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# Effects of *Sesuvium verrucosum* Raf. Compost and vermicompost on the growth and production parameters of the *Solanum lycopersicum* L. crop

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**ABSTRACT:** The objectives of this work were to use *Sesuvium verrucosum* to produce stable and mature compost and vermicompost and to evaluate their influence on the growth and production parameters of the *Solanum lycopersicum* L. crop. For the preparation of vermicompost, the earthworm *Eisenia fetida* (Savigny) was used. The proposed treatments were: T1 (negative control) [no organic fertilizer + urea], T2 (positive control) [bovine manure (100%) + urea], T3 (compost) [bovine manure (100%) + urea], T4 (compost) [*S. verrucosum* (25%) + bovine manure (75%) + urea], T5 (compost) [*S. verrucosum* (50%) + bovine manure (50%) + urea], T6 (compost) [*S. verrucosum* (75%) + bovine manure (25%) + urea], T7 (vermicompost) [bovine manure (100%) + urea], and T8 (vermicompost) [*S. verrucosum* (25%) + bovine manure (75%) + urea]. The results showed that all the treatments were stable, mature and rich in nutrients after 140 days. In general, treatments made from *S. verrucosum* showed a high pH (7.97–8.45) and electrical conductivity (3.83–8.85 dS $m^{-1}$). Nonetheless, excluding T7, the treatments made from a proportion of 25% halophyte and 75% bovine manure (T8 and T4) achieved the highest morphological parameters in the different variables that were evaluated, as well as the highest yields compared to controls T1 and T2, followed by T3, T5 and T6, respectively. Therefore, it was concluded that *S. verrucosum* can serve as a stable and mature organic amendment, rich in nutrients, and that can be used to improve the growth and development of the *S. lycopersicum* crop.

**Key words:** bovine manure, drip irrigation, *Eisenia fetida*, halophyte, sodium concentration.

## INTRODUCTION

A wide range of studies highlight the benefits of phytodesalination around the world (Saddhe et al. 2020). Nevertheless, so far few studies have explored the potential of halophyte species as organic fertilizer in the form of compost and vermicompost after having been implemented in the remediation of soils that are seriously affected by salinity, in other words, subjecting the vegetable matter to a biological oxidation process in which millions of bacteria, fungi and different microorganisms degrade the matter—as happens in the case of compost (Waqas et al. 2018)—and in which, moreover, epigeal species such as *Eisenia fetida* are used to accelerate this process, as occurs with vermicompost (Karmegam et al. 2019).

It is important to notice that the relevance of using halophyte species as organic fertilizer in the form of compost and vermicompost stems from the fact that, when halophytes are subjected to a biodegradation process, there is a possibility that the NaCl content that is immersed in the tissues would decrease during the decomposition process because the $Na^+$ of the NaCl remains in the organic acids that are produced during decomposition, and, in this way, the $Cl^-$ is released, thereby causing the reduction of NaCl jointly (Ravindran et al. 2007). Moreover, the leaching of compost and vermicompost that is caused by irrigation could also reduce a significant portion of the concentrations of soluble salts (Watson 2003).

Consequently, the efficiency of the compost and vermicompost depends on both the halophyte species that have been selected and the physicochemical and microbiological quality of the manure that is being used (Vázquez and Loli 2018).

It has been found recently that the species *Sesuvium verrucosum* Raf.—a succulent of the Aizoaceae family—has a high growth rate and an enormous phytodesalination potential, as well as a wide phenotypic plasticity to be used for agricultural purposes (Lastiri-Hernández et al. 2021). However, being a halophytic species that bioaccumulates a large amount of sodium in its tissues, there is a possibility that it may become a serious threat to the proper growth and development of various glycophyte crops when applied to the soil in the form of compost or vermicompost (Zörb et al. 2019).

Therefore, the objective of this study was to use the *S. verrucosum* species to produce compost and vermicompost in combination with bovine manure, in order to determine its quality in terms of stability and maturity and, in turn, to evaluate its influence in the growth and production parameters of the *Solanum lycopersicum* L.

## MATERIALS AND METHODS

The compost and vermicompost were manufactured under greenhouse conditions, between January and May 2020. The greenhouse is located in the municipality of Jiquilpan de Juárez, Michoacán, Mexico, at an altitude of 1,560 m.a.s.l. and coordinates 19°59'57.6456" N and -102°42'24.0336" W. On average, the temperature and relative humidity conditions in the greenhouse were 36/10 °C (day/night) and 60% (± 10%), respectively.

### Vegetable matter

The vegetable matter used for the development of the experiment was extracted from a geothermal area known as Los Negritos, in the municipality of Villamar, Michoacán, Mexico, at an altitude of 1,540 m.a.s.l. and coordinates 20°03'47.2248" N and -102°36'52.776" W. The type of vegetation in this area is secondary. The vegetable matter was extracted at the beginning of October 2019, in the dry season, when it was in a reproductive phenological stage.

An extraction of 380 *S. verrucosum* plants was carried out and placed in black polystyrene bags with a capacity of 10 kg in order to be taken to the greenhouse. The halophytes had an average fresh weight of 183.51 ± 17.26 g at the time of extraction.

### Organic amendment

The bovine manure was obtained from a barn located in the municipality of Jiquilpan, Michoacán, at coordinates 20°00'01.5804" N and -102° 42'25.1424" W.

### Precomposting

The *S. verrucosum* plants were washed with potable water to eliminate the soil particles adhering to the roots and leaves. Afterwards, the plants were cut into segments of 1 to 1.5 cm.

The precomposting of the *S. verrucosum* plants and bovine manure consisted of forming two piles 0.50-m high, which were covered with dark plastic (600 gauge). The piles were turned every third day, over a period of 20 days, to remove volatile gases that could be potentially toxic to the *E. fetida* earthworms used to make vermicompost.

### Preparation of compost and vermicompost

For the preparation of compost and vermicompost, containers 0.35-m wide, 0.40-m long and 0.40-m high were used, which were drilled on the bottom to facilitate leaching during irrigation.

To each container, 4.8 kg of precomposed raw material—*S. verrucosum* plants and bovine manure—were added. The raw material was watered, and aeration was provided every seven days, moving it into the interior of the containers with a three-toothed hand rake.

For vermicompost production, 4.8 kg of precomposed raw material and 600 g of Californian red worm (*E. fetida*) were added, in a ratio 8:1, respectively; therefore, 769 worms were used. The humidity content was kept at 80% daily.

## Chemical and microbiological characteristics of irrigation water

The compost and vermicompost were irrigated with tap water. The chemical characteristics of the irrigation water were: electrical conductivity (ECe) of 0.58 $dS \cdot m^{-1}$, pH of 8.1, hardness of 262 $mmol_c \cdot L^{-1}$, total dissolved solids (TDS) of 155 ppm, 1.2 $mmol_c \cdot L^{-1}$ of $Ca^{2+}$, 2.1 $mmol_c \cdot L^{-1}$ of $Mg^{2+}$, 1.75 $mmol_c \cdot L^{-1}$ of $Na^{+}$, 0.3 $mmol_c \cdot L^{-1}$ of K+, 0.48 $mmol_c \cdot L^{-1}$ of $CO_3^{-2}$, 8.6 $mmol_c \cdot L^{-1}$ of $HCO_3^{-}$, 0.153 $mmol_c \cdot L^{-1}$ of $SO_4^{-2}$, and sodium adsorption ratio (SAR) of 1.36.

The microbiological characteristics of the water were: total coliforms 17 $MPN \cdot 100\ ml^{-1}$, fecal coliforms 3 $MPN \cdot 100\ ml^{-1}$ and *Escherichia coli* 3 $MPN \cdot 100\ ml^{-1}$.

## Survival rate of *Eisenia fetida*

In order to evaluate the survival rate of the *E. fetida* worms, a sample was taken using a frame of 0.15 × 0.15 m, placed in the middle of the container at a depth of 20 cm to prevent the edge effect.

Survival was calculated as the ratio between the number of organisms collected at the end of the experiment and the number of initial organisms (Álvarez Bernal et al. 2016). After 120 days, the *E. fetida* worms were extracted from the containers using specific traps. A sample was collected from each container and dried at room temperature in the shade, finally stored in a plastic bag for its subsequent analysis.

## Germination index

The germination index of the different treatments was determined using Raphanus sativus seeds, in accordance with Zucconi et al. (1981).

## Physicochemical analysis of compost and vermicompost

At the end of the compost and vermicompost preparation, each sample was analyzed for the following parameters: pH and ECe using distilled water at 1:10 (w/v), total organic carbon (Nelson and Sommers 1982), total Kjeldahl nitrogen (Bremner and Mulvaney 1982), humidity (Alef and Nannipieri 1995), oxidable organic carbon and $CO_2$ (Sánchez-Monedero et al. 1996), inorganic carbon (Page 1982), cation exchange capacity (Uehara and Gillman 1981), ammonium ($NH_4^{+}$), and nitrate ($NO_3^{-}$) (APHA 1998). Subsequently, $K^{+}$, $Mg^{2+}$, $Na^{+}$ and $Ca^{2+}$ were determined by atomic absorption spectroscopy (Allen 1989) using a GBC SensAA spectrometer (Mexico). Chloride determinations were obtained by the Mohr method using $K_2CrO_7$ as indicator in the titration of Cl ions with a standard solution of $AgNO_3$ (Johnson and Ulrich 1959).

## Microbiological analysis

For the determination of *E. coli* and total and fecal coliforms, the United States Environmental Protection Agency (USEPA) 1680 method (USEPA 2010) was used for both the compost and vermicompost of the various treatments. For *Salmonella* spp., the method 1682 (USEPA 1998) was used, and for helminth eggs the following procedure was followed: samples were mixed with buffered water containing 0.1% surfactant (Triton X-100). Subsequently, large particles were allowed to precipitate, and the supernatant was decanted. The sediment was subjected to density gradient centrifugation using magnesium sulfate (specific gravity 1.2 g·cm$^{-3}$). Small particles were removed by sieving it once more with a small mesh (US standard 400 mesh, 38 µm, stainless steel) and proteinaceous material by an acid alcohol/ethyl ether extraction.

Subsequently, the concentrate was incubated at 26 °C for 10 days and microscopically examined for helminth eggs in a Sedgewick-Rafter counting chamber (Hausser Scientific, Horsham, Pa.) (USEPA 2003).

## Field experiment

In a second stage, at the beginning of April 2020, in order to evaluate the influence of compost and vermicompost on the growth and production parameters of the *S. lycopersicum* crop, an experiment was established in a 117-m$^2$ plot in the municipality of Villamar, Michoacán, Mexico, located between coordinates 20°01'57.7056"N and -102°36'49.1832"W.

The experiment was carried out in two different seasons, the first one in the spring-summer agricultural cycle (April-June), and the second one in the autumn-winter cycle (October-December) of the year 2020. In each season, the study was carried out with three repetitions in a single experimental run. Each repetition occupied an area of 13 × 3 m.

## Treatments

The proposed treatments were:

- T1: negative control [without fertilizer];
- T2: positive control [bovine manure (100%)];
- T3: compost [bovine manure (100%)];
- T4: compost [*S. verrucosum* (25%) + bovine manure (75%)];
- T5: compost [*S. verrucosum* (50%) + bovine manure (50%)];
- T6: compost [*S. verrucosum* (75%) + bovine manure (25%)];
- T7: vermicompost [bovine manure (100%)];
- T8: vermicompost [*S. verrucosum* (25%) + bovine manure (75%)].

The treatments were arranged through a randomized complete block design with two repetitions. The compost and vermicompost were applied in two portions. The first portion was applied three days before planting, placing it at the transplant site, and the second portion 30 days after planting, placing the organic fertilizer in a 10-cm hole that was dug next to the plants, which was later covered with the same soil of the crop.

The seeds of the Rio Grande variety were used for the development of the crop. They were disinfected by immersing them for 5 min in a sodium hypochlorite solution with 5% of active chlorine and subsequently washed with distilled water.

The seeds were sown in trays of 60 cavities, which contained commercial substrate. To maintain the humidity of the seeds, daily watering was applied in order to achieve a homogeneous emergence of the *S. lycopersicum* seedlings.

The seedlings were transplanted into the plot after 30 days of germination and showed fresh weight of 13.14 ± 0.85 g, height of 18.71 ± 1.56 cm, root length of 6.35 ± 0.92 cm and stem diameter of 0.36 ± 0.05 cm.

Before transplanting, the soil was subjected to various traditional tillage practices, including fallowing, harrowing and manual furrowing. The furrows had the length of 9 m, the height of 0.20 m and the width of 1 m, and the separation between them was 1 m. In addition, the furrows were covered with a 50-µm white polyethylene film.

Twelve experimental units were established in each furrow. Each experimental unit consisted of a *S. lycopersicum* seedling. The separation between the seedlings was 0.50 m, equivalent to a density of 10,000 plants·ha$^{-1}$. The applied dose of compost and vermicompost was 4,000 kg·ha$^{-1}$, in addition to 600 kg·ha$^{-1}$ of urea for each one of the established treatments, all this in accordance with the recommendations of Roblero Ramírez et al. (2014) for this specific type of crop.

## Physicochemical characteristics of the soil

The soil of the experimental area presented the following characteristics: vertisol with a clay texture (30% sand, 46% clay, 24% silt); ECe of 1.93 dS·m$^{-1}$, pH of 7.89, 3.8% organic matter (% OM), bulk density (BD) of 1.08 g·cm$^{-3}$, water holding capacity (WHC) of 83.7%, SAR of 4.05 $(mmol_c·L^{-1})^{1/2}$, cation exchange capacity (CEC) of 35.62 $cmol_c·kg^{-1}$, and an exchangeable sodium percentage (ESP) of 16.28, as well as 0.22% of total nitrogen, 16.17 $mg·kg^{-1}$ of available phosphorus, 3.8 $mmol_c·L^{-1}$ of carbonates, 12.98 $mmol_c·L^{-1}$ of bicarbonates, 4.07 $mmol_c·L^{-1}$ of chlorides, and 7.85 $mmol_c·L^{-1}$ of sulfates.

### Irrigation

Throughout the experiment, the treatments were watered daily for 15 min using a drip irrigation system. Three drippers were used per experimental unit, having each dripper a flow rate of 8 L per hour. Irrigation was applied based on accumulated evaporation, measured in a type A tank (De Tar 2004). To carry out the irrigation process, a tank (Rotoplas®, model 500021) with the capacity of 2.5 $m^3$ was used. On average, each experimental unit received 6 L of water every day. The water that was used for irrigation was the same as the one used for the preparation of compost and vermicompost.

## Morphometric variables

The length of the primary root and the height of *S. lycopersicum*—from the soil surface to the tip of the mature leaf—were measured with a Stanley® FatMax® tape measure (model H-1842). The diameter of the plant stems and the equatorial diameter of the fruits were measured with a Vernier caliper (model H-7352). The leaf area was measured using the free software ImageJ version 1.52 (Guerrero et al. 2012), and the fruits were counted manually. The plants (stems and leaves) and fruits were washed with distilled water and quantified by their fresh weight (g) using a precision balance (Brainweigh® model B5000). Finally, the yield of the fruits of each treatment was determined by the average fresh weight.

## Statistical analysis

The data obtained from the variables that were evaluated during the two seasons were averaged and subjected to the Shapiro-Wilk's normality test ($p \leq 0.05$) and Levene's test of homogeneity of variance.

The variables that met the criteria of both tests were subjected to the analysis of variance (ANOVA), and the Tukey's mean comparison test ($p \leq 0.05$). The variables that did not fulfill the tests of normality and homogeneity of variance were transformed to the natural logarithm (Ln) until normality and homoscedasticity were observed; later, the ANOVA and Tukey's mean comparison tests were calculated ($p \leq 0.05$).

Data that did not meet the criteria of both tests were subjected to a non-parametric Kruskal-Wallis' analysis and a Wilcoxon rank-sum test. In all cases, the software Statistical Analysis System (SAS) version 9.1 was used (SAS Institute Inc. 2004).

# RESULTS AND DISCUSSION

Stable and mature compost and vermicompost were obtained after 140 days, and their chemical and physical properties are shown in Table 1. According to Álvarez Bernal et al. (2016) and Kranz et al. (2020), the optimal time needed to make compost and vermicompost depends on various factors, such as:

- The population density of worms;
- The type of species that were used;
- The preferred eating habits of the worms regarding organic waste;
- The quality of organic materials.

In this sense, Ramnarain et al. (2019) have indicated that only a period of 120 days is required in order to obtain a stable and mature vermicompost; however, other works have established a period of 110 days as the optimal time (Álvarez Bernal et al. 2016), differently to compost, which can present the same condition of stability and maturity within 90 days (Ravindran et al. 2007). Therefore, the period of 140 days that was established in this research was considered adequate because, according to Mupambwa et al. (2020), longer periods of biodegradation and an earthy smell are considered as indicators of a better quality in organic fertilizers.

In the case of vermicompost, the survival rate of earthworms was 100%, whereas in the treatment V25S it was 82% ± 2, which indicates that the *E. fetida* worms were able to adapt themselves to the raw material that was used thanks to the precomposting process that prevented the presence of volatile compounds that could interfere with their development. This finding coincides with Nazarizadeh et al. (2018), that found a decrease in the survival of *E. fetida* as the salinity increased due to NaCl.

According to Sharif et al. (2016), salinity hinders the neurosecretory activity of worms and causes the body cuticle of these organisms to be permeable to water and ions in dissolution, which causes a deadly osmotic imbalance that reduces the survival, growth, biomass and reproduction rates. For this reason, it has been established as a recommendation that ECe should be kept at values lower than 2 $dS{\cdot}m^{-1}$ if the survival of the worms—especially the young ones—is to be guaranteed (Mamani-Mamani et al. 2012).

In addition, significant differences ($p \leq 0.05$) were observed in the pH and ECe of the various compost and vermicompost treatments (Table 1). The pH ranged from slightly alkaline to moderately alkaline (7.60–8.45), whereas the ECe ranged between 1.87 and 8.85 $dS{\cdot}m^{-1}$, which indicates a significant presence of salts, mainly in the treatments C50S and C75S, in which a high halophyte content was used for their preparation (≥ 50%).

The level of alkalinity observed in the different treatments could be explained by various factors, such as:

- The leaching of soluble salts caused by irrigation (Watson 2003);
- The calciferous glands that *E. fetida* worms possess to add calcium to the organic amendments (Sun et al. 2020);
- The production of organic acids during the decomposition of the organic fertilizer (Das and Singh 2014);
- The intestinal secretion produced by worms that neutralize the carboxylic and phenolic groups of the humic acids (Sharif et al. 2016);
- The mineralization rate of organic matter (Acquah et al. 2021);
- The nitrification process (Gusain and Suthar 2020).

Moreover, it was observed that the organic matter content (HA/FA) and CEC in the different compost and vermicompost treatments were found in the optimal interval of > 4.1 and ≤ 52.16 $g{\cdot}kg^{-1}$, respectively (Table 1), which indicates that they are rich in nutrients and therefore suitable to be used as organic amendments. According to Ayyappan and Ravindran (2014), the nutrient content of halophyte species is higher compared to that of green manures; however, the nutrient content that was obtained depended also on the quality of the materials that were used and the percentages or proportions established during the preparation process, as other authors have noticed (Singh et al. 2008).

Furthermore, it was observed that the stability of the compost and vermicompost in the various evaluated treatments—measured in the form of oxidable organic carbon in a C:N ratio—was optimal (Table 1), since it is known that the decomposition of OM is related to the mineralization of carbon ($CO_2$) and nitrogen ($NH_4^+$) (Marzi et al. 2020).

Additionally, a reduction in total organic carbon (TOC) could be observed in the treatments (from 274.6 to 408.5 $g{\cdot}kg^{-1}$), which was directly proportional to the percentage of bovine manure (100%) that was used and inversely proportional to the percentage of halophyte content used as raw material. This situation could be explained by the fact that manure is the main food of *E. fetida* worms, as it contains semi-composted carbon compounds that can be easily assimilated by them (Sharma and Garg 2020). Therefore, the TOC decreased as the proportion of bovine manure prevailed (100%) as a source of raw material. Hence, significant differences ($p \leq 0.05$) were observed in the TOC of the different compost and vermicompost treatments (Table 1). This finding agrees with Sharma and Garg (2018), that reported a reduction of up to 51.37% in the TOC of vermicompost after applying the following proportion: 90% cow manure + 10% rice straw.

Likewise, it was observed that the maturity parameters of the compost and vermicompost—such as oxidable organic carbon (Table 1), C/N ratio (Table 2) and germination index (Fig. 1)—showed significant differences ($p \leq 0.05$) among the treatments, mainly in organic amendments with low (*S. verrucosum* [25%]) or zero halophyte content (bovine manure [100%]), which suggests a rapid degradation of OM and an increase in mineralization rate during this period, since those treatments had a C/N ratio that ranged between 5.23 and 12.01.

**Table 1.** Maturity and stability indexes of compost and vermicompost at 140 days of their preparation*.

| Parameters | Treatments | | | | | | | Maturity and stability index |
|---|---|---|---|---|---|---|---|---|
| | M | CM | C25S | C50S | C75S | VM | V25S | |
| pH | $7.84 \pm 0.05^{e}$ | $7.71 \pm 0.05^{f}$ | $7.97 \pm 0.04^{d}$ | $8.22 \pm 0.05^{b}$ | $8.45 \pm 0.04^{a}$ | $7.60 \pm 0.04^{g}$ | $8.08 \pm 0.05^{c}$ | - |
| ECe | $2.93 \pm 0.13^{e}$ | $2.25 \pm 0.17^{f}$ | $3.83 \pm 0.22^{d}$ | $6.39 \pm 0.15^{b}$ | $8.85 \pm 0.12^{a}$ | $1.87 \pm 0.19^{g}$ | $4.71 \pm 0.15^{c}$ | - |
| $N\text{-}NH_4^+$ ($mg \cdot kg^{-1}$) | $216.5 \pm 5.41^{a}$ | $164.3 \pm 3.55^{d}$ | $155.4 \pm 3.72^{e}$ | $175.7 \pm 3.95^{c}$ | $187.9 \pm 4.69^{b}$ | $135.5 \pm 2.85^{g}$ | $143.1 \pm 3.12^{f}$ | < 400[1] |
| $N\text{-}NO_3^-$ ($mg \cdot kg^{-1}$) | $185.8 \pm 3.62^{a}$ | $125.2 \pm 2.42^{a}$ | $159.1 \pm 2.76^{c}$ | $118.4 \pm 2.34^{a}$ | $110.2 \pm 2.21^{a}$ | $165.7 \pm 3.31^{b}$ | $132.9 \pm 2.65^{a}$ | < 500[2] |
| $NH_4^+/NO_3^-$ | $1.16 \pm 0.02^{d}$ | $1.31 \pm 0.02^{c}$ | $0.97 \pm 0.01^{f}$ | $1.48 \pm 0.02^{b}$ | $1.70 \pm 0.03^{a}$ | $0.82 \pm 0.01^{g}$ | $1.07 \pm 0.02^{e}$ | < 3[2] |
| HA/FA | $2.6 \pm 0.21^{g}$ | $5.2 \pm 0.16^{d}$ | $5.7 \pm 0.11^{c}$ | $4.7 \pm 0.17^{e}$ | $4.1 \pm 0.13^{f}$ | $6.6 \pm 0.18^{a}$ | $6.1 \pm 0.15^{b}$ | > 1.9[4] |
| CEC ($g \cdot kg^{-1}$) | $27.19 \pm 1.08^{g}$ | $40.64 \pm 1.12^{d}$ | $43.87 \pm 0.82^{c}$ | $36.81 \pm 1.25^{e}$ | $31.37 \pm 1.19^{f}$ | $52.16 \pm 1.04^{a}$ | $46.52 \pm 0.96^{b}$ | ≤ 60[1] |
| TOC ($g \cdot kg^{-1}$) | $486.1 \pm 14.5^{a}$ | $341.8 \pm 10.2^{d}$ | $318.9 \pm 8.56^{e}$ | $373.8 \pm 17.3^{c}$ | $408.5 \pm 12.2^{b}$ | $274.6 \pm 13.8^{g}$ | $302.6 \pm 5.78^{f}$ | > 200[5] |
| $CO_2$ (mg/kg/day) | $40.24 \pm 1.67^{a}$ | $24.16 \pm 1.23^{d}$ | $20.74 \pm 0.94^{e}$ | $29.22 \pm 1.42^{c}$ | $34.49 \pm 1.29^{b}$ | $12.07 \pm 1.16^{g}$ | $17.65 \pm 1.05^{f}$ | ≤ 120[3] |

*In each row, the different letters represent the least significant difference according to Tukey's test ($p \leq 0.05$). Values are the mean ± standard deviation (n = 12); M: bovine manure (100%); CM: compost of bovine manure (100%); C25S: compost of *Sesuvium verrucosum* (25%) + bovine manure (75%); C50S: compost of *S. verrucosum* (50%) + bovine manure (50%); C75S: compost of *S. verrucosum* (75%) + bovine manure (25%); VM: vermicompost of bovine manure (100%); V25S: vermicompost of *S. verrucosum* (25%) + bovine manure (75%)]; ECe: electrical conductivity; HA/FA: humic-acid/fulvic-acid ratio; CEC: cation exchange capacity; TOC: total organic carbon; [1]Bernai et al. (1998); [2]TMECC (2010); [3]Hue and Liu (1995); [4]Iglesias-Jiménez and Pérez-García (1992); [5]Lasaridi et al. (2006).

According to Khatua et al. (2018), the mineralization of OM tends to increase even more in vermicompost due to the fact that *E. fetida* worms have the ability to reduce carbon through various metabolic activities, at the same time that they contribute to increase nitrogen content and humification rate, especially when adequate conditions of humidity, temperature and pH (7–8) prevail (Gusain and Suthar 2020).

Although the sensitivity shown by radish seeds (*R. sativus*) to the phytotoxic compounds and salts provided by the different compost and vermicompost treatments was varied (Fig. 1), the best response was found in the treatments that were made only from bovine manure (100%), as was the case of VM, CM and M, respectively. Whereas, in the case of the treatments made from the species *S. verrucosum*, the best response was found in V25S and C25S, respectively (Table 2). This shows their potential as organic fertilizers, since they are stable and mature.

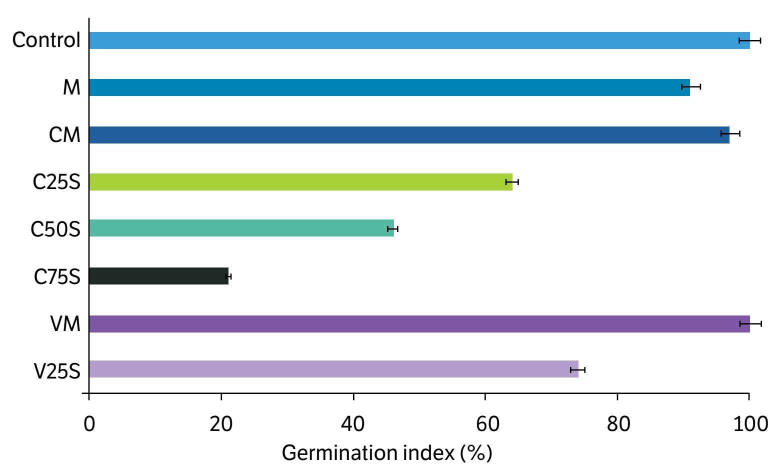


**Figure 1.** Germination index in seeds of *Raphanus sativus* with extracts of M: bovine manure (100%), CM: compost of bovine manure (100%), C25S: compost of *Sesuvium verrucosum* (25%) + bovine manure (75%), C50S: compost of *S. verrucosum* (50%) + bovine manure (50%), C75S: compost of *S. verrucosum* (75%) + bovine manure (25%), VM: vermicompost of bovine manure (100%), V25S: vermicompost of *S. verrucosum* (25%) + bovine manure (75%), in a period of 120 hours. Bars with the same letter mean that there are no significant differences ($p \leq 0.05$).

According to Meloni et al. (2017), salinity is one of the most important abiotic stresses that can negatively affect the germination process of seeds, because it hinders the decreasing of water mobility and thus the speed of seed imbibition, which in turn affects the synthesis of biopolymers, proteins, nucleic acids and the amount of regulatory hormones in the plant cell, aspects that are of vital importance in the growth processes as the seeds develop. For this reason, Vázquez and Loli (2018) indicated the need to produce compost and vermicompost with low ECe values, based on:

- A longer time in the mineralization processes, in order to have a lower production of soluble metabolites, such as ammonium;
- The implementation of a greater amount of irrigation, in order to reduce the concentration of soluble salts, such as potassium and sodium.

Regarding the accumulation of cations (Table 2), the different compost and vermicompost treatments—made from the species *S. verrucosum*—showed the following classification: $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$. The concentrations of these cations were higher as the percentages of halophyte content used for their preparation increased. Likewise, the different treatments with halophytes showed a greater accumulation of $Cl^-$, mainly in C75S, since an increase of 1.61, 1.43 and 1.64 times greater was found, compared to the concentrations of the treatments C25S, C50S and V25S (Table 2).

In the case of compost and vermicompost treatments, made only from bovine manure (100%), they showed the following classification: $Ca^{2+} > Mg^{2+} > K^+ > Na^+$ (Table 2). It is worth mentioning that the concentrations of these cations increased significantly in the vermicompost, compared to the different compost treatments, except for Na+ and Cl-.

According to Ganiger et al. (2020), the variation in the nutritional content of both the compost and the vermicompost of the different treatments could be explained through various factors, such as:

- The chemical composition and texture of the raw material, according to the halophyte content percentages that were implemented during its preparation;
- The leaching of cations during irrigations;
- The excretory activity of the worms;
- The preferred eating habits of the worms;
- The acceptability of the nutritional content by the worms during the biodegradation process.

**Table 2.** Nutrient content of compost and vermicompost*.

| Parameters | Treatments | | | | | | |
|---|---|---|---|---|---|---|---|
| | M | CM | C25S | C50S | C75S | VM | V25S |
| C (%) | 58.07 ± 1.38$^b$ | 28.56 ± 0.61$^d$ | 26.42 ± 0.56$^e$ | 49.71 ± 1.19$^c$ | 74.94 ± 1.74$^a$ | 10.68 ± 0.25$^g$ | 14.35 ± 0.34$^f$ |
| N (%) | 1.28 ± 0.05$^g$ | 2.38 ± 0.06$^d$ | 2.73 ± 0.07$^c$ | 3.12 ± 0.08$^b$ | 3.67 ± 0.09$^a$ | 2.04 ± 0.05$^e$ | 1.79 ± 0.04$^f$ |
| C/N | 45.36 ± 1.36$^a$ | 12.01 ± 0.36$^d$ | 9.68 ± 0.29$^e$ | 15.93 ± 0.48$^c$ | 20.41 ± 0.61$^b$ | 5.23 ± 0.42$^g$ | 8.02 ± 0.24$^f$ |
| $K^+$ (ppm) | 2,898 ± 75$^g$ | 2,937 ± 83$^f$ | 4,339 ± 102$^d$ | 5,389 ± 145$^b$ | 6532 ± 176$^a$ | 3,564 ± 121$^e$ | 4,652 ± 119$^c$ |
| $Mg^{2+}$ (ppm) | 2,553 ± 68$^g$ | 2,810 ± 81$^f$ | 3,355 ± 102$^d$ | 5,082 ± 129$^b$ | 6,228 ± 158$^a$ | 3,108 ± 85$^e$ | 3,624 ± 109$^c$ |
| $Ca^{2+}$ (ppm) | 3,293 ± 94$^a$ | 3,654 ± 113$^a$ | 4,847 ± 150$^a$ | 5,886 ± 182$^c$ | 6,971 ± 216$^a$ | 5,472 ± 175$^d$ | 6,419 ± 198$^b$ |
| $Na^+$ (ppm) | 2,157 ± 58$^e$ | 1,472 ± 42$^f$ | 6,792 ± 183$^c$ | 11,688 ± 315$^b$ | 17,429 ± 470$^a$ | 1,058 ± 29$^g$ | 6,058 ± 162$^d$ |
| $Cl^-$ (ppm) | 1,938 ± 51$^e$ | 1,327 ± 35$^f$ | 6,054 ± 163$^c$ | 10,521± 284$^b$ | 15,436 ± 412$^a$ | 922 ± 24$^g$ | 5,227 ± 141$^d$ |

*In each row, the different letters represent the least significant difference according to Tukey's test ($p \leq 0.05$). Values are the mean ± standard deviation (n = 12); M: bovine manure (100%); CM: compost of bovine manure (100%); C25S: compost of *Sesuvium verrucosum* (25%) + bovine manure (75%); C50S: compost of *S. verrucosum* (50%) + bovine manure (50%); C75S: compost of *S. verrucosum* (75%) + bovine manure (25%); VM: vermicompost of bovine manure (100%); V25S: vermicompost of *S. verrucosum* (25%) + bovine manure (75%).

In this regard, authors such as Villegas-Cornelio and Laines-Canepa (2017) have indicated higher contents of macro and micronutrients during the vermicompost process than in the compost process, due to their richness in humic and fulvic compounds, which allow for a greater conversion of mineral elements during the biodegradation and mineralization process.

About microbial quality, in accordance with the regulations of the USEPA, European Commission and Waste and Resources Action Programme, the different compost and vermicompost treatments showed low value ranges concerning the presence of total coliforms (110–35 CFU·g$^{-1}$), fecal coliforms (160–5 CFU·g$^{-1}$), helminth eggs (1–0.05 HE·g$^{-1}$), *E. coli*

(180–1 CFU·g$^{-1}$) and *Salmonella* (3–1 CFU·g$^{-1}$), especially in the treatments in which the halophyte species was used as a source of raw material for their preparation (Table 3), indicating that there is no risk that pathogens would damage the health of those who wish to manipulate this type of organic amendments. However, it is important to mention that a more effective reduction of these pathogenic microorganisms was achieved in the vermicompost treatments, compared to the compost treatments.

**Table 3.** Microbial content of compost and vermicompost*.

| Parameters | Treatments | | | | | | | Upper limit |
|---|---|---|---|---|---|---|---|---|
| | M | CM | C25S | C50S | C75S | VM | V25S | |
| *Escherichia coli* (CFU·g$^{-1}$) | 1,070 ± 32[a] | 180 ± 5.4[b] | 130 ± 3.9[c] | 85 ± 2.5[d] | 40 ± 1.5[e] | 1 ± 0.03[g] | 2.5 ± 0.08[f] | < 1,000[abc] |
| *Salmonella* spp. (CFU 25·g$^{-1}$) | 340 ± 17[a] | 3 ± 0.3[b] | 2.5 ± 0.2[b] | 1.5 ± 0.12[c] | 0.5 ± 0.01[e] | 1 ± 0.02[d] | 1.5 ± 0.09[c] | Absent[ab] < 3-300 |
| Total coliforms (CFU·g$^{-1}$) | 1,560 ± 42[a] | 110 ± 2.9[b] | 80 ± 2.1[c] | 65 ± 1.75[d] | 50 ± 1.3[e] | 20 ± 0.5[g] | 35 ± 0.9[f] | - |
| Fecal coliforms (CFU·g$^{-1}$) | 1,190 ± 27[a] | 160 ± 3.7[b] | 110 ± 2.5[c] | 70 ± 1.6[d] | 30 ± 0.7[e] | 3 ± 0.07[g] | 5 ± 0.1[f] | < 1,000-2×10$^{-6}$[c] |
| Helminth eggs (HE·g$^{-1}$) | 43 ± 1[a] | 1 ± 0.02[b] | 0.38 ± 0.005[c] | 0.22 ± 0.005[d] | 0.15 ± 0.001[f] | 0.16 ± 0.005[e] | 0.05 ± 0.001[g] | < 10-35[c] |

*In each row, the different letters represent the least significant difference according to Tukey's test ($p \leq 0.05$). Values are the mean ± standard deviation (n = 12); [a]Source: European Commission (2014), [b]Source: WRAP (2014), [c]Source: US Composting Council (TMECC 2010); M: bovine manure (100%); CM: compost of bovine manure (100%); C25S: compost of *Sesuvium verrucosum* (25%) + bovine manure (75%); C50S: compost of *S. verrucosum* (50%) + bovine manure (50%); C75S: compost of *S. verrucosum* (75%) + bovine manure (25%); VM: vermicompost of bovine manure (100%); V25S: vermicompost of *S. verrucosum* (25%) + bovine manure (75%).

According to Soobhany (2018) and Acquah et al. (2021), the reduction of these pathogens in the different compost and vermicompost treatments could be explained by:

- The established pre-compost process;
- The alteration of the composition of microbial communities during the biodegradation process;
- The relatively high temperatures reached during the thermophilic phase (in the case of compost);
- The ability of the worms to inactivate pathogens;
- The bacterial activity and intestinal enzymes of the worms;
- The coelomic fluids secreted by the worms;
- The diversity of anaerobic and gram-positive bacteria that inhabit the intestine of the worms.

On the other hand, the various compost and vermicompost treatments showed significant differences ($p \leq 0.05$) in height, fresh weight, root length, stem diameter and leaf area of the crop (Table 4). Moreover, it could be observed that—except for treatment T7—the treatments with a proportion of 25% *S. verrucosum* and 75% bovine manure (T8 and T4) achieved the highest morphological parameters in the different variables that were evaluated, as well as the highest yields compared to controls T1 and T2 (Table 4), followed by T3, T5 and T6, respectively.

These results suggest that both compost and vermicompost are excellent organic fertilizers, rich in micro and macronutrients and soil conditioners (Kranz et al. 2020), which improve the physicochemical and microbiological properties of the soil, such as BD, infiltration, hydraulic conductivity, CEC, as well as microbial population and diversity (El-Haddad et al. 2020).

Besides, both organic fertilizers are rich in humic substances and growth-regulating hormones, such as zeatin, kinetin, cytokinin, auxin and abscisic acid (in the case of vermicompost), which possibly had a stimulating effect on root development and plant growth (Zhang et al. 2015), since the humic substances tend to improve humidity, nutrient holding capacity and levels of microbial activity; while the growth-regulating hormones promote cell division, cell growth and tissue expansion in certain parts of the plant, aspects that in conjunction might have helped the *S. lycopersicum* crop to better regulate its cellular metabolism, photosynthesis and enzymatic activity (Silveira-Corrêa et al. 2013). Moreover, the aforementioned could explain the increases found in its biomass and, consequently, in the obtained yields (Table 4).

**Table 4.** Effects of compost and vermicompost on the morphometric variables of the *Solanum lycopersicum* crop*.

| Parameters | Treatments | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | T1 | T2 | T3 | T4 | T5 | T6 | T7 | T8 |
| Plant height (cm) | 58.88 ± 1.53$^{h}$ | 63.76 ± 1.65$^{g}$ | 82.57 ± 2.14$^{d}$ | 90.42 ± 2.35$^{c}$ | 75.82 ± 1.97e | 74.69 ± 1.81$^{f}$ | 109.43 ± 2.84$^{a}$ | 98.21 ± 2.55$^{b}$ |
| Plant fresh weight (g) | 1,221.6 ± 29.3$^{h}$ | 1,412.7 ± 33.9$^{g}$ | 1,929.8 ± 4.71$^{d}$ | 2,139.2 ± 51.3$^{c}$ | 1,755.2 ± 46.3$^{e}$ | 1,548.4 ± 37.1$^{f}$ | 2,853.7 ± 68.4$^{a}$ | 2,551.3 ± 61.2$^{b}$ |
| Root length (g) | 21.54 ± 0.64$^{h}$ | 24.44 ± 0.73$^{g}$ | 36.55 ± 1.09$^{d}$ | 40.81 ± 1.22$^{c}$ | 32.25 ± 0.96$^{e}$ | 27.63 ± 0.82$^{f}$ | 50.72 ± 1.53$^{a}$ | 44.27 ± 4.71$^{b}$ |
| Plant stem diameter (cm) | 1.87 ± 0.02$^{h}$ | 2.17 ± 0.03$^{g}$ | 2.56 ± 0.04$^{d}$ | 2.72 ± 0.04$^{c}$ | 2.41 ± 0.03$^{e}$ | 2.30 ± 0.03$^{f}$ | 3.23 ± 0.05$^{a}$ | 2.96 ± 0.04$^{b}$ |
| Leaf area (cm$^2$) | 1,153.2 ± 16.8$^{h}$ | 1,310.6 ± 17.8$^{g}$ | 1,809.5 ± 25.9$^{d}$ | 1,975.8 a ± 28.4$^{c}$ | 1,656.7 ± 23.3$^{e}$ | 1,524.3 ± 21.1$^{f}$ | 2,462.5 ± 61.1$^{a}$ | 2,215.3 ± 32.2$^{b}$ |
| Fruit equatorial diameter (cm) | 3.86 ± 0.07$^{h}$ | 4.09 ± 0.08$^{g}$ | 4.97 ± 0.10$^{d}$ | 5.24 ± 0.11$^{c}$ | 4.68 ± 0.09$^{e}$ | 4.36 ± 0.09f | 5.87 ± 0.12$^{a}$ | 5.55 ± 0.11$^{b}$ |
| Fruit fresh weight (g) | 67.55 ± 1.33$^{h}$ | 74.45 ± 1.48$^{g}$ | 88.32 ± 1.75$^{d}$ | 93.24 ± 1.87$^{c}$ | 83.70 ± 1.62$^{e}$ | 78.84 ± 1.54$^{f}$ | 106.12 ± 2.14$^{a}$ | 99.02 ± 2.01$^{b}$ |
| Number of fruits (plant$^{-1}$) | 23.84 ± 0.42$^{h}$ | 26.02 ± 0.44$^{g}$ | 32.15 ± 0.58$^{d}$ | 34.58 ± 0.62$^{c}$ | 30.23 ± 0.54$^{e}$ | 27.72 ± 0.48$^{f}$ | 40.86 ± 0.74$^{a}$ | 37.96 ± 0.51$^{b}$ |
| Yield (g·plant$^{-1}$) | 1,610 ± 41.8$^{h}$ | 1,937 ± 50.3$^{g}$ | 2839 ± 73.6$^{d}$ | 3,224 ± 83.8$^{c}$ | 2,530 ± 65.7$^{e}$ | 2,185 ± 56.8$^{f}$ | 4,336 ± 112$^{a}$ | 3,758 ± 97.7$^{b}$ |
| Yield (Mg·ha$^{-1}$) | 16.10 ± 0.41$^{h}$ | 19.37 ± 0.50$^{g}$ | 28.39 ± 0.73$^{d}$ | 32.24 ± 0.84$^{c}$ | 25.30 ± 0.65$^{e}$ | 21.85 ± 0.56$^{f}$ | 43.36 ± 1.12$^{a}$ | 37.58 ± 0.97$^{b}$ |

*In each row, the different letters represent the least significant difference according to Tukey's test ($p \leq 0.05$). Values are the mean ± standard deviation (n = 12). A density of 10,000 *S. lycopersicum* seedlings was considered for extrapolation to one hectare; T1: negative control [no organic fertilizer + urea]; T2: positive control [bovine manure (100%) + urea]; T3: compost [bovine manure (100%) + urea]; T4: compost [*Sesuvium verrucosum* (25%) + bovine manure (75%) + urea]; T5: compost [*S. verrucosum* (50%) + bovine manure (50%) + urea]; T6: compost [*S. verrucosum* (75%) + bovine manure (25%) + urea]; T7: vermicompost [bovine manure (100%) + urea]; T8: vermicompost [*S. verrucosum* (25%) + bovine manure (75%) + urea].

Also, the content of macro and micronutrients in vermicompost was higher than in compost, as indicated in other studies (Villegas-Cornelio and Laines-Canepa 2017). It was observed that bovine manure without composting, despite being rich in nutrients, could not properly contribute to crop nutrition when applied directly since most of those nutrients—being organically united—require a mineralization process to convert organic nutrients into inorganic forms and thus achieve plant nutrition (Mupambwa et al. 2020), which could explain the low growth and development of the *S. lycopersicum* crop in treatment T2.

## CONCLUSION

The compost and vermicompost made from a reduced portion of halophyte content of *S. verrucosum* (25%) and a greater portion of manure (75%) in a period of 140 days can serve as a stable and mature organic amendment, rich in nutrients, and that can be used to improve the growth and development of the *S. lycopersicum* crop. Therefore, the production of compost and vermicompost and their implementation under these conditions could be presented as a good agronomic strategy that would allow for the development of more sustainable agriculture.

## AUTHORS' CONTRIBUTION

**Conceptualization:** Lastiri-Hernández, M. A. and Álvarez-Bernal, D.; **Methodology:** Lastiri-Hernández, M. A. and Flores-Magallón, R.; **Investigation:** Conde-Barajas, E., Silva-García, J.T . and Cruz-Cárdenas, G.; **Writing – Original Draft:** Lastiri-Hernández, M. A., and Álvarez-Bernal, D.; **Writing – Review and Editing:** Lastiri-Hernández, M. A., Álvarez-Bernal, D., Conde-Barajas, E., Silva-García, J. T. and Cruz-Cárdenas, G.; **Funding Acquisition:** Álvarez-Bernal, D.; **Supervision:** Álvarez-Bernal, D.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

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