

## RESEARCH ARTICLE

# Composting and vermicomposting of spent mushroom substrate to produce organic fertilizer

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## ABSTRACT

Spent mushroom substrate (SMS) is a by-product of the mushroom cultivation industry. Mexico produces more than 350 thousand tons of SMS annually. Attempts have been made to use SMS as a soil amendment, among other applications, with some success. However, leaching from the SMS can discard into groundwater and potentially lead to eutrophication in discharge areas. These problems can be overcome by bioconversion of the waste. Thus, the present study aimed to apply composting and vermicomposting methods on a pilot scale, to convert SMS into a highly enriched substrate suitable for soil amendment and horticulture. For this purpose, 800 kg (fresh weight) of SMS was processed by each of the above-mentioned bioconversion methods for 120 days. The physicochemical properties of the initial material (SMS) and the compost and vermicompost obtained at the end of the two processes were analyzed by measuring pH, electrical conductivity, organic matter, total carbon, nitrogen content, cation exchange capacity (CEC), C/N, and micro- and macronutrient contents. Both processes reduced the volume of SMS substantially (by around 60%), partly as a result of organic matter mineralization. The main characteristic of the vermicompost was its higher  $\text{NO}_3^-$  content (292%) compared to the compost. The concentrations of most salts were significantly reduced, and the CEC increased, confirming the stability of the SMS at the end of both processes. In summary, the findings highlight the potential value of scaling up the composting/vermicomposting processes for industrial application in environmental waste management, particularly for SMS.

**Keywords:** Composting; Horticulture; Industrial application; Vermicomposting; Waste management

## INTRODUCTION

Mexico occupies 13<sup>th</sup> place regarding the production of cultivated mushrooms worldwide (Royse et al., 2017). This production has increased enormously in the last few decades, yielding about 62 thousand tons annually of edible fresh mushrooms, of which 95% are white mushrooms (Martínez-Carrera et al., 2012). However, for each kilogram of mushrooms harvested, about five kilograms of spent mushroom substrate (SMS) are generated (Paredes et al., 2009; Rosmiza et al., 2016). In Mexico, current production yields more than 350 thousand tons of SMS per year. This waste product is not managed and is simply piled up outdoors and left to weather. Thus, SMS is currently an environmental and possibly also a public health hazard owing to its accumulation in increasingly limited spaces and to the leaching of nitrates ( $\text{NO}_3^-$ ), sulphates ( $\text{SO}_4^{2-}$ ) and other salts during natural decomposition of the SMS.

The leachates can potentially reach and contaminate groundwater systems (Medina et al., 2009; Ribas et al., 2009; Abbiramy and Ross, 2012; Cebula et al., 2013).

The particular composition of the SMS depends on the diversity of available agro-industrial waste rich in polysaccharides and nitrogen (N). The main components of the original substrate (MS) in which the mushrooms are cultivated include straw, (barley, corn, wheat) fermented with cattle or poultry manure, peat moss, gypsum, urea and water (Paredes et al., 2009; Grujić et al., 2015). All of the components are partially composted before being mixed and pasteurized to eliminate pathogens. The SMS remaining after the mushrooms are harvested is predigested as a result of mycelial enzymatic activity; it is also a uniform substrate, easy to handle and cheap, or even free. For all of these reasons, SMS is considered suitable for recycling.

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In relation with the bio-based circular economy, SMS could cease to be a pollution waste if it continues to be used to generate other products (Smart Mushroom, 2021). Has been used as animal feeding (Baek et al., 2017), to produce biogas (Najafi and Ardabil, 2018; Luo et al., 2018), biochar (Lou et al., 2017), for the purification of polluted water (García-Delgado et al., 2017) and it has been applied directly as a part of growth medium (Esmailpour et al., 2017). However, for direct application as a fertilizer, it is required to stabilize the SMS through composting methods (Paula et al., 2017).

Conventional composting and vermicomposting are validated, effective methods that facilitate the management of large amounts of hazardous organic waste rapidly and inexpensively (Domínguez and Edwards, 2011). Bioconversion of SMS into valuable, stabilized products such as compost and vermicompost is an environmentally-friendly process that prevents contamination and promotes soil restoration. The products can be used as soil amendments (Tan, 2014) or as organic fertilizers to enhance crop production (Domínguez and Edwards, 2011). Furthermore, the vermicompost and compost can be sold as a source of income. The objective of this study was to establish whether SMS can be composted and vermicomposted and to determine the quality of the compost/vermicompost produced.

## MATERIALS AND METHODS

### Bioconversion of spent mushroom substrate

The SMS was obtained from a commercial mushroom producer (ALTEX-Rioxal SA de CV, Veracruz, Mexico) (Fig. 1A) and bio-stabilized and matured in two different ways. Composting was carried out by constructing a rectangular pile of SMS (810 kg) with a base of 1.8 x 2.5 m and 1.5 m high (approximate volume, 2.25 m<sup>3</sup>) (Fig. 1B). The pile was turned manually once every week for 120 days to produce compost (C-SMS).

For vermicomposting, a rectangular, brick-built pilot-scale vermireactor (5 x 1 x 0.50 m; vol 5 m<sup>3</sup>), without temperature control, was installed outdoors under natural environmental conditions. SMS (810 kg) was placed in the vermireactor up to a height of about 45 cm. Earthworms, mainly *Eisenia andrei* (Bouché, 1972), were added (Fig. 1C). The initial density was  $1,910 \pm 3$  individuals m<sup>-2</sup>, representing an earthworm biomass of  $450 \pm 5$  g m<sup>-2</sup> (Fig. 1D). In both processes, the moisture content of the SMC was maintained at approximately 85-95% (by covering the compost pile with a plastic sheet and the vermireactor with a roof tiles to prevent desiccation of the substrate). The vermicomposting process was completed in 90 days, and

the earthworms were separated from the vermicompost (V-SMS) (Fig. 1E). The composting process was completed in 120 days. The C-SMC and V-SMS collected on completion of the respective processes were stored and allowed to mature for another 30 days, after that were dried (Fig. 1F) before analysis of the physiochemical properties.

### Density and biomass of earthworms

The density and biomass of the earthworm population were monitored every 15 days by randomly collecting 10 samples of the SMS with a rectangular prism sampler (10.5 x 9.5 x 30 cm) during the vermicomposting trial. The density and biomass of earthworms were estimated on the base of the total number of earthworms and their weight.

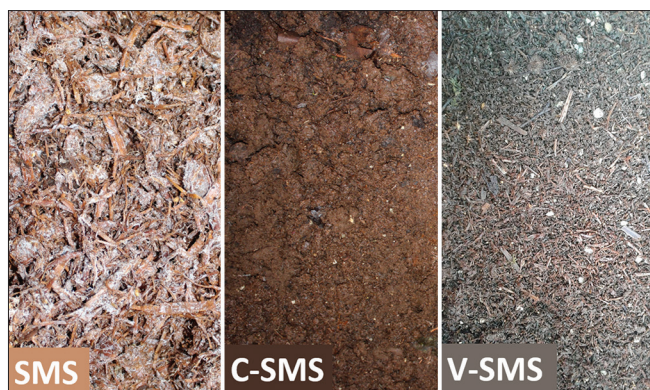
### Collection, classification and preparation of samples

At the beginning and end of the trials, nine samples of SMS (500 g fresh weight) were randomly collected from the compost pile and the vermireactor (Fig. 2). The inorganic N content was determined immediately after sample collection in subsamples of each substrate. The remaining samples were dried, sieved and stored in a vacuum pack until analysis of the physicochemical properties.



**Fig 1.** Composting and vermicomposting setup for SMS. A) Reception of >1.6 tons of SMS for bioconversion. B) Installation of composting pile. C) Installation of the vermicomposting reactor. D) Earthworm biomass. E) Volume reduction in vermicomposting at 90 days. F) Compost and vermicompost drying.





**Fig 2.** SMS immediately before bioconversion, C-SMS after 120 days of composting and V-SMS after 90 days of vermicomposting.

### Analysis

The measurements were made according to the standardized Mexican protocols NOM-021-RECNAT-2000. The moisture content and bulk density were measured in samples dried for 24 h at 105°C. The pH (ratio 1:2 soil: water) was measured with a potentiometer and electrical conductivity (EC) was measured with a conductivity meter. The organic matter (OM) and ash contents were determined by weight loss as described by Jackson (1964). Total carbon (TC) and total nitrogen (TN) were determined in a sample dried in an induction furnace, by thermal conductivity, using the LECO TruSpec™ CN analyzer.

### Nutrient analysis (P, K, Ca, Mg, Na, Fe, Zn and Mn)

Dried samples of the substrates were subjected to acid digestion for determination of the total Ca, Mg, Fe, Zn, Mn and Cu and quantified by atomic absorption spectrometry using Fast Sequential Atomic Absorption Spectrometer (Model: VARIAN-AA240FS) and flame spectrophotometry for the total K and Na were analyzed using Flame Photometer (Model: CORNING-410). The cation exchange capacity (CEC) and exchangeable cations were measured by extraction with ammonium acetate (1N) at pH7 and quantified by atomic absorption spectrometry (for  $Mg^{2+}$  and  $Ca^{2+}$ ) and flame spectrophotometry (for  $K^+$ ,  $Na^+$ ). Available P was measured with Bray-Kurtz's method (1945).

### Mineral nitrogen ( $NH_4^+$ , $NO_3^-$ ) analysis

The mineral N concentration was determined in fresh samples by distillation KCl 2 N extracts (Alvarez, 1988; Etchevers 1987; Keeney and Nelson, 1982; Rodríguez et al., 1977).

### Fiber

The fiber contents (hemicellulose, cellulose and lignin components) were measured in an Ankon Fiber Analyzer, according to Van Soest's method (1967).

### Statistical analysis

One-way analysis of variance (ANOVA) of the mean values of each parameter (physico-chemical properties) in the three substrates (SMS; C-SMS and V-SMS), was used to detect significant differences between treatments. Prior to ANOVA, the normality and homoscedasticity of the variances were checked using the Shapiro–Wilk test implemented with SPSS 21 statistical software. Tukey's b test was used to identify the differences between the specific treatments (considering a significance level of  $p < 0.05$ ) and was carried out using the JMP 13.2.1 statistical software.

## RESULTS AND DISCUSSION

### Population dynamics of earthworms during vermicomposting of spent mushroom substrate

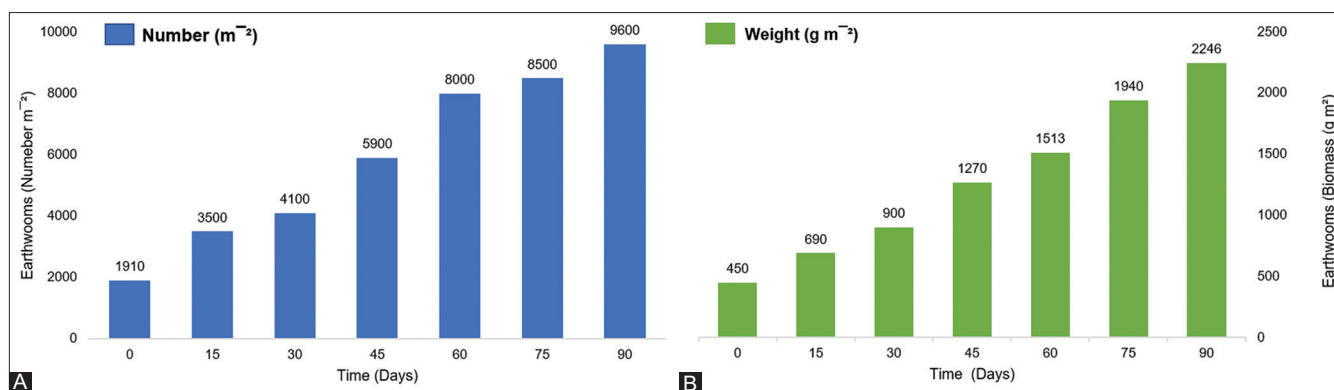
The initial density of earthworms in the vermireactor was about  $1,910 \pm 3$  individuals  $m^{-2}$ , and the average biomass was  $450 \pm 5$  g live weight  $m^{-2}$  (Fig. 2). The total number of earthworms and their biomass increased significantly throughout the vermicomposting process, reaching a density of  $9,600 \pm 20$  individuals  $m^{-2}$  and a biomass of  $2,246 \pm 1.9$  g  $m^{-2}$  on day 90 (Fig. 3). The fivefold increase in the earthworm population during the bioconversion process indicates that the OM in the SMS was a good source of energy for the earthworms.

The increase in earthworm population may be due to mobile fractions (e.g. carbohydrates and amino acids) of the soluble organic matter in the SMS (Becher and Pukula, 2014), and its content in mycelium. It is known that earthworms feed on mycelium (Curry and Schimdt, 2007).

### Bioconversion of spent mushroom substrate

When we observed the SMS with the naked eye many vegetal fibers were still recognizable and it was light brown in color. The C-SMS did not show any fibers but instead irregular lumps (large and small) and was dark brown and homogeneous in color. The V-SMS had a fibrous aspect, but the fibers were smaller and homogeneous than the SMS and its color was grey-black and the non-fibrous material had a small grain (Fig. 2). These granulometric differences are also reflected in their respective bulk density, the SMC had the lowest (0.037) and the V-SMC the highest (1.024 g  $cm^{-3}$  Table 1).

In both processes (conventional composting and vermicomposting), the initial quantity of the SMS was  $800 \pm 0.06$  kg fw (60%) ( $325 \pm 12.02$  kg dw). The biomass decreased by >53%, as a result of mineralization of SMC during both bioconversion processes until reaching a final fresh weight of 378.8 kg (C-SMS) and 378.2 kg (V-SMS), and in dry weight (dw) 151 and 150 kg, respectively. The volume of SMC decreased by >58% in both processes, e.g. from an initial value of 2.25  $m^3$  to a final value of 0.90  $m^3$  at the



**Fig 3.** A) Earthworm density (individuals m<sup>-2</sup>), and B) earthworm biomass (g m<sup>-2</sup> fw) during vermicomposting of spent mushroom substrate. Values are means (n=10).

**Table 1: Changes in the physicochemical properties of the spent mushroom substrate throughout conventional composting and vermicomposting processes**

Parameter	Spent mushroom substrate (SMS)	Composted spent mushroom substrate (C-SMS)	Vermicomposted spent mushroom substrate (V-SMS)	T-test (sig)
	Day 0	Day 120	Day 90	
Moisture (%)	60.13 ± 0.60 <sup>c</sup>	71.21 ± 1.05 <sup>b</sup>	85.56 ± 1.75 <sup>a</sup>	<0.001
pH	6.26 ± 0.03 <sup>c</sup>	7.48 ± 0.03 <sup>a</sup>	6.80 ± 0.03 <sup>b</sup>	<0.001
Electric conductivity (EC) (mS cm <sup>-1</sup> )	9.79 ± 0.09 <sup>a</sup>	8.43 ± 0.04 <sup>b</sup>	6.86 ± 0.14 <sup>c</sup>	<0.001
Cation exchange capacity (CEC)	19.75 ± 0.42 <sup>b</sup>	31.08 ± 0.71 <sup>a</sup>	31.84 ± 0.79 <sup>a</sup>	<0.001
Organic matter (%)	57.69 ± 0.47 <sup>a</sup>	50.74 ± 0.26 <sup>b</sup>	50.67 ± 0.25 <sup>b</sup>	<0.001
Ashes (%)	42.3 ± 0.48 <sup>b</sup>	49.25 ± 0.26 <sup>a</sup>	49.32 ± 0.25 <sup>a</sup>	<0.001
C to N Ratio	10.00 ± 0.00 <sup>b</sup>	11.00 ± 0.00 <sup>a</sup>	11.00 ± 0.00 <sup>a</sup>	<0.001
Total macronutrient content				
Total C (%)	23.45 ± 0.37 <sup>b</sup>	24.01 ± 0.38 <sup>a</sup>	25.45 ± 0.23 <sup>a</sup>	0.0011
Total N (%)	2.30 ± 0.03 <sup>a</sup>	2.17 ± 0.03 <sup>b</sup>	2.24 ± 0.02 <sup>ab</sup>	0.0133
Total P (%)	0.704 ± 0.01 <sup>b</sup>	0.712 ± 0.00 <sup>ab</sup>	0.731 ± 0.01 <sup>a</sup>	0.0837
Total K (%)	1.57 ± 0.07 <sup>a</sup>	1.33 ± 0.21 <sup>ab</sup>	0.96 ± 0.14 <sup>b</sup>	0.0175
Total Mg (%)	1.03 ± 0.04 <sup>a</sup>	0.90 ± 0.03 <sup>b</sup>	0.81 ± 0.02 <sup>b</sup>	0.0004
Total Na (%)	2.55 ± 0.17 <sup>a</sup>	1.80 ± 0.20 <sup>b</sup>	1.33 ± 0.12 <sup>b</sup>	<0.0001
Total micronutrient content				
Total Fe (%)	0.194 ± 0.03 <sup>b</sup>	0.268 ± 0.02 <sup>a</sup>	0.276 ± 0.01 <sup>a</sup>	0.0068
Total Mn (%)	0.028 ± 0.00 <sup>b</sup>	0.040 ± 0.00 <sup>a</sup>	0.044 ± 0.00 <sup>a</sup>	<0.001
Total Ca (%)	5.62 ± 0.26 <sup>a</sup>	4.84 ± 0.14 <sup>b</sup>	4.68 ± 0.15 <sup>b</sup>	0.006
Total Zn (%)	0.024 ± 0.00 <sup>b</sup>	0.045 ± 0.00 <sup>a</sup>	0.048 ± 0.00 <sup>a</sup>	<0.001
Available nutrient content				
K <sup>+</sup> (cmol kg <sup>-1</sup> )	39.11 ± 0.43 <sup>a</sup>	42.86 ± 1.34 <sup>a</sup>	33.01 ± 1.47 <sup>b</sup>	<0.001
Na (cmol kg <sup>-1</sup> )	100.43 ± 1.33 <sup>a</sup>	90.41 ± 0.74 <sup>b</sup>	67.24 ± 1.31 <sup>c</sup>	<0.001
Mg <sup>2+</sup> (cmol kg <sup>-1</sup> )	25.62 ± 0.33 <sup>b</sup>	30.71 ± 0.33 <sup>a</sup>	24.65 ± 0.53 <sup>b</sup>	<0.001
NH <sub>4</sub> <sup>+</sup> (mg kg <sup>-1</sup> )	324.78 ± 14.66 <sup>a</sup>	44.38 ± 2.73 <sup>b</sup>	64.85 ± 1.91 <sup>b</sup>	<0.001
NO <sub>3</sub> <sup>-</sup> (mg kg <sup>-1</sup> )	96.57 ± 3.49 <sup>c</sup>	2012.8 ± 16.21 <sup>b</sup>	5880.5 ± 42.26 <sup>a</sup>	<0.001
Fibers				
Lignin (%)	2.94 ± 0.29 <sup>b</sup>	7.31 ± 0.35 <sup>a</sup>	7.74 ± 0.64 <sup>a</sup>	<0.001
Cellulose (%)	6.85 ± 0.10 <sup>a</sup>	6.59 ± 0.26 <sup>a</sup>	6.63 ± 0.15 <sup>a</sup>	n/s
Hemicellulose (%)	5.04 ± 0.06 <sup>b</sup>	6.61 ± 0.29 <sup>a</sup>	7.28 ± 0.37 <sup>a</sup>	<0.001
Bulk density (g cm <sup>-3</sup> )	0.037 ± 0.80 <sup>b</sup>	0.96 ± 0.01 <sup>a</sup>	1.024 ± 0.02 <sup>a</sup>	<0.001

Values are means ± standard error (n=9). Different letters within the same row indicate a significant difference in the parameter between the sampling times, according to Tukey's HSD test. Data are expressed on a dry weight basis.

end of the trials. Thus, each kilogram of fresh SMS yielded approximately 400 - 415 g (dw) of C-SMS and V-SMS.

### Biodegradation of fibers

Bioconversion of the SMS caused a decrease in OM

(>13%) in both processes (Table 1). This can be attributed to the consumption of soluble or digestible C and the enrichment of stable C fractions (Paul and Clark, 1996), which constitute the recalcitrant matter such as fibers like lignin (Martínez-Cordeiro et al., 2015).

Organic matter mineralization is another indication of the amount of OM consumed, which results in an increase in the proportion of ashes (>14%) in both processes (Table 1).

The lignin and hemicellulose contents of the substrates increased significantly, by >148 and >31%, respectively in both processes (Table 1). By contrast, the cellulose was conserved because it is a biopolymer that resists degradation (Benítez *et al.*, 2005), and one of the main C sources for microorganisms (Hubbe *et al.* 2010). On the other hand, the lignin tended to increase or concentrate over time as it degrades slowly (Lima *et al.*, 2009). The recalcitrant nature of lignin stabilizes the resulting substrates, a necessary condition for humidification. Lignocellulosic compounds are continually degraded (Martínez-Cordeiro *et al.*, 2015) until their eventual transformation into humic acid (Smidt *et al.*, 2008). Standard NADF-020-AMBT-2011 establishes an OM content of >20 % for substrates destined for agricultural and horticultural purposes, and both C-SMS and V-SMS comply with this criterion. The OM content in the initial SMS was  $57.69 \% \pm 0.47$  and decreased significantly ( $p=0.001$ ) throughout the composting and vermicomposting processes until reaching final levels of respectively  $50.74 \pm 0.26$  and  $50.67 \pm 0.25 \%$ , respectively (Table 1). Similar results were found by Paredes *et al.* (2009) with the characterization of organic matter fractions of several samples of SMS from the industry in Spain.

### Organic carbon cycle degradation

The TC content of the initial SMS was  $23.45 \% \pm 0.3$  and increased significantly ( $p=0.0011$ ) throughout the composting and vermicomposting processes by 2.4 and 8.5 %, respectively (Table 1). The increase was due to the input of microbial necromass during the SMS bioconversion (Almendros, 2004), despite the consumption of soluble or easily digestible C (Hossain *et al.*, 2017). On the other hand, the volume and mass reduced (>50%) of OM decay by the end of both processes, explained as a spatial and temporal heterogeneous matrix of organic resource (Domínguez, 2011), confer to the final C content the feature to maintain the stable and humified fractions (Tan, 2014).

The C: N ratio increased from 10 to 11 between day 0 and the end of each bioconversion process. The metabolic cycles involved in the oxidative bioconversion processes depend on C and N assimilation. The necromass contributed to the energy flow to support vital microorganism functions (Durán, 2009), slowing down the gradual OM degradation and lignocellulosic mass until their neoformation in stabilized material. C-SMS and V-SMS were equally suitable for this purpose, as the optimal C: N ratio ranges from 10 to 15, according to Gómez-Brandon and Domínguez (2010) and Sánchez *et al.* (2015). This range in the final substrate

ensures the availability and slow release of nutrients (Chaoui *et al.*, 2003).

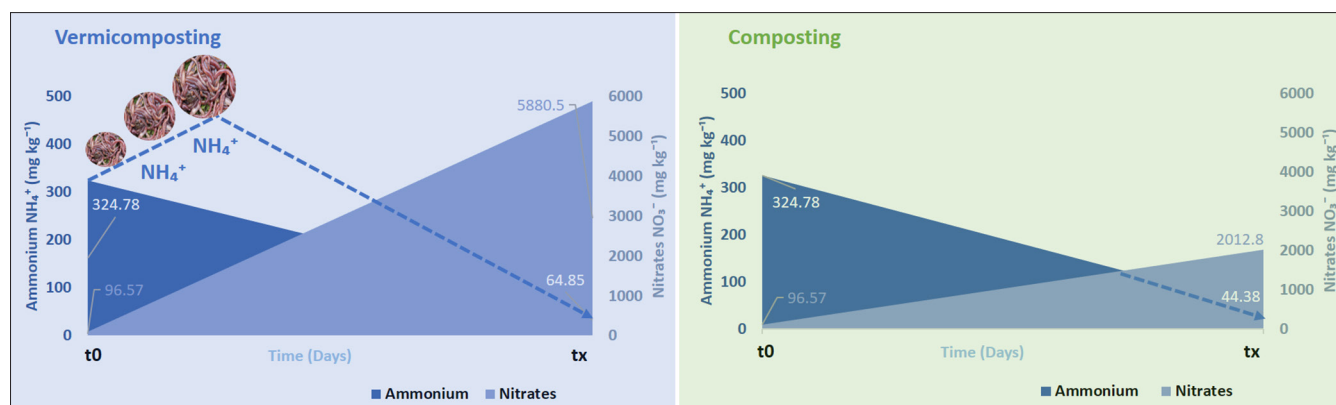
### Nitrogen mineralization

The organic N content tended to decrease slightly throughout both processes. The initial organic N content of the SMS was  $2.30\% \pm 0.03$  and reached values of  $2.17\% \pm 0.0$  and  $2.24\% \pm 0.02$  in C-SMS and V-SMS, respectively, although the difference was not statistically significant (Table 1). Nonetheless, the labile organic N in SMS underwent strong mineralization during both processes, especially in the vermicomposting process. On the one hand, the  $\text{NH}_4^+$  decreased significantly ( $p<0.001$ ) at 86.3 and 80% to C-SMS and V-SMS, respectively. On the other hand, the  $\text{NO}_3^-$  content increased by more than 20.84 times in the composting process and by more than 60.89 times in the vermicomposting process (Fig. 4). In waste substrates, N mineralization is initially regulated by the amounts of organic N and  $\text{NH}_4^+$ , which determine the starting point of any aerobic bioconversion process (Bardgett, 2005). The  $\text{NH}_4^+$  content is in general higher in other vermicomposts like that derived from coffee pulp, and  $\text{NO}_3^-$  content is more or less the same (Aranda *et al.*, 1999).

The concentration of  $\text{NH}_4^+$  reached in C-SMS ( $44.38 \text{ mg kg}^{-1} \pm 2.73$ ) is consistent with the values reported by Paredes *et al.* (2013) and Lou *et al.* (2017), who attributed the increase in  $\text{NO}_3^-$  to a large decrease in the  $\text{NH}_4^+$  after incubation of a SMS, reaching a value of  $26.03 \text{ mg kg}^{-1}$ . Consequently, the large increase in the  $\text{NO}_3^-$  content in V-SMS ( $5880.5 \text{ mg kg}^{-1} \pm 42.26$ ) was probably due to the loss of  $\text{NH}_4^+$  ( $324.78 \text{ mg kg}^{-1} \pm 14.66$  at the beginning) during the process, which was ascribed to strong nitrification (Aira *et al.*, 2005; Lazcano *et al.*, 2008; Domínguez and Aira, 2009), and thus to the rapid conversion of  $\text{NH}_4^+$  into  $\text{NO}_3^-$  (Domínguez and Gómez-Brandon, 2013). In addition, Singh and Suthar (2012) attributed the release of polymeric N from organic N to enzymes excreted and secreted by earthworms (Paul and Clark, 1996; Suthar, 2008). In particular, such enzymes catalyse the hydrolysis of urea from the cast to form  $\text{CO}_2$  and  $\text{NH}_3$ , the latter of which may be volatilized. However, due to the high humidity content in the vermireactor ( $85.56\% \pm 1.75$ ), it can probably react with the water to form  $\text{NH}_4^+$ , suggesting a feedback loop in the N mineralization and nitrification cycles (Suthar, 2009).

The moisture, and especially the pore space filled with water, contributed to controlling the direction of nitrification or denitrification (Chapin *et al.*, 1993, Tasistro *et al.*, 2007). Therefore, the relatively low humidity and higher temperature during the composting process may increase the organic N reserves, leading to mineralization of the N to form  $\text{NH}_4^+$  and thus delaying the nitrification





**Fig 4.** Ammonium (NH<sub>4</sub><sup>+</sup>) and nitrates (NO<sub>3</sub><sup>-</sup>) content and dynamics during composting and vermicomposting of spent mushroom substrate. Spent Mushroom Substrate (SMS), Vermicompost of SMS (V-SMS), Compost of SMS (C-SMS).

relative to the vermicomposting process (Tasistro et al., 2007; Aira et al., 2008). Nonetheless, the inorganic N contents of C-SMS and V-SMS also indicate the remarkable potential use of the products as organic fertilizers in different environmental conditions and agrosystems.

#### pH and EC

The pH and EC values of the SMS were respectively  $6.26 \pm 0.03$  and  $9.79 \text{ mS cm}^{-1} \pm 0.09$  (Table 1). After 120 days of composting, the pH increased significantly ( $p \leq 0.0001$ ) reaching a value of  $7.48 \pm 0.03$ . By contrast, the EC decreased significantly ( $p \leq 0.0001$ ) reaching a value of  $8.43 \text{ mS cm}^{-1} \pm 0.04$ . By the end of the vermicomposting process, both parameters had decreased significantly ( $p \leq 0.0001$ ) reaching a final value of  $6.80 \pm 0.03$  and  $6.86 \text{ mS cm}^{-1} \pm 0.14$ , respectively. According to Mexican agricultural standards (NMX-FF-109-SCFI-2007), both substrates are suitable for plant growth. However, the EC values for C-SMS and V-SMS exceeded the threshold value of  $4 \text{ mS cm}^{-1}$ , despite the capacity of earthworms to regulate EC (Edwards, 1988; Ansari and Rajpersaud, 2012).

#### Ionic content

The initial total Na content in SMS decreased significantly ( $p \leq 0.001$ ) to 29.4% in C-SMS and to 47.8 % in V-SMS (Table 1). A similar trend resulted in decreases in exchangeable Na of 9.97 and 33.04 %, respectively. These findings are consistent with those of Domínguez and Gómez-Brandón (2013), who related earthworm cast-associated processes and formation of insoluble salts.

The initial Ca content also decreased significantly ( $p \leq 0.006$ ) by 13.87 and 16.72 % for CSP and VSP, respectively. Nonetheless, the final levels of Ca in both substrates ( $4.84 \% \pm 0.14$  to C-SMS,  $4.68 \% \pm 0.15$  to V-SMS) exceeded the threshold of  $\leq 0.05 \%$  according to NMX-FF-109-SCFI-2007. Similarly, the total Mg content decreased significantly ( $p < 0.001$ ) from  $1.03 \% \pm 0.04$  in the SMS (Table 1) to 0.90 and 0.81 % for C-SMS and V-SMS,

respectively. But the available Mg increased significantly by 16.57% only in C-SMS ( $p < 0.001$ ). This last, probably owing to mass and volume reduction on SMS throughout the composting, concentrating Mg<sup>2+</sup> in the process. And the excess Ca in the substrates could compete with the absorption of Mg and K, potentially leading to deficiencies in these elements (Johnson et al., 2003; Cebula et al., 2013). Nevertheless, the outcome in the total Ca and Mg content depends mostly on the parent wastes (Yadav and Garg, 2011; Domínguez and Gómez-Brandón, 2013), which in the case of SMS, and according to Beyer (2011), is due to the addition of calcium carbonate, gypsum, poultry manure during the substrate mixture before the mushroom cultivation.

In general, the salts content in the substrates exceeded the threshold proposed by SEDESOL (2004), because of the properties of the parent material. Thus, the doses of the products applied must be controlled, to prevent the formation of calcium phosphate, which immobilizes phosphates or inorganic N (Johnson et al., 2003).

#### Cation exchange capacity

The initial CEC of SMS was  $19.75 \pm 0.09 \text{ cmol/kg}$  and increased significantly ( $p < 0.0001$ ), by 60%, reaching  $31.08 \pm 0.71$  and  $31.84 \pm 0.79 \text{ cmol/kg}$  in C-SMS and V-SMS, respectively. This produces sites available for cation retention, so that the substrate acts as a reserve of nutrients for plants (Edwards, 2011), and provides the capacity to hold or release available nutrients (Six et al., 2002).

#### Phosphorus

Regarding the available P (aP) content, there was no significant difference ( $p = 0.83$ ) between the initial content in SMS and the content in the resulting substrates. Unlike N, P is not volatile and is not consumed at the same rate as C, and therefore P tended to be conserved during both composting processes. On the other hand, the reduction in mass (>50%) throughout the processes led to an increase in the available P in C-SMS and V-SMS (Irissón-Name et al.,

1999). In the vermicomposting process, P mineralization was due to the effect of earthworms, leading to the production of phosphatases (Aira et al., 2007), and in general, to the action of bacteria in the earthworm gut and fungi and enzymes in the SMS (Chaloux et al., 1993), which contributed to the solubilization of P (Pramanik et al., 2007; Prakash and Karmegum, 2010).

### Enrichment of metals

The total metal contents (Fe, Mn, and Zn) increased significantly, by approximately 35% for Fe, >42% for Mn and >88% for Zn in both C-SMS and V-SMS. This is consistent with the findings of Domínguez and Gómez-Brandón (2013), who reported that fluctuations in Mn depend on parent material and the increase in Zn and Fe are influenced by earthworms and reduction of mass during the bioconversion processes.

The observed overall level of nutrient availability is possible because of microbial community succession in composting and the interaction between earthworms and microbial activity in vermicomposting, both of which catalyze useful compounds for soil amendment and crop nutrition (Singh and Suthar, 2012).

## CONCLUSIONS

Both composting and vermicomposting processes yielded stabilized spent mushroom substrate on a pilot scale, as indicated by the reduction in volume, mass and final values of nutrients relative to the initial material. The presence of sodium and calcium salts (which can leach into groundwater and potentially lead to eutrophication of discharge areas) decreased significantly during the processes. Nevertheless, the concentration in the final compost and vermicompost remained too high for healthy plant growth. The doses of vermicompost/compost applied to land must therefore be regulated according to specific agro-ecological conditions.

The earthworm populations developed well in this SMS and their activity led to higher concentrations of available nutrients in the final vermicompost than in the compost. The increase in the nitrates was particularly elevated, indicating high-quality properties for organic fertilization. Besides the SMS vermicompost was ready 30 days before the compost.

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### Authors contributions

Mario Domínguez-Gutiérrez. Writing - original draft preparation, bioconversion of spent mushroom substrate data acquisition and analysis, writing - review and editing. Rigoberto Gaitán-Hernández. Research conceptualization, funding acquisition, composting testing supervision, data interpretation, writing - review and editing. Itzel Moctezuma-Pérez. Nutrient analysis supervision, review, and editing. Isabelle Barois. Density and biomass of earthworms analysis supervision, writing - review and editing. Jorge Domínguez. Data interpretation, review, and editing.

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