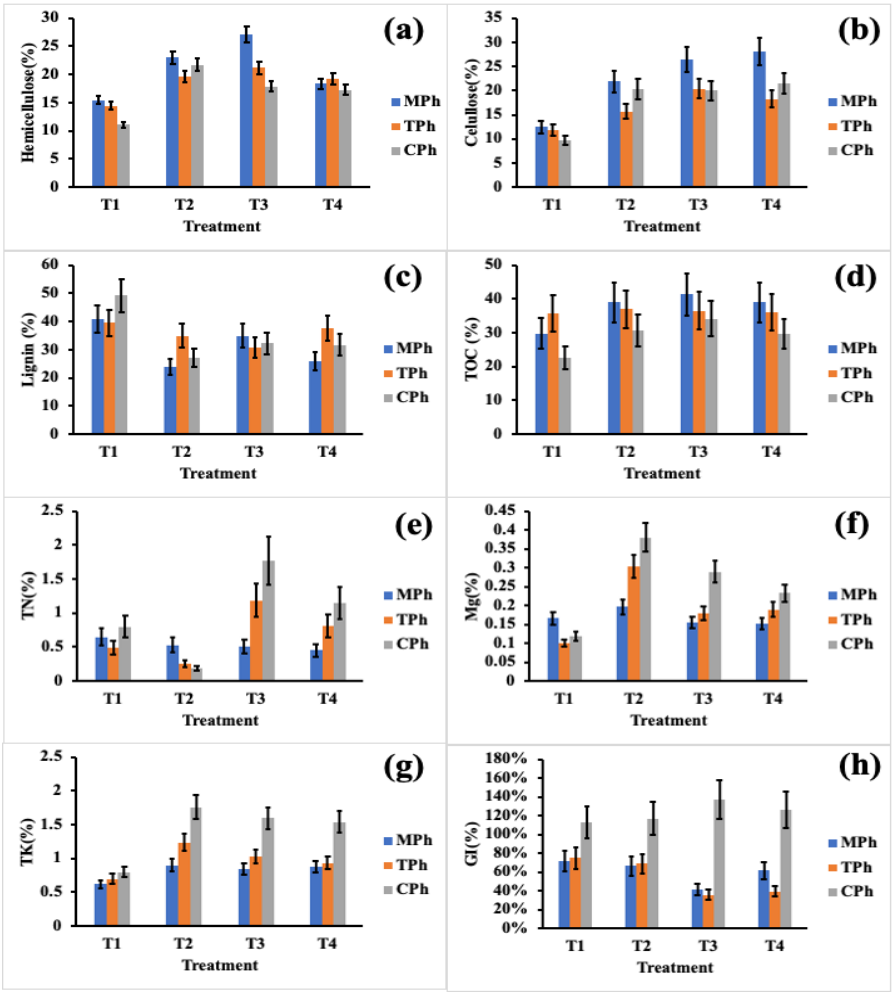

Figure 4. Monitoring of organic matter degradation and micronutrients during the co-composting process phases: mesophilic (MPh), thermophilic (TPh), and cooling (CPh). Behavior of: (**a**) hemicellulose; (**b**) cellulose; (**c**) lignin; (**d**) total organic carbon (TOC); (**e**) total nitrogen (TN); (**f**) magnesium (Mg); (**g**) TK; and (**h**) germination index (GI). The bars represent the standard deviation. Source: Authors.

In the treatments with Bch (T_3 and T_4), a greater lignocellulose degradation occurred in comparison to T_1 and T_2, with T_3 (2% Bch) having the greatest hemicellulose (33.9%) (Figure 4a), cellulose (23.3%) (Figure 4b) and lignin (7.7%) degradation (Figure 4c). This degradation was higher for cellulose and slightly lower for lignin compared to reports from

Liu et al. [65], who, with a 6% Bch dose in a 60-day co-composting process (contrasted with 44 days of this study), achieved a cellulose and lignin reduction of 13.4% and 13.8%, respectively. According to Yu et al. [66], adding Bch in doses between 10 and 15% improves lignocellulose degradation with an extended thermophilic phase. Furthermore, the Bch effect also depends on its physicochemical characteristics. These aspects could, in this study, explain the important reductions in the lignocellulosic structure during the co-composting process of GW, even at the low doses used.

Figure 4d presents the TOC during the process. A decrease in TOC was observed in all treatments in agreement with the hemicellulose and cellulose degradation. Similar results were reported by Feng and Zhang [64] in the co-composting of GW with sediment sludge, who found that Bch has an aromatic structure similar to graphite that promotes electron transfer through the carbon matrix. The process of electron transference in the composting system can augment the oxygen input from the composting materials and, thus, improve organic matter biodegradation. These characteristics indicate that introducing FW simultaneously with additives in the co-composting of the GW boosted the biological activity and promoted the secretion of enzymes specialized in organic matter degradation [30].

On the other hand, the results show a shorter time for the degradation of lignin in the GW. In this study, the processing time was 45 days. However, the strategies of FW and GW co-composting combined with the Bch addition reduced the lignin concentration during the experiment duration.

Figure 4e shows that in the treatments without Bch (T_1 and T_2), the TN reduced at the start of the process and onward, which is associated with biological activity and nitrogen volatilization and the consequent increase in temperature and pH in the thermophilic phase [47]. The TN differs in the treatments with Bch (T_3 and T_4), which increased by 70% compared to in T_1 and T_2. T_3 was the treatment with lower nitrogen content during the process, which can be attributed to the Bch dose in this treatment that could enhance the nitrogen adsorption and keep a neutral pH during the thermophilic phase. This could lead to lower volatilization of ammoniacal nitrogen and reduced nitrogen losses. In addition, this difference could result from a lower ammonia loss and a higher TN concentration due to water loss and CO_2 emissions. These results are consistent with findings from Godlewska et al. [56] using Bch in composting processes of MSW.

Mg and TK noticeably increased in T_2, T_3, and T_4 (Figure 4f,g). In the case of Mg, this was due to the disintegration of chlorophyll, a predominant molecule in GW whose structure is made up of a porphyrin ring containing Mg. As the protective lignocellulosic layer decomposes, chlorophyll is accelerated, and Mg increases in the medium [67]. On the other hand, the TK increase could be associated with the mineralization of the hemicellulose in the plantain peels from the FW [60]. Kalemelawa et al. [68] indicated that K and Mg ions are available in soluble form in water because, during the initial phase of the process, the decrease in pH solubilizes these metals and, combined with the bicarbonate ions (HCO_3^-) produced during the organic matter mineralization, they can form strong bases, such as hydroxide. This behavior concurs with arguments from Feng and Zhang [64], who indicate that adding Bch to GW facilitates the transformation of hard-to-degrade organic matter such as lignocellulose, which allows for increasing micronutrients such as TK in the compost.

Figure 4h shows the values of the GI during the process. In all treatments, the GI was lower than 65% during the initial phases (15 days), which indicates phytotoxicity. According to Yu et al. [69], phytotoxic substances from leaves and grass clippings are released faster during the active process phase, which could be the situation in this study. Later, the GI gradually increased due to the degradation of phytotoxic compounds (i.e., ammonia volatilization and microbial consumption of organic acids) [32]. At the end of the process, T_3 and T_4 had the highest GIs (137% and 126%, respectively) compared to T_1 and T_2 (113% y 117%, respectively). Thus, Bch treatments generated a biostimulating effect on the root system of the radish seeds. Coelho et al. [70] adduce that a GI of over 120% indicates the presence of easily assimilated organic matter and nutrients essential to the plant, including iodine (I), an element detected in the Bch. Although this nutrient is not

essential for plants, it positively influences their growth and metabolism. Consequently, adding the Bch led to a more mature final product than that from the treatments without this additive.

3.3. End-Product Quality

Table 4 shows the physicochemical characteristics of the end-product for each treatment. In all treatments, moisture was over 35%, the maximum value suggested by the NTC 5167. This moisture could be associated with the last addition of water before the process end in all treatments. On the other hand, the self-heating test showed that all treatments had consistent characteristics (Degree V) [6,47]. Regarding the pH values, these were in the recommended range for organic amendments

Table 4. Physicochemical and microbiological characterization of the end-product from the co-composting process according to the Colombian standard on organic products used as fertilizers and soil conditioning amendments—NTC 5167.

Parameter	Unit	NTC 5167	T_1	T_2	T_3	T_4
Physicochemical						
pH *	Units	7.0–9.0	7.13 ± 0.47^{a}	7.16 ± 0.13^{a}	6.93 ± 0.03^{a}	7.06 ± 0.30^{a}
Moisture	%	>35.0	55.87 ± 5.22^{a}	47.70 ± 8.2^{b}	55.28 ± 1.19^{a}	54.11 ± 2.82^{a}
CEC *	meq/100 g	≥30.0	29.3 ± 2.97^{a}	31.60 ± 0.99^{a}	35 ± 0.66^{b}	38.30 ± 2.97^{b}
EC	dS/m	<3.0	0.14 ± 0.01^{a}	0.21 ± 0.01^{a}	0.16 ± 0.06^{a}	0.11 ± 0.02^{a}
WRC	%	R.D	194.5 ± 62.01^{a}	299.4 ± 27.7^{b}	333.90 ± 25.03^{c}	312.90 ± 56.4^{c}
TOC *	%	≥15	18.15 ± 2.19^{a}	33.30 ± 2.55^{b}	31.35 ± 1.34^{b}	34.40 ± 2.12^{b}
TN *	%	>1.0	0.35 ± 0.21^{a}	1.05 ± 0.49^{b}	1.30 ± 0.16^{c}	1.32 ± 0.14^{c}
TP *	%	>1.0	0.47 ± 0.36^{a}	2.85 ± 0.46^{b}	2.14 ± 0.25^{c}	1.20 ± 0.16^{d}
TK *	%	>1.0	1.3 ± 0.10^{a}	1.8 ± 0.03^{b}	1.52 ± 0.02^{a}	1.61 ± 0.16^{b}
Microbiological						
FC *	MPN/g	<1000	>2400	>2400	240	>2400
TC *	MPN/g	<1000	>2400	>2400	240	>2400
Salmonella sp. *	CFU/25 g	A	A	A	A	A
Enterobacteria *	CFU/g	<1000	0	490 ±650	11.5 ± 16.26	450 ± 63.64
Mesophiles *	CFU/g	R.D	4.3×10^{9}	3.41×10^{9}	1×10^{8}	7×10^{5}
Agronomic						
FI	-	5.00	3.40^{a}	4.25^{b}	4.50^{c}	4.40^{c}

Notes: CEC: cation exchange capacity; EC: electrical conductivity; WRC: water retention capacity; TOC: total organic carbon; TN: total nitrogen; TP: total phosphorus; TK: total potassium; FC: fecal coliforms; TC: total coliforms; R.D: report data; A: absence * mandatory parameters according to the NTC 5167. Equal letters indicate that there is no statistically significant difference between the treatments.

The CEC is an essential property in compost, since it allows cation retention to avoid lixiviation losses, preserves soil moisture, and holds potential contaminants in the soil [71]. In this study, T_3 and T_4 had a higher CEC than T_1 and T_2 (T_3 and T_4 had statistically significant differences compared to T_1 and T_2), which can be explained by the humification processes in the lignocellulosic material enhanced by the Bch, since this additive produces functional groups that, given the pH conditions, could promote H^+ deionization, producing negative charges [23].

The EC values were lower than the standard proposed by the NTC 5167 for all treatments (there were no statistically significant differences), indicating the low presence of salts essential in reducing phytotoxicity in plants [64]. The low values could be explained by the minimum fraction of processed food and the salt transformations, which could support end-product use in agricultural activities.

The WRC value demands, as a minimum, half of its weight; thus, all treatments fulfilled this requirement (>50%) [72], and the Bch treatments stand out due to the Bch adsorption capacity that allows storing water in the media. The content of TOC, TN, TP,

and TK was higher in T_2, T_3, and T_4 compared with T_1. This shows that the co-composting process improved the end-product characteristics and, thus, its potential for agricultural use, as explained by Zhang and Sun [73], who argue that the addition of co-substrates or additives facilitates GW degradation, especially in the thermophilic phase, which leads to compost with a higher potential for agricultural use [22,30].

Regarding the microbiological quality of the end product, even if treatments fulfilled the standards for *Salmonella* sp. and Enterobacter, only T_3 satisfied all the parameters required by the NTC 5167. This result could be attributed to an effective hygienization process during the thermophilic phase and to the iodine (I) effect from the Bch with an effective antifungal and antibacterial activity, since its spectrum includes Gram-positive and -negative bacteria, spores, fungi, viruses, cysts, and protozoa [74].

Finally, all four treatments had FI values higher than 3.4 (5.0 is optimal), showing a high fertilization potential, according to the values recommended by Saha et al. [42]. T_3 had the highest FI (4.5) among the treatments, followed by T_4 (4.4). Therefore, adding Bch to the co-composting process of GW and FW positively affected the end product's agronomic quality. In addition, T_3, besides fulfilling the legal requirements of the NTC 5167, also had a higher agronomic value than the other treatments investigated.

Figure 5 shows the PCA for each treatment's analyzed parameters for the end-product quality. The two principal axes had eigenvalues higher than 1. The principal components F1 and F2 explained 48.46% and 23.13% of the data variability, respectively. These results are represented in Figure 5 as load charts. The length of the line of each response indicates a greater correlation with the principal component. Thus, the nutrient content (TN, TP, and TK) strongly correlates with TOC. Likewise, a similar trend was observed for the TOC, cellulose, and hemicellulose, in which complex structure and resistance to degradation increase the TOC. The PCA results also show that an increase in nutrients leads to lower pH, EC, and coliforms in the end product, which improves their agricultural quality [75]. The supplementary material expands on this information by showing the Pearson correlation matrices for the analyzed parameters for the end-product quality from each treatment (see Table S1).

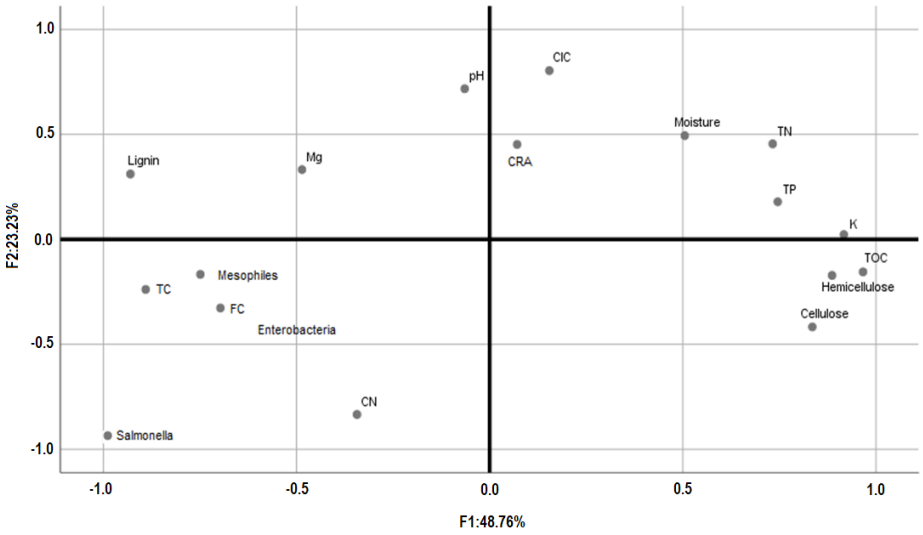

Figure 5. Principal component analysis of the assessed end-product quality parameters from each treatment.

Regarding treatments, Figure 6 shows three clusters: (i) control treatment only with GW; (ii) treatments of GW and FW without Bch; and (iii) treatments with Bch. Results from the treatment with Bch at 2% were in the upper right quadrant, opposite the location of treatments with only GW.

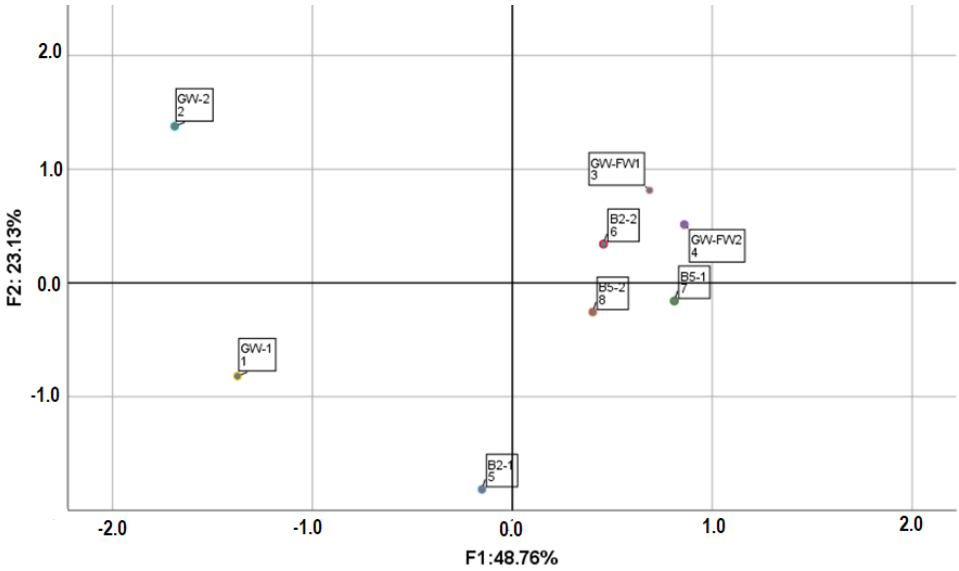

Figure 6. Clusters of the analyzed parameters in the end product according to treatment.

The cluster analysis shows that adding Bch (2%-dose) had a synergistic effect on the end-product, evidenced by the higher nutrient content (TN, TP, and TK), CEC, WRC, and better microbiological characteristics compared with treatments without Bch. Bch can buffer pH and improve aeration conditions and moisture regulation by stimulating microbial activity and increasing GI and CEC [56]. A 5% dose of Bch, as seen in the lower left quadrant, showed greater dispersion. The 5% dose of Bch compared to the control treatment (only GW) had an end-product quality with a higher TOC, cellulose, and hemicellulose content and a higher final C/N ratio (a consequence of less OM degradation), and less stability. Despite these observations, in this study, the effect of Bch was not statistically significant ($p = 0.67$) compared to the strategy of only including FW.

4. Conclusions

This study shows that adding a 2% dose of biochar to the co-composting of green waste and food waste increased biological activity during the active phase of the process. This increase was evidenced by an extended duration of the thermophilic phase (up to six days); a higher reduction in the concentrations of hemicellulose (33.9%), cellulose (23.3%), and pathogen organisms; and lower total nitrogen losses during the process compared to the other studied treatments. With regards to the end product, although there were no statistically significant differences between treatments, the end product from the treatment with 2% biochar was characterized by a higher fertility index (4.5) and by microbial conditions that facilitate its use as a soil improver. Results show that adding low doses of biochar to the FW and GW co-composting is a promising strategy for managing complex waste such as green and food waste.

Future research could (i) assess the effect of biochar produced with different biomasses; (ii) scale up the experiment (e.g., real-scale) to analyze the effect of biochar addition on the degradation of lignocellulosic substances and end-product quality; (iii) monitor the effect of biochar addition on the microbial community; (iv) incorporate parameters that allow a better understanding of the effect of the biochar addition on the nitrogen behavior during the co-composting process; and (v) compare the effect of adding biochar at different phases of co-composting (e.g., mesophilic and thermophilic) on the process and end-product quality.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15097437/s1, Figure S1: Thermographic profile that represents the temperature pattern in the piles. (a) mesophilic phase. (b) thermophilic phase. (c) cooling phase and (d) maturation phase; Table S1: Pearson correlation matrix for the analyzed parameters in the end-product quality from each treatment.

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