agronomy

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Application of Spent Sun Mushroom Substrate in Substitution of Synthetic Fertilizers at Maize Topdressing

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Abstract: Synthetic fertilization can increase maize yields, but also cause environmental impacts, as well as increasing production costs and food security risks. Sun mushroom (*Agaricus subrufescens*) is an important Brazilian fungus used to generate large amounts of spent mushroom substrate. This residue can be used for maize fertilization, but little is known about its ideal application rates to reduce maize dependence on synthetic fertilizers. Therefore, this study aimed to evaluate the agronomic performance of a maize crop under different combinations of synthetic fertilizers and two different spent mushroom substrate doses. The experiment was carried out in pots and evaluated maize germinate and biometric parameters, as well as soil and leaf chemical characteristics. The results showed that residue application increased maize germination and Emergence Speed Index. Regarding the maize biometric parameters, height, stem diameter, shoot fresh and dry masses, and leaf area were superior for residue with synthetic fertilization at sowing only at higher doses. Moreover, residue with synthetic fertilization at sowing proved to be more relevant for maize growth according to canonical discriminant analysis. In terms of nutrients, the use of spent mushroom substrate increased significantly leaf P, K, and S levels and mainly K content in the soil, justifying non-application at maize topdressing.

Keywords: *Agaricus subrufescens*; organic fertilizers; spent mushroom substrate; sustainability; *Zea mays*

Citation: Alves, L.d.S.; Caitano, C.E.C.; Ferrari, S.; Vieira Júnior, W.G.; Heinrichs, R.; de Almeida Moreira, B.R.; Pardo-Giménez, A.; Zied, D.C. Application of Spent Sun Mushroom Substrate in Substitution of Synthetic Fertilizers at Maize Topdressing. *Agronomy* **2022**, *12*, 2884. https://doi.org/10.3390/agronomy12112884

Academic Editors: David Correa-Galeote and Antonio Serrano

Received: 1 September 2022
Accepted: 14 October 2022
Published: 18 November 2022

1. Introduction

Besides being a staple food and related to the origin and evolution of society, maize is one of the most important foods in the world [1]. Its world production in 2020 was over 1.15 million tons, within a planted area of about 200 million hectares [2]. Moreover, this grain is an essential source of energy for food security in underdeveloped countries [3].

Maize has high nutritional requirements, mainly for primary macronutrients such as nitrogen, phosphorus, and potassium [4]. Soil fertility depletion is one of the biggest problems in sustaining agricultural production and productivity, especially in poor countries [5,6]. To meet the nutrient demands in these regions, synthetic fertilization has been the most common practice [7].

However, synthetic fertilizers pose several problems. These inputs are directly dependent on oil, a non-renewable natural source [8]. When used intensively, this resource causes the deterioration of soil health and affects microbial diversity [9], resulting in hardness, acidification, and a decline in soil fertility and organic matter [10,11], causing environmental impacts such as soil and water contamination, in addition to increasing greenhouse gas emissions [12–14].

Despite being one way to compensate for the loss of soil fertility in cropping systems, the use of synthetic fertilizers increases costs, an investment that, in many cases, is unjustified in production [15,16]. Such a cost increase consequently raises the prices of maize, making it impossible to buy safe and affordable food in different regions of the world [17].

Therefore, new alternatives for the full or partial replacement of synthetic fertilizers are topics of great relevance. Morgan et al. showed that practices such as the retention of crop residues and the application of organic residues are ways to reduce the need for fertilizers in maize crops [18]. Tanumihardjo et al. mentioned that high-quality organic materials are of paramount importance to achieve agronomic increments in a maize production system [3]. This practice, in addition to being sustainable, improves the nutrition and health of the population [19].

Agaricus subrufescens, known as sun mushroom, is an edible fungus rich in medicinal properties [20]. Brazil is the only producer of sun mushrooms in South America due to its adequate environmental conditions [21], and about 80% of the growers are located in the State of São Paulo [22]. After being produced, sun mushroom generates a post-harvest residue known as the spent mushroom substrate (SMS). However, managing this residue is a challenge for producing regions, since its volume is about five times greater than the amount of mushroom harvested in production [23–25]. However, when properly managed, this residue can increase the content of organic matter and improve the physicochemical characteristics in the soil [26,27], in addition to promoting plant growth and soil diversity due to its rich microbiota [28,29].

SMS from different fungal species have proven to be a good source of macronutrients for healthy plant growth [30]. Moreover, studies have indicated that this residue can be a sustainable alternative for fertilizing several crops, including maize [25,28,31,32]. Nutritionally, maize requires high levels of N, K, and P, in that order [33], and these nutrients are found in the sun mushroom SMS [25]. Still, no reports in the literature have demonstrated that sun mushroom SMS can be a full or partial substitute for synthetic fertilization.

The reuse of this residue may be a sustainable solution to reduce the amount of synthetic fertilization used to grow maize. Therefore, this study hypothesizes that sun mushroom SMS application would eliminate the synthetic fertilization required for maize. The objective was to evaluate the agronomic performance of two different SMS doses under different kinds of maize fertility management, as well as to evaluate soil and leaf chemical characteristics (after 70 days of growing in pots).

2. Materials and Methods

2.1. Trial Site

The experiment was carried out in the School of Agricultural and Technological Sciences, São Paulo State University—Campus of Dracena (21°29′ S latitude, 51°52′ W longitude, and 420 m mean altitude). The study was performed in a greenhouse in the months of June and July of 2020. The temperature at the site was kept between 18 and 28 °C.

2.2. Spent Mushroom Substrate (SMS) and Experimental Soil

The spent mushroom substrate (SMS) was obtained from experimental cultivation by Vieira Júnior et al. [22], which was carried out at the Mushroom Study Center of the School of Agricultural and Technological Sciences (CECOG/FCAT UNESP). The mushroom species used was *Agaricus subrufescens*. After cultivation in chambers, the SMS was separated, dried in the shade, and then used in the experiment.

The soil used was collected from the 0–20 cm depth layer in an area of the Experimental Farm of the UNESP/Dracena. It was characterized as an Ultisol with sandy texture [34]. The chemical properties of soil and SMS are given in Table S1. For pH correction, the soil was sieved (4 mm) and its base saturation increased to 70% by adding dolomitic limestone (12 g dm^{-3} with relative power of total neutralization = 90%). Afterwards, it was incubated for 30 days in pots for soil acidity correction, maintaining humidity at 60% of the field capacity for retention water.

2.3. Experimental Design

Four maize seeds of the hybrid K9606VIP3 from KWS Group® (Einbeck, Lower Saxony) were sown in 6.5 dm^{-3} pots filled with soil. All seedlings were grown and evaluated for 10 days. Thereafter, the most vigorous plant in each pot was selected. The pots were irrigated with deionized water daily (twice a day) for 70 days, in order to maintain humidity at 60% field capacity for retention water.

The pots received two SMS doses. Dose 1 (22.75 g dm^{-3}) refers to the field conditions after cultivation where Brazilian producers grow *A. subrufescens* [22], and is close to the best application rate (20 g dm^{-3}) for leafy vegetables in previous experiments [25]. Dose 2 (45.5 g dm^{-3}) is equivalent to twice the SMS dose applied and is based on the application of high amounts, which can be an option for sun mushroom growers to produce high volumes of SMS.

Five fertilization modes were also proposed, mixing SMS and synthetic fertilizer applications (SMS: applying only the residue; SMS + S: applying the residue with synthetic fertilization at sowing, SMS + S + TD: applying the residue with synthetic fertilization at sowing and topdressing; NC: control without fertilization; and PC: applying synthetic fertilization at sowing and topdressing as recommended).

The treatments were arranged in a 5 × 2 factorial scheme, which consisted of five fertilization managements and two SMS doses (D1 and D2) with eight replications for each treatment (Table 1).

Table 1. Description of experimental treatments.

Treatment	N [1] (mg dm^3)	P [1] (mg dm^3)	K [1] (mg dm^3)	SMS (g dm^3)
		SMS Dose 1		
SMS	N.A.	N.A.	N.A.	22.75
SMS + S	300	200	300	22.75
SMS + S + TD [2]	495 (195)	200	550 (250)	22.75
		SMS Dose 2		
SMS	N.A.	N.A.	N.A.	45.5
SMS + S	300	200	300	45.5
SMS + S + TD [2]	495 (195)	200	550 (250)	45.5
		Control		
NC	N.A.	N.A.	N.A.	N.A.
PC [2]	495 (195)	200	550 (250)	N.A.

N: nitrogen provided by urea (45% N), P: phosphorus provided by triple superphosphate (42% P_2O_5), K: potassium provided by potassium chloride (60% K_2O), SMS: spent mushroom substrate, SMS + S: SMS applied with sowing fertilizer, SMS + S + TD: SMS applied with sowing and topdressing fertilizer, NC: negative control, PC: positive control, N.A.: not applicable. [1] Proposed requirement for pot experimentation by Malavolta [35]. [2] Topdressing fertilization recommendations for the crop by Raij et al. [36]; the values in parentheses refer to the values applied at topdressing fertilizer equally to the 20 DAS (97.5 mg dm^{-3} for N and 125 mg dm^{-3} for K) and 35 DAS (97.5 mg dm^{-3} for N and 125 mg dm^{-3} for K).

Except for the negative control and SMS treatment, the other pots were minerally corrected at sowing following the method described by Malavolta [35]. In both conditions, fertilizers were added before sowing and incorporated into the soil in the pots, individually.

Treatments containing conventional N and K fertilizations at topdressing (SMS + S + TD and PC, in both doses) followed the recommendations of Bulletin 100 [36]. These topdressings were applied 20 and 35 days after sowing (DAS) 5 cm away from the maize seedlings on the soil surface, which was irrigated immediately afterwards.

2.4. Biometric Parameters

During the first 10 days after maize sowing, the seedlings were counted daily to obtain the germination (G) and emergence speed index (ESI) for each treatment. The latter was estimated according to Equation (1) [37]:

$$ESI = E1/N1 + E2/N2 + \ldots + En/Nn \quad (1)$$

where ESI: Emergence Speed Index; E: number of normal seedlings computed at the last count; N: number of days of sowing to the first, second . . . and last count. The final number of seedlings emerging on the tenth experimental day was transformed into a percentage and considered the germination percentage. SMS + S + TD was not evaluated because the topdressing occurred at 20 and 35 DAS.

At 70 DAS, the following maize biometric parameters were evaluated: height, stem diameter, number of leaves, shoot and root fresh masses, shoot and root dry masses, and leaf area of all leaves using the equation: leaf length × sheet width × 0.75. For shoot and root dry mass measurements, the plants were dried in a forced circulation oven at 65 °C until reaching a constant weight.

2.5. Soil and Leaf Characteristics

After the biometric analysis, the soil profile was sampled on the side of each pot, with the aid of an auger (50 mm section diameter), separating the samples by treatment in plastic bags. The samples were air-dried, shredded, and passed through a 2 mm mesh sieve, and then measured in triplicate for electrical conductivity (EC) and potential of hydrogen (pH in water) according to Carmo and Silva [38].

The soil samples were also analyzed in triplicate for their contents of macronutrients (P, K, Ca, Mg, and S) and organic matter (OM), as described by Borges et al. [39]. The last fully opened maize leaves were also sampled for the analysis of macronutrients (N, P, K, Ca, Mg, and S) in triplicate, according to method described by Michalovicz et al. [40].

2.6. Statical Analysis

After applying an analysis of variance (ANOVA) to the data, the Student *t*-test was used for the SMS dose factor and Tukey's test for the SMS management factor ($p < 0.05$). All data were analyzed using the SISVAR software (version 5.7.91).

The R software (version 4.1.0) was used to evaluate the data through figures. The biometric variables collected at 70 DAS were assessed by canonical discriminant analysis (CDA) and confidence ellipses ($p < 0.01$), and the 'candisc' function of the 'candisc' package [41].

3. Results

3.1. Analysis of Variance

The analysis of variance showed that the parameters of number of leaves, shoot and root fresh masses, shoot and root dry masses, leaf area, and K content in the soil showed significant differences regarding the SMS dose factor, while only Ca content in leaves had no significant differences regarding the SMS management factor (Table 2).

3.2. Biometric Parameters

Table 3 shows the isolated effects of dose and management factors at 10 and 70 DAS. Initially, the SMS doses had no effect on the biometric parameters (10 DAS). However, the addition of synthetic fertilizers (PC and SMS + S) harmed germination and ESI. The SMS and NC treatments had the highest ESI values, with SMS being the only one to germinate 100% of the seeds tested.

Table 2. Summary of the variance analysis of the factors (SMS dose and SMS management) on the biometric and chemical characteristics of maize plants cultivated in pots.

Analysis of Variance		Source of Variation			Analysis of Variance		Source of Variation		
		SMS Dose	SMS Management	CV (%)			SMS Dose	SMS Management	CV (%)
F-calculated	G	0.28 ^{ns}	9.93 **	8.9	F-calculated	N leaf	1.28 ^{ns}	96.27 **	11.7
	ESI	0.66 ^{ns}	28.11 **	15.8		P leaf	0.05 ^{ns}	28.62 **	13.2
	NL	5.60 *	29.30 **	13.7		K leaf	0.09 ^{ns}	6.37 **	22.4
	H	13.17 **	17.00 **	10.0		Ca leaf	2.45 ^{ns}	1.66 ^{ns}	34.8
	D	7.87 **	20.65 **	17.1		Mg leaf	0.26 ^{ns}	3.56 *	48.1
	SFM	13.18 **	23.85 **	26.1		S leaf	2.08 ^{ns}	10.85 **	9.9
	RFM	7.76 **	7.36 **	33.1		P soil	0.09 ^{ns}	3.58 *	12.3
	RL	0.04 ^{ns}	4.01 **	20.5		K soil	13.18 **	34.25 **	19.1
	SDM	6.52 *	7.25 **	21.2		Ca soil	0.28 ^{ns}	3.37 *	38.2
	RDM	16.07 **	16.58 **	34.4		Mg soil	1.04 ^{ns}	10.45 **	13.3
	LA	13.13 **	25.20 **	28.1		S soil	0.52 ^{ns}	50.07 **	29.5
	pH	3.14 ^{ns}	28.14 **	3.7		OM	1.65 ^{ns}	3.69 *	17.9
	EC	0.61 ^{ns}	57.27 **	21.5					

* Significant at 5% ($p < 0.05$), ** significant at 1% ($p < 0.01$) and ^{ns} not significant at 5% ($p \geq 0.05$). G: germination, ESI: emergence speed index, NL: number of leaves, H: height, D: stem diameter, SFM: aerial part fresh matter, RFM: root fresh matter, RL: root length, SDM: aerial part dry matter, RDM: root dry matter, LA: leaf area, pH: potential of hydrogen, EC: soil electrical conductivity, OM: soil organic matter.

Table 3. Biometric productive data were collected from plants at 10 DAS and 70 DAS.

SMS Management	G (%)	ESI
	10 DAS	
NC	95.8 ab	11.5 a
PC	79.1 bc	6.9 b
SMS	100.0 a	11.3 a
SMS + S	75.02 c	4.2 b

	NL (un)	D (mm per plant)	RL (cm per plant)
	70 DAS		
NC	6.2 c	10.7 c	31.2 b
PC	9.3 a	16.1 a	40.6 a
SMS	7.6 b	13.5 b	36.4 ab
SMS + S	9.6 a	18.0 a	38.1 ab
SMS + S + TD	10.0 a	16.8 a	40.3 a

SMS Dose	G (%)	ESI	NL (un)	D (mm per plant)	RL (cm per plant)
	10 DAS		70 DAS		
D1	88.5	8.7	8.2 B	14.2 B	37.2
D2	86.4	8.2	8.9 A	15.8 A	37.5

Means followed by different lowercase or uppercase letters in the column differ according to the Tukey test or t-LSD test ($p > 0.05$), respectively. G: germination, ESI: Emergence Speed Index, NL: number of leaves, D: stem diameter, RL: root length.

Notably, the number of leaves, stem diameter, and root length showed results statistically similar to those of PC when grown only with SMS + S (Figure S1). The parameters number of leaves and stem diameter were positively influenced by the SMS dose increase, with values higher than D1 by about 7.8% and 11.2% higher, respectively.

Figure 1 displays the results of the shoot and root fresh masses, and shoot and root dry masses. The variables of height and leaf area are displayed in Table S2. SMS treatment obtained satisfactory responses (as it did not differ from PC) for shoot dry matter and root fresh matter (Figure 1a,b).

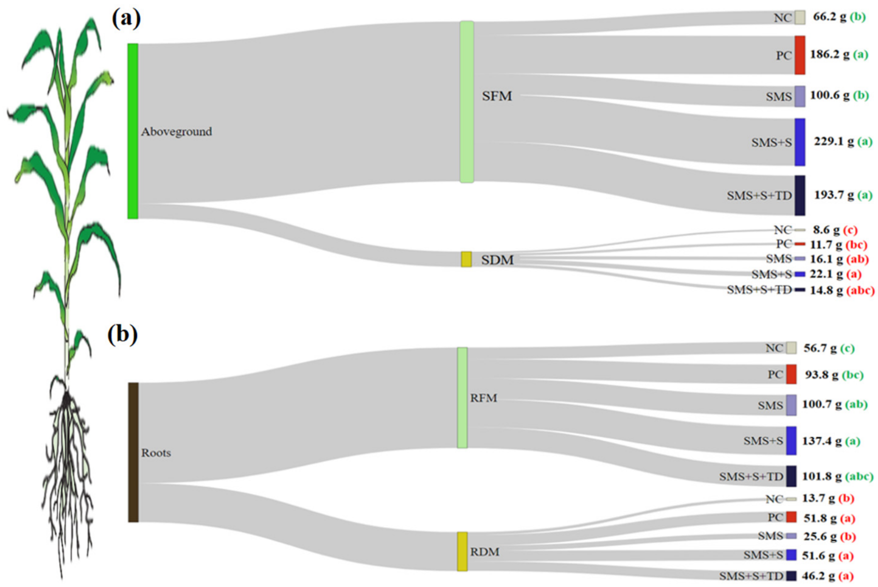

Figure 1. Aboveground and root mass of maize under different SMS managements at 70 DAS. SFM: shoot fresh matter and SDM: shoot dry matter (**a**), RFM: root fresh matter and RDM: root dry matter (**b**). Means followed by different lowercase letters for the same color differ according to Tukey's test ($p > 0.05$).

The leaf area (Table S2) in the SMS treatment was about 2236 cm^2 per plant, which is an intermediate result. SMS + S was the only treatment to achieve significant increases in height, being about 10.5% greater than PC (Table S2). When compared to PC, SMS + S also had significantly higher values for shoot dry matter and root fresh matter, with increments of 10.4 and 43.6 g per plant, respectively (Figure 1a,b).

Between the doses, D2 significantly increased the biometric characteristics of maize (Figure S2). The parameters shoot and root fresh masses, and shoot and root dry masses showed increments of about 34, 33, 35, and 50% from D1 to D2, respectively (Figure 2a,b).

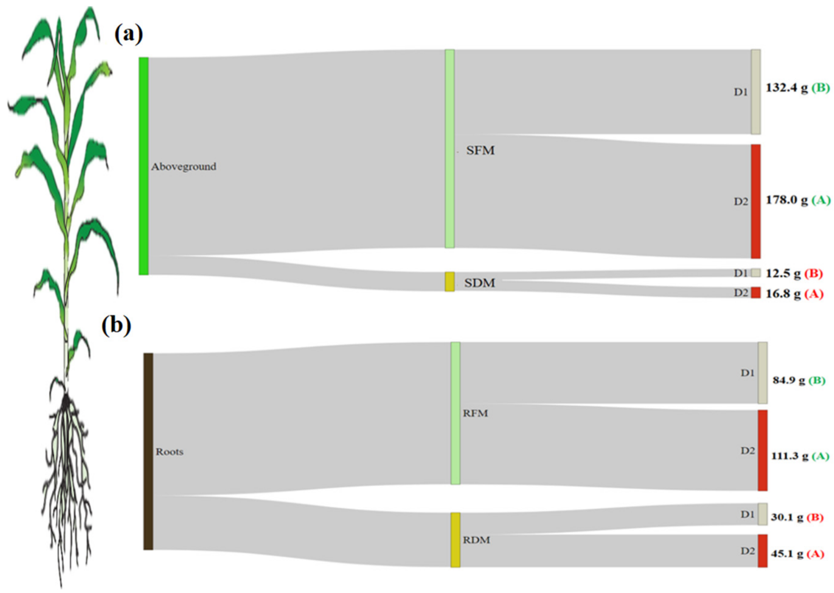

Figure 2. Aboveground and root mass of maize under different SMS doses at 70 DAS. SFM: shoot fresh matter and SDM: shoot dry matter (**a**), RFM: root fresh matter and RDM: root dry matter (**b**). Means followed by different uppercase letters for the same color differ according to the t-LSD test ($p > 0.05$).

Figure 3 shows the canonical discriminant analysis (CDA) of height, stem diameter, number of leaves, shoot and root fresh masses, shoot and root dry masses, and leaf area at 70 DAS (Figure 3). CDA reduced the high-dimensional biometric dataset to two subsets, Canonical I (Can1) and Canonical II (Can2), for both doses tested. The two canonicals explained about 78.4% (for SMS D1) and 93.9% (for SMS D2) of the variability in SMS management.

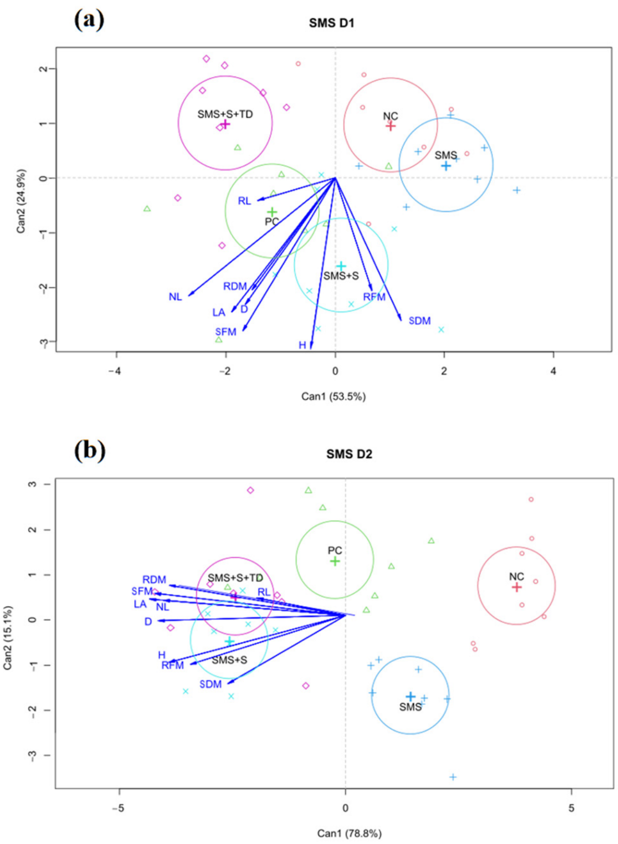

Figure 3. Canonical discriminant analysis (CDA) of 70 DAS maize plants cultivated under different types of SMS management at two different doses. (**a**) Analysis under the SMS Dose 1 condition and (**b**) the condition of double the previous condition—SMS Dose 2. NC: negative control, PC: positive control, SMS: residue application only, SMS + S: SMS application with sowing fertilization, SMS + S + TD: SMS application with sowing and topdressing fertilization.

Regarding biometric measurements, the CDA showed that most vectors were on the left quadrants. The parameters of leaf area, height, and shoot and root fresh masses had the largest vectors for both doses and were the main ones responsible for maize growth.

At Dose 1 (Figure 3a), the NC and SMS treatments lay in the negative quadrants of the vectors, therefore they had a low response in terms of maize development. Dose 2 had a similar negative effect, with greater relevance mainly for NC (Figure 3b).

The main analogue between the doses is related to the effect of SMS + S. At Dose 1, SMS + S and PC were the ones that most induced initial biometric increments in maize (Figure 3a). At Dose 2, SMS + S and SMS + S + TD were the ones that most induced plant growth (Figure 3b). SMS + S is a combination of organic and synthetic fertilizers that reduce the cost of production and are relevant for the initial growth of maize at both doses.

3.3. Soil Electrical Conductivity and pH

Figure 4 exhibits the results of soil electrical conductivity (EC) and pH. The highest EC values (0.36 and 0.37 dS m^{-1}) were reached in SMS + S + TD under D1 and D2, respectively. NC had the lowest EC values at both doses, whereas PC, SMS, and SMS + S achieved intermediate results (between 0.18 and 0.20 dS m^{-1}, regardless of the dose). Comparing the doses in SMS, EC increased by only 6%, that is, the residue had a low impact on EC.

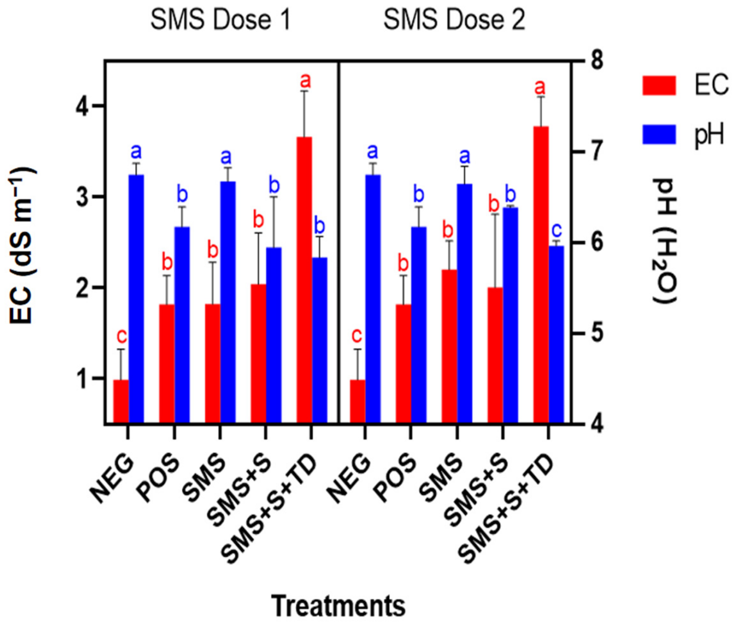

Figure 4. Electrical conductivity (EC) and pH. Lowercase letters between columns in the same dose differ according to the Tukey test ($p < 0.05$).

For all treatments, the pH values were between 5.83 and 6.74. SMS showed values statistically similar to those of NC for both doses. The presence of synthetic fertilizer (PC, SMS + S, and SMS + S + TD) reduced the pH, mainly for SMS + S + TD, which had the lowest values (5.83 and 5.96 under D1 and D2, respectively).

3.4. Soil and Leaf Chemical Characteristics

Table 4 describes the soil chemical characteristics and organic matter content. SMS had higher soil contents of S (13.2 mg dm^{-3}) and Mg (9.1 $mmol_c$ dm^{-3}) than did PC (see Table S3). Strikingly, the soil OM, P, K, and Ca contents obtained in SMS did not differ from those of PC.

Table 4. Mineral composition and organic matter of soil in maize cultivation at 70 DAS.

SMS Management	OM (g dm^{-3})	P Soil [1] (mg dm^{-3})	K Soil [1] ($mmol_c$ dm^{-3})	Ca Soil [1] ($mmol_c$ dm^{-3})	Mg Soil [1] ($mmol_c$ dm^{-3})	S Soil (mg dm^{-3})
NC	6.8 b	5.8 ab	1.8 b	26.2 ab	8.9 a	4.4 c
PC	7.6 ab	5.4 ab	2.3 b	23.1 b	6.8 c	3.2 c
SMS	8.1 a	5.1 b	2.3 b	31.1 ab	9.1 a	13.2 a
SMS + S	7.9 ab	5.6 ab	2.2 b	32.8 ab	7.3 bc	8.5 b
SMS + S + TD	8.0 a	6.1 a	4.0 a	39.2 a	8.2 ab	15.9 a
SMS Dose	**O.M. (g dm^{-3})**	**P soil [1] (mg dm^{-3})**	**K soil [1] ($mmol_c$ dm^{-3})**	**Ca soil [1] ($mmol_c$ dm^{-3})**	**Mg soil [1] ($mmol_c$ dm^{-3})**	**S soil (mg dm^{-3})**
D1	7.6	5.6	2.3 B	29.7	7.9	8.8
D2	7.9	5.7	2.8 A	31.3	8.2	9.3

Means followed by different lowercase or uppercase letters in the column differ according to the Tukey test or t-LSD test ($p > 0.05$), respectively. [1] P, K, Ca, and Mg soil: extracted by resin method.

SMS + S showed intermediate conditions in terms of the soil contents of OM, P, K, Ca, and Mg. Moreover, this treatment had soil S contents 165% higher than those of PC. The only soil mineral parameter that increased with D2 application was the K content (about 21.7% higher than in D1).

Table 5 displays the content of minerals in the last fully opened leaves. When comparing SMS with PC, the first could not supply two of the three primary macrominerals in the maize leaves, showing significant reductions in N and P leaf contents (77.5 and 29.2%, respectively). However, SMS provided suitable levels of K and S in the leaves, with increments of about 42.8% and 15.3% compared to PC, respectively. Moreover, SMS + S + TD could increase N leaf levels by about 5.7 g kg^{-1}. Yet for Mg, the leaf content was higher (3.9 g kg^{-1}) in PC, while the Ca leaf content showed no significant differences among the treatments. There were no significant differences between the doses.

Table 5. Mineral composition of the last fully opened maize leaf collected at 70 DAS.

SMS Management	N Leaf (g kg^{-1})	P Leaf (g kg^{-1})	K Leaf (g kg^{-1})	Ca Leaf (g kg^{-1})	Mg Leaf (g kg^{-1})	S Leaf (g kg^{-1})
NC	13.3 c	1.1 c	3.5 c	2.6	2.1 ab	1.2 c
PC	22.4 b	1.9 a	4.3 bc	3.5	3.9 a	1.3 bc
SMS	12.9 c	1.4 b	5.0 ab	3.1	2.3 ab	1.5 a
SMS + S	22.9 b	1.7 a	5.5 a	2.7	3.4 ab	1.4 ab
SMS + S + TD	28.1 a	1.9 a	4.5 abc	3.2	1.9 b	1.5 a
SMS Dose	**N leaf (g kg^{-1})**	**P leaf (g kg^{-1})**	**K leaf (g kg^{-1})**	**Ca leaf (g kg^{-1})**	**Mg leaf (g kg^{-1})**	**S leaf (g kg^{-1})**
D1	19.6	1.6	4.5	2.8	2.6	1.3
D2	20.2	1.6	4.7	3.2	2.8	1.4

Means followed by different lowercase or uppercase letters in the column differ according to the Tukey test or t-LSD test ($p > 0.05$), respectively.

4. Discussion

4.1. Biometric Parameters

SMS provided increased germination for both doses, as well as higher ESI than those in treatments with the addition of synthetic fertilizers, regardless of the dose (Table 3). Such a positive influence on germination has already been reported in the literature, either by in vitro or in vivo tests and for different mushrooms and crops [42–44]. This effect may be due to the presence of plant growth-promoting microorganisms in SMS such as *Trichoderma* spp. and *Bacillus* spp. [45].

SMS may have reached 100% germination due to its richness in organic materials. *A. subrufescens* is composed of several raw materials such as manure and limestone, among other residues [46]. Such an abundance of materials causes improvements, mainly in the physical properties and availability of nutrients in the soil [47].

The use of a synthetic fertilizer with SMS at sowing reduced the ESI. This can be attributed to the higher osmotic activity caused by the potassium chloride (KCl) fertilizer. After KCl is applied, K is absorbed and exported by plants as a nutrient, while Cl concentrates in soil pore water and is transformed into salt after evapotranspiration, thus causing soil salinization [48]. George et al. suggested that Cl toxicity is the major limitation for plants grown in saline substrates and soils [49].

The use of SMS would be interesting when synthetic fertilizers cannot be produced. Given the increases in germination, ESI, height, root fresh matter, and shoot dry matter (Table 3, Figure 1), the use of this residue becomes an easy practice, reducing investments in input and improving the outcome. Still, SMS + S was substantial to achieve higher production parameters under both doses, as demonstrated in the CDA results. Furthermore, SMS + S + TD showed more promising results by the CDA analysis when combined with D2 (Figure 3).

The agronomic results of many crops can be improved by using the residues of several mushroom species, enriched or combined with synthetic or organic fertilizers [25,28,30,50]. Maize exports high amounts of minerals [51], and synthetic fertilization is therefore recommended to increase production. In this sense, SMS + S becomes a feasible approach to reduce the dependence on topdressing.

As SMS disposal is a major environmental problem, D2 would be a better option as it deposits greater amounts of the residue in the soil throughout a crop season, improving it qualitatively [27].

Coles et al. (2020) evaluated different spent *Agaricus bisporus* substrate application rates on maize cultivation combined with the synthetic fertilizers recommended [52]. They observed the highest yields using application rates of 40 tons per acre, which is equivalent to 50 g SMS dm^{-3} (similar to D2), considering the 0–20 cm depth layer. As *A. subrufescens* and *A. bisporus* substrates have the same nutritional habits [46], their spent substrates have similar physicochemical characteristics, justifying the increments found herein.

4.2. Soil Electrical Conductivity and pH

Soil EC and pH are soil attributes that influence the cultivation of various crops and are of high importance [53]. The former is a surrogate measure of salinity [54]; therefore, this measure has been of concern to several authors who used SMS in plant fertilization. These authors reported that this residue increases salinization levels, especially due to the high K levels made available [30,55,56].

Among the soil properties, pH is the most informative since it indicates the hydrogen ion concentration in a soil solution [57]. Dose 2 provided good EC or pH conditions, which remained within the ideal range (EC between 0.13 and 0.27 dS m^{-1}; and pH between 6.3 and 6.8). When evaluating the use of SMS as an inoculant and organic fertilizer in *Hibiscus sabdariffa* L., Ngan and Riddech [58] observed pH and EC averages similar to those obtained in our research (6.35 and 0.26 dS m^{-1}, respectively), characterizing D2 as ideal for plant growth.

SMS + S + TD promoted the highest EC and lowest pH values (Figure 4). These pH reductions and EC elevations can be explained by the use of urea as a N source at topdressing [59]. After application to the soil, urea is rapidly hydrolyzed by urease, releasing ammonium, which is consumed by microorganisms in nitrite and nitrate reactions, a process that releases two H^+ ions and potentiates soil acidification [60,61].

Ozlu and Kumar carried out continuous comparisons between cattle manure residue and synthetic fertilizer applications into the soil [62]. These authors concluded that both pH and EC were constant for the organic sources, while the addition of NPK synthetic fertilizers only promoted high EC and low pH values, corroborating our data. Remarkably, both SMS doses promoted higher pH values than SMS and PC (Figure 4). An elevated pH in tropical acidic soils due to the use of SMS as fertilizer increases soil quality and reduces the use of carbonate rocks to neutralize acidity [63].

4.3. Soil and Leaf Chemical Characteristics

The treatment PC soil promoted very low P (5.4 mg dm^{-3}), low S (3.2 mg dm^{-3}), intermediate K (2.3 $mmol_c$ dm^{-3}), and high Ca (23.1 $mmol_c$ dm^{-3}) and Mg (26.2 $mmol_c$ dm^{-3}) levels according to the recommendations of São Paulo State [36] (Table 4). The content of OM was considered low for medium sandy-textured soils (7.6 g dm^{-3}) (Table 4) [64].

Furthermore, SMS was not a good source of P for tropical soils. Neither dose was sufficient to elevate the P interpretation class, with results remaining at very low levels (Table 4). Testing NPK-added SMS granulated fertilizer sources, Kuśmirek observed a very low potential for SMS to elevate the P class interpretation, corroborating our findings [65].

We argue that the need for KCl fertilization in maize topdressing can be reduced if SMS is applied to the soil. The soil K content increased significantly at D2, while SMS + S + TD increased the K interpretation class regarding that of PC. Therefore, SMS + S + TD was classified as a promoter of high soil K content. The SMS + S treatment was similar to the conventional fertilization performed by Brazilian farmers (PC) and promoted intermediate K content in the soil (Table 4). Average levels of K are sufficient for annual crops to produce up to 100% of the expected productivity [36]. Other studies have shown that spent substrates from other mushroom species are excellent K sources [31,55]. Conversely, the K content was low in the presence of SMS, as the residue supplied a high amount of

Ca to the soil (Table 4), which was considerably absorbed by the plants (Table 5). This is because K and Ca have a negative interaction, in which the absorption of one inhibits the accumulation of the other [66]. Despite this, the application of SMS was enough to satisfy the maize agronomic demands.

Even though most countries use KCl to overcome K deficiencies [67], K topdressing requires extra labor and damaging methods at the end of crop growth [68]. Furthermore, this fertilizer has to be applied twice (20 and 35 DAS), increasing diesel expenses and greenhouse gas emissions.

Accordingly, new alternatives of eco-friendly fertilizers should be prospected for cereal crops to meet their needs with a single application, e.g., the agricultural residue tested in our study. Furthermore, there are economic gains from the adoption of SMS + S. Synthetic potassium fertilization for maize cultivation costs USD 82 [69]. About 30% of this fertilization is applied in topdressing, and the SMS + S would generate savings of about USD 25 for the farmer.

When compared to PC, SMS was superior in supplying Mg to the soil (Table 4), but insufficient to supplement it to maize leaves (Table 5). This mineral is responsible for important functions in maize growth, as it is a constituent of chlorophyll and cofactor of enzymatic processes [70]. Stewart et al. demonstrated that mushroom post-harvest residues increase the Mg availability in the soil due to its fast release in the first weeks of application [71]. However, high concentrations of soluble Mg^{2+} in the soil do not increase the Mg availability to plants.

Regarding S, SMS proved to be an excellent source since its content increased significantly and a positive change in the S interpretation class was observed (from low to high compared to PC). Although non-significant, the S increased by 0.5 mg dm^{-3} from D1 to D2, improving the soil's nutritional conditions for maize (Table 4). Sulfur is important for plants as it is used in amino acid synthesis, in addition to regulating physiological processes and increasing tolerance to abiotic stresses [72].

Our study also showed that N uptake was negatively affected in the treatments without synthetic fertilization. Even with SMS addition, the leaf N levels did not increase (Table 5), which indicates the need for additional N fertilization. We observed that SMS does not have as high N levels (4.9 g kg^{-1}) (Table S1) as other residues used as fertilizers such as Biochar corn cob (8.8 g kg^{-1}) or cattle manure (13.1 g kg^{-1}) [73], which can justify our results.

A few experiments have shown that continuous annual applications of SMS can increase organic matter accumulations in the soil, maintaining the agricultural ecosystem and soil N levels [29,74]. Our findings showed that, besides increasing OM, SMS applications raise the contents of humic and fulvic acid, which are relevant for a better soil quality [27]. Still, future long-term field studies are needed on maize crops grown in tropical sandy soils to better understand OM deposition after SMS application.

5. Conclusions

The use of a spent mushroom substrate (SMS) from *Agaricus subrufescens* improves maize germination parameters compared to treatments only receiving synthetic fertilizers. Although it is not a good nitrogen source for tropical soils, this residue is a good supplier of potassium and sulfur. The dose of 45.5 g dm^{-3} is the best to raise the main maize biometric parameters and potassium contents in the soil, in addition to allocating a greater amount of the waste. The application of SMS combined with synthetic fertilizers at sowing is interesting because it can reduce the use of potash synthetic fertilizers, which is a profitable condition for maize producers and has less environmental impact.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12112884/s1, Table S1: Mineral composition of soil and SMS; Table S2: Height and leaf area of maize plants at 70 DAS; Table S3: Interpretation of soil analysis results for samples of soil collected in the experimentation; Figure S1: Maize plants at 70 DAS under the effect of treatments; Figure S2: Maize roots at 70 DAS.

Author Contributions: Conceptualization, L.d.S.A. and D.C.Z.; methodology, L.d.S.A., R.H. and D.C.Z.; formal analysis, L.d.S.A., B.R.d.A.M. and D.C.Z.; investigation, L.d.S.A., C.E.C.C. and W.G.V.J.; resources, L.d.S.A. and D.C.Z.; data curation, L.d.S.A., B.R.d.A.M. and D.C.Z.; writing—original draft preparation, L.d.S.A. and D.C.Z.; writing—review and editing, L.d.S.A., R.H., A.P.-G. and D.C.Z.; supervision, R.H., S.F. and D.C.Z.; funding acquisition, D.C.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001 and the São Paulo Research Foundation (FAPESP) (Grant #2018/21492-2, #2019/00419-8 and #2019/19866-4).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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