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abanicoboletin@gmail.com

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Dynamics of the physical-chemical properties of vermicompost from ovine manure combined with forage

Dinámica de las propiedades fisicoquímicas de lombricomposta de estiércol de ovino combinado con forrajes

Bañuelos-Valenzuela Rómulo*[1] ID, Meza-López Carlos[1] ID, Echavarría-Chairez Francisco[2] ID, Delgadillo-Ruiz Lucía[3] ID**

[1]Universidad Autónoma de Zacatecas, Unidad Académica de Medicina Veterinaria y Zootecnia. Carretera Panamericana Zacatecas-Fresnillo, Km 31.5 Calera de Víctor Rosales, Zacatecas, México. CP. 98500 [2]Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Campo experimental Zacatecas, México. CP. 98500 Calera de Víctor Rosales, Zacatecas, México. [3]Universidad Autónoma de Zacatecas, Unidad Académica de Ciencias Biológicas. Avenida Preparatoria s/n colonia Hidráulica, CP. 98068, Zacatecas, Zacatecas, México. * Responsible author: Rómulo Bañuelos-Valenzuela ** Corresponding autor: Carlos Meza-López. e-mail: apozolero@hotmail.com, carmezlop@yahoo.com.mx, fechava1@yahoo.com, luciadelgadillo@uaz.edu.mx

ABSTRACT

The physicochemical properties of vermicompost produced by the "red Californian" (*Eisenia foetida)* worm from sheep manure and three types of forage (bean, corn, alfalfa) were evaluated to describe its dynamics. One kilogram of material mix was used per experimental unit, with a planting density of 150 worms per container. Watering was done every 3 days, with an adaptation period of one month. Four samplings were conducted (at 30, 45, 60, and 90 days), with three repetitions. The properties evaluated included the interaction of pH over time (p<0.05), starting as alkaline and trending towards acidity. The opposite occurred with electrical conductivity (EC), which showed an increase in values as the study progressed. Nitrogen increased, and the percentage of organic matter decreased, leading to a reduction in the carbon ratio. The phosphorus and potassium content in the final vermicompost decreased; however, other salts (Ca, Na, Cl, HCO_3, SO_4, Mg) increased. This was corroborated by ash content and EC values, which were different (p<0.05). The best vermicompost was the one that integrated all three forages, while the highest accumulation of sodium and carbonates occurred in the treatment with bean residues, and the lowest contribution of organic matter was observed.
Keyword: organic fertilizers, *Eisenia foetida*, vermicompost, organic solid waste.

RESUMEN

Se evaluaron propiedades fisicoquímicas de lombricompostas producidas por la lombriz “roja californiana” (*Eisenia foetida)* a partir de estiércol ovino y tres tipos de forrajes (frijol, maíz, alfalfa), para describir su dinámica. Se utilizó un kilogramo de mezcla de material por unidad experimental, densidad de siembra 150 lombrices por recipiente; el riego se realizó cada tres días, periodo de adaptación un mes, se hicieron cuatro muestreos (30, 45, 60 y 90 días), con tres repeticiones. Las propiedades determinadas fueron: interacción del pH con el tiempo, la conductividad eléctrica (CE), determinación del nitrógeno, fosforo y potasio, porcentajes de la materia orgánica y relación carbono:nitrógeno. El contenido de fósforo y potasio del

producto final en las lombricompostas disminuyó, sin embargo, otras sales se incrementaron (Ca, Na, Cl, HCO_3, SO_4, Mg), se corroboró con valores del contenido de ceniza y CE, que fueron diferentes ($p<0.05$). Con lo cual se concluye que la mejor lombricomposta fue la que integró los 3 forrajes y la mayor acumulación de sodio y carbonatos en el tratamiento con residuos de frijol y el menor aporte de materia orgánica.
Palabras clave: abonos orgánicos, *Eisenia foetida*, lombricomposta, residuos sólidos orgánicos.

INTRODUCTION

Globally, urbanization and the continuous growth of the human population have resulted in the generation of large quantities of waste. These waste streams have led to a series of environmental, social, and economic challenges, particularly in developing countries (Onwosi *et al*., 2017).

Among the most significant challenges facing agriculture are soil erosion and the progressive loss of soil fertility. Traditionally, organic solid wastes (OSW) have been incorporated into agricultural soils to increase organic matter content and serve as a source of nitrogen for crops. However, these materials are often applied without considering soil characteristics or the degree of decomposition of the organic residues. Such inappropriate management practices may adversely affect ecosystem health by promoting soil salinization, the leaching of phytotoxic substances, and the runoff of nitrates and phosphates into aquifers and surface water bodies. These processes contribute to soil degradation and the consequent reduction in the capacity of agricultural systems to provide food for a growing population, representing a critical issue for national food security (Hernández-Rodríguez *et al*., 2010).

Organic solid wastes are generally regarded as a problem by producers because appropriate alternatives for their utilization are often unknown. In many cases, inadequate management practices and a lack of environmental awareness lead to pollution problems. Consequently, the valorization of organic residues has gained increasing attention as an efficient strategy for the rational recycling of nutrients. This approach promotes plant growth and returns to the soil many of the elements removed during agricultural production processes (Ramos & Terry, 2014).

The treatment of organic solid wastes has become a key component in the search for alternatives to mitigate severe environmental, social, and economic impacts. One of the most widely adopted practices, and one considered a biotechnology, is vermiculture. This technology contributes to reducing the accumulation of organic residues on our planet by combining the activity of earthworms and microorganisms that accelerate the decomposition of organic matter. Among its various applications, one of the best known is the production of vermicompost, an organic fertilizer that provides numerous benefits for the cultivation of virtually all plant species (González, 2013). Since the onset of the

Green Revolution, chemical fertilizers, pesticides, and herbicides have been extensively applied to increase soil productivity and meet the growing demand for food crops. Chemical fertilizers improve crop yields because plants directly or indirectly utilize the nutrients supplied by these inorganic inputs. Nevertheless, the continuous and intensive use of chemical fertilizers has generated numerous undesirable effects on agricultural ecosystems, including soil degradation, loss of crop genetic resources and microbial diversity, groundwater contamination, and atmospheric pollution (Maji *et al*., 2016). In Mexico, which encompasses approximately 196 million hectares, extensive areas exhibit severe soil degradation. Approximately 64% of the country's soils are degraded, primarily due to water and wind erosion. However, these soils also experience nutrient depletion, losses of organic matter and soil microorganisms, compaction, acidification, and other degradation processes (Hernández-Rodríguez *et al*., 2010). Vermiculture is an agricultural technology that transforms various types of organic residues through the intensive rearing of earthworms, producing a high-value bio-organic fertilizer known as vermicompost. It is a natural decomposition process that resembles thermophilic composting; however, in vermicomposting, organic material is not only decomposed by naturally occurring microorganisms—including fungi, bacteria, actinomycetes, and yeasts—but also by the complex digestive system of earthworms (Delgado *et al*., 2004). Vermicompost is a soil amendment rich in nitrogen, potassium, phosphorus, and magnesium, and its beneficial properties have been extensively documented (Ruiz *et al*., 2013). Vermicomposting is considered an important recycling strategy for organic solid wastes because substantial quantities of vermicompost are frequently applied in agriculture to satisfy crop nitrogen requirements and increase soil organic matter content (John *et al*., 2011). Vermicomposting has emerged as one of the most effective alternatives for recycling organic solid wastes from a wide range of sources, including household kitchen waste and sewage sludge from large urban centers. Through this process, these materials are transformed into a high-quality organic fertilizer that provides crops with nutrients in forms that are more soluble and bioavailable than those present in the original substrate. Additionally, vermicomposting generates animal biomass with a high protein value that may be utilized in both animal and human nutrition (Polo *et al*., 2012). Therefore, the objective of the present study was to evaluate changes in the physicochemical characteristics of vermicompost produced from sheep manure using the California red earthworm, *Eisenia fetida*.

MATERIALS Y METHODOS

The study was conducted at the Academic Unit of Veterinary Medicine and Animal Science of the Autonomous University of Zacatecas, Mexico, located at 22°58′ N latitude and 102°30′ W longitude, at an elevation of approximately 2,150 m above sea level. The region is characterized by a dry to semi-arid climate, with average annual precipitation ranging from 400 to 500 mm and a mean annual temperature of approximately 17°C (INEGI, 2021). The experiment was carried out inside a fully protected facility consisting of a roofed structure enclosed with wire mesh.

Sheep manure was selected as the primary substrate because it is widely available in the state of Zacatecas, where the sheep population has steadily increased over time. Moreover, sheep manure represents an important source of nutrients for crop production. Alfalfa, bean straw, and corn stover were used as supplementary sources of plant material. When combined with sheep manure, these materials served as substrates for earthworm feeding and vermicompost production. Specimens of Eisenia fetida were obtained from a commercial vermiculture operation located in the municipality of Pánuco, Zacatecas, Mexico. The sheep manure and the selected organic materials underwent a pre-composting process using the windrow (pile) method. The materials received periodic irrigation and turning to promote aeration, stabilize temperature and pH, and reduce excess moisture. Four treatments were established, all based on sheep manure combined with plant residues in the following proportions: 60% sheep manure + 40% alfalfa (SMA); 60% sheep manure + 40% bean straw (SMB); 60% sheep manure + 40% corn stover (SMC); and 61% sheep manure + 13% alfalfa + 13% bean straw + 13% corn stover (61:13:13:13; SMABC). Plastic containers measuring 55 cm in length, 36 cm in width, and 25 cm in depth were used as experimental units. Each container was filled with 1 kg of the corresponding treatment mixture. The earthworm species used was Eisenia fetida, commonly known as the California red worm. Earthworms were introduced at a stocking density of 150 individuals per container. Only mature and fully developed individuals exhibiting a well-formed clitellum were used in the experiment. Water was applied to the solid mixture every three days to maintain adequate moisture conditions in the rearing units. An adaptation period of one month was allowed, beginning on June 6. Subsequently, solid-liquid samples were collected at 30, 45, 60, and 90 days after the initiation of the vermicomposting process. Three replicates were obtained for each sampling time (Polo *et al*., 2012).

The solid-liquid samples collected at 30, 45, 60, and 90 days were analyzed for pH, electrical conductivity (EC), ammoniacal nitrogen, phosphorus, and the cations potassium, calcium, magnesium, and sodium, as well as the anions bicarbonate, chloride, and sulfate. The solid fraction of the vermicompost was analyzed for bulk density, ash content, and organic matter (OM). Organic carbon content was estimated as:

$$P = 1 - \frac{da}{dr}\,(100) \qquad \text{(ec 1)}$$

where:

P= porosity

da= bulk density

dr= particle density (2.65 gr/cm3)

Data obtained from each determination were analyzed using a repeated-measures analysis. Mean comparisons were performed using Fisher's Least Significant Difference (LSD) test implemented in SAS software (SAS, 2012).

RESULTS AND DISCUSSION

Table 1 presents the mean values of pH and major nutrient determinations for the four vermicompost formulations. Significant differences were observed among treatments and in their interaction with time ($P < 0.05$) (Figure 1). The vermicomposts containing sheep manure supplemented with a single plant substrate (SMA, SMB, and SMC) exhibited similar patterns throughout the experimental period (Figure 1). These treatments showed relatively high pH values at the beginning of the vermicomposting process, followed by a gradual decline toward the end of the study, with average values decreasing from approximately 8.5 to 7.5. In contrast, the SMABC treatment, which consisted of sheep manure combined with three plant substrates, maintained pH values close to neutrality throughout the study, ranging from 7.4 to 7.5 from the beginning to the end of the experimental period. The production of vermicompost under near-neutral pH conditions provides a more favorable environment for earthworm activity and creates conditions conducive to nutrient mineralization from the early stages of the composting process.

Table 1. Mean values of pH and major agricultural nutrients in the solid fraction of vermicompost produced from four substrate formulations and sheep manure

Treatment	pH	EC (dS/m)	Nitrogenus (%)	Phosphorus	Potassium (%)
SMA	6.8±0.036 ^{ab*}	9.9±0.25 ^{a}	6.48±0.48 ^{ab}	0.0341±0.0015 ^{a}	0.081±0.00567 ^{a}
SMB	6.72±0.43 ^{b}	8.8±0.34 ^{b}	6.01±0.36 ^{b}	0.0288±0.0016 ^{b}	0.057±0.00511 ^{b}
SMC	6.68±0.039 ^{bc}	8.6±0.29 ^{b}	6.85±0.41 ^{ab}	0.0285±0.0015 ^{b}	0.038±0.0053 ^{bc}
SMABC	6.9±0.049 ^{a}	9.4±0.46 ^{ab}	7.44±0.33 ^{a}	0.0295±0.0017 ^{b}	0.0333±0.0048 ^{bc}

* Mean values followed by different letters within the same column are significantly different ($P < 0.05$).
SMA: 60% sheep manure + 40% alfalfa. SMB: 60% sheep manure + 40% bean straw. SMC: 60% sheep manure + 40% corn stover. SMABC: 61% sheep manure + 13% alfalfa + 13% bean straw + 13% corn stover.

The behavior of pH values is associated with the type of material or mixture of materials used to produce compost, making pH a reliable indicator of the composting process because it generally follows a regular and predictable pattern (Acosta-Durán *et al*., 2013). The changes observed in pH values over time and according to the maturation stage of the decomposing material showed a tendency to decrease as the material matured and became stabilized. The first three treatments exhibited slightly alkaline values during the initial sampling period; however, as time progressed, a gradual shift toward neutrality was observed. At the end of the experiment, pH values ranged from 6.2 to 6.6, with the lowest value corresponding to the SMC treatment, which exhibited a pronounced decline toward acidic conditions throughout the evaluation period. The behavior of this treatment appears to be associated with a slower transformation process, thereby favoring humus formation. In contrast, the other three treatments maintained pH values that promote mineralization and, consequently, nutrient availability while preventing the formation of insoluble chemical complexes within the vermicompost (Polo *et al*., 2012).

The decline in pH values observed in the SMC treatment can be explained by the formation of carbon dioxide and organic acids produced by microorganisms during the degradation process, which may be related to the components that constitute the substrate (Malińska *et al*., 2017) as discussed below.

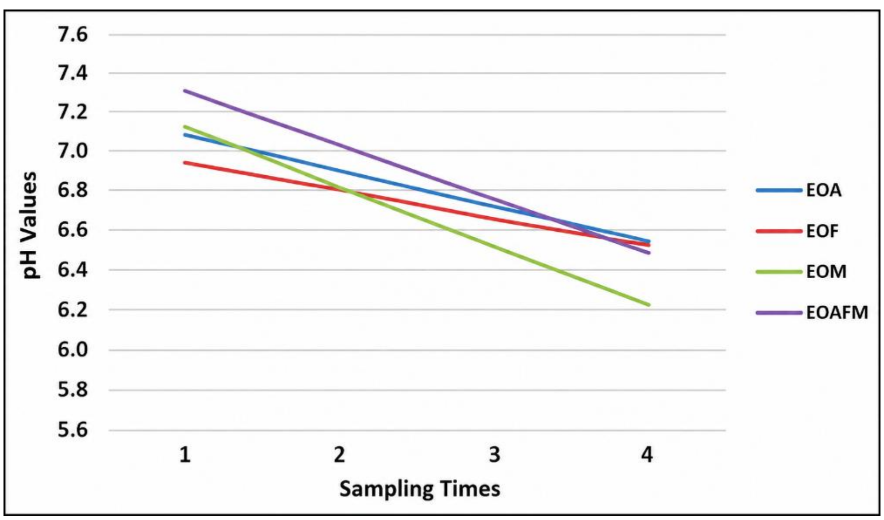

Figure 1. pH values of four vermicomposts throughout the study period

Regarding nitrogen content (Table 1), ammoniacal nitrogen values increased gradually from the beginning of the study (Figure 2). In this respect, the treatment consisting of three different plant materials (SMABC) accumulated the greatest amount of ammoniacal nitrogen, resulting in significant differences over time ($P < 0.05$) compared with the other treatments (Figure 2).

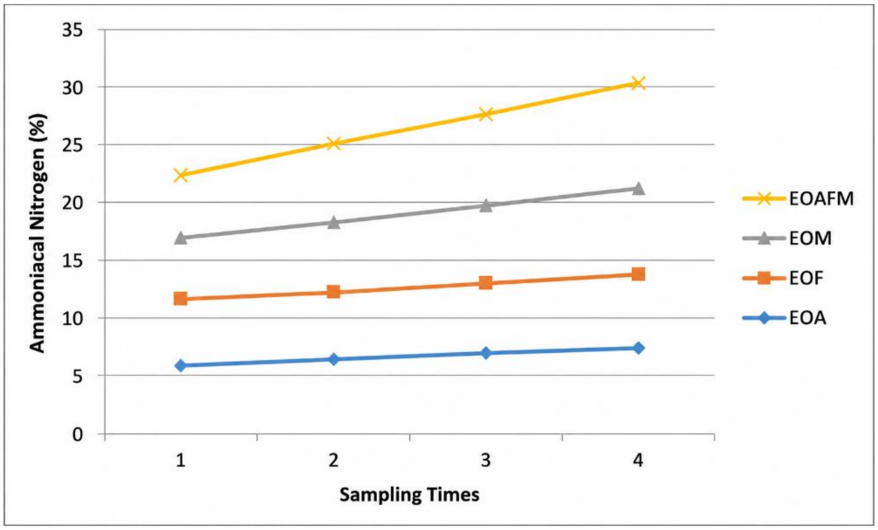

Figure 2. Ammoniacal nitrogen values of the four vermicomposts during the study period

In particular, the vermicompost that exhibited the greatest increase in ammoniacal nitrogen was the treatment in which pH remained stable and showed a slight tendency toward acidity (SMABC). In contrast, in the other three treatments, ammoniacal nitrogen values increased more slowly as the materials became increasingly acidic, thereby reducing the rate of mineralization. Associated with the increase in nitrogen under near-neutral pH conditions are the percentages of organic matter (Table 2), which showed a continuous decline until the end of the experiment, as illustrated in Figure 3. Significant differences were observed among treatments ($P < 0.05$), although the rate of decrease was similar for the SMA, SMC, and SMABC treatments, whereas the SMB treatment exhibited the lowest rate of decline.

When the C ratios of the treatments were estimated, they showed a decreasing trend throughout the study period, which corresponded to the observed increase in nitrogen and the decline in organic carbon (OC). Because the loss of OC in gaseous form was greater than the loss of nitrogen, the C ratio gradually decreased during the process, reaching lower values as the degree of decomposition increased. The rates of decline were similar among the first three treatments; however, the SMABC treatment exhibited even lower values, although these differences were not statistically significant (P > 0.05). Nevertheless, this trend indicates that the SMABC treatment reached stability more rapidly.

Table 2. Mean values of organic matter, ash content, and bulk density in the solid fraction of vermicompost produced from four substrate formulations and sheep manure

Treatment	Bulk Density (g/mL)	Ash (%)	Organic Matter (%)	Organic Carbon (%)	Relación C:N
SMA	0.46±0.044 [a*]	30.8±1.88 [bc]	69.1±1.88 [a]	40.1±1.09 [a]	6.5±1.74 [a]
SMB	0.47±0.055 [a]	37.3±0.89 [a]	62.6±0.89 [bc]	36.3±0.52 [bc]	6.7±2.32 [a]
SMC	0.44±0.044 [a]	30.6±1.57 [bc]	69.3±1.5 [a]	40.2±0.91 [a]	6.9±2.35 [a]
SMABC	0.47±0.05 [a]	32.9±2.02 [b]	67.0±2.02 [b]	38.9±1.17 [b]	5.7±2.28 [a]

* Mean values followed by different letters within the same column are significantly different (P < 0.05). SMA**:** 60% sheep manure + 40% alfalfa. SMB**:** 60% sheep manure + 40% bean straw. SMC**:** 60% sheep manure + 40% corn stover. SMABC**:** 61% sheep manure + 13% alfalfa + 13% bean straw + 13% corn stover.

During the vermicomposting process, a fraction of the organic matter contained in the residues is mineralized; consequently, total organic carbon values and, therefore, the C ratio are markedly reduced (Gómez-Brandón *et al*., 2010). The same pattern was observed in the present study, in which the C ratio began at relatively low values and tended to decline even further, undoubtedly representing one of the principal advantages of vermicompost. Durán & Henríquez (2007) reported that C ratios ranging from 10 to 15 are indicative of a properly stabilized compost. Regarding nitrogen determination, the values increased gradually in all four treatments throughout the study period and reached their highest levels at the final sampling date, with the SMABC treatment exhibiting the highest values. This increase is associated with the mineralization of organic matter, which, as it undergoes transformation, increases the total nitrogen content, a response that is consistent with the conditions observed in the vermicomposting system (Castillo *et al*., 2010). The increase in nitrogen levels in the final product is not solely attributable to the mineralization of residues by earthworms. It is also influenced by the amounts of nitrogen excreted by these annelids through their secretions, mucus, body fluids, enzymes, and the decomposition of earthworm tissues following mortality during the vermicomposting process (Polo *et al*., 2012).

This mineralization process is also influenced by the decrease in pH, which promotes the transformation of nitrogen into ammonium and subsequently into nitrates (David-Santoya *et al*., 2018). The above findings are corroborated by the gradual decline in organic matter observed in all four treatments. As expected, organic matter (OM) decreased due to the activity of earthworms and microorganisms acting upon the substrates, resulting in OM percentages ranging from 62% to 70% (Figure 3). This reduction in OM content at the end of the process is associated with the mineralization of organic residues by earthworms and the microorganisms present in the medium (Polo *et al*., 2012). Significant differences (P < 0.05) revealed that the SMB treatment exhibited the lowest initial OM content and maintained the lowest OM values at the end of the study. In this case, the added bean straw was readily degraded because, as a leguminous residue, it contains relatively low concentrations of lignin. In contrast, the SMC treatment exhibited a slower rate of degradation because corn stover is characterized by higher concentrations of lignin, cellulose, and other polysaccharides. Although mineralization is desirable during vermicomposting, maintaining relatively high levels of organic matter is also advantageous because it increases the residual effect of the amendment in soil, thereby prolonging the persistence of its beneficial physical and chemical properties. This behavior was observed in the SMA, SMC, and SMABC treatments. A similar pattern was observed for organic carbon content, which also exhibited significant differences (P < 0.05) and followed the same declining trend as OM because organic carbon constitutes a major component of organic matter.

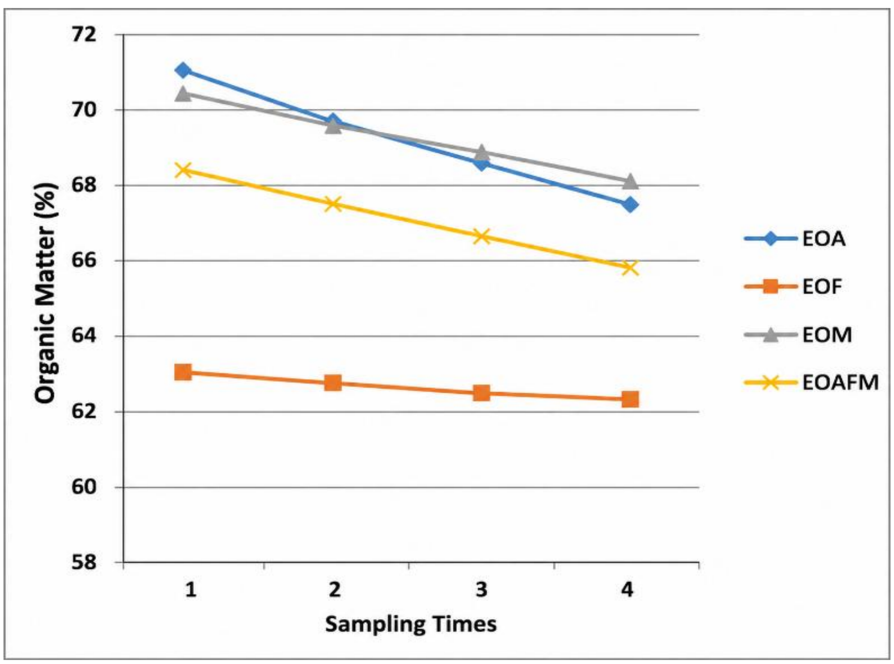

Figure 3. Variation in organic matter percentage values in four vermicomposts during four sampling periods

The decrease in total organic carbon concentration over time showed similar initial values (approximately 40%) among treatments at the first sampling date, except for the SMB treatment, which began with values near 36% and exhibited little variation by the end of the study. This decline suggests the partial mineralization of a fraction of organic carbon as the composting process progresses or its volatilization in the form of CO_2 (Castillo *et al*., 2010). As previously reported John *et al*., (2011), microbial respiration may lead to rapid carbon losses through CO_2 production. In addition, the digestion of carbohydrates, lignin, cellulose, and other polysaccharides contained in the substrates by the inoculated earthworms can contribute to carbon reduction during the decomposition of organic wastes.

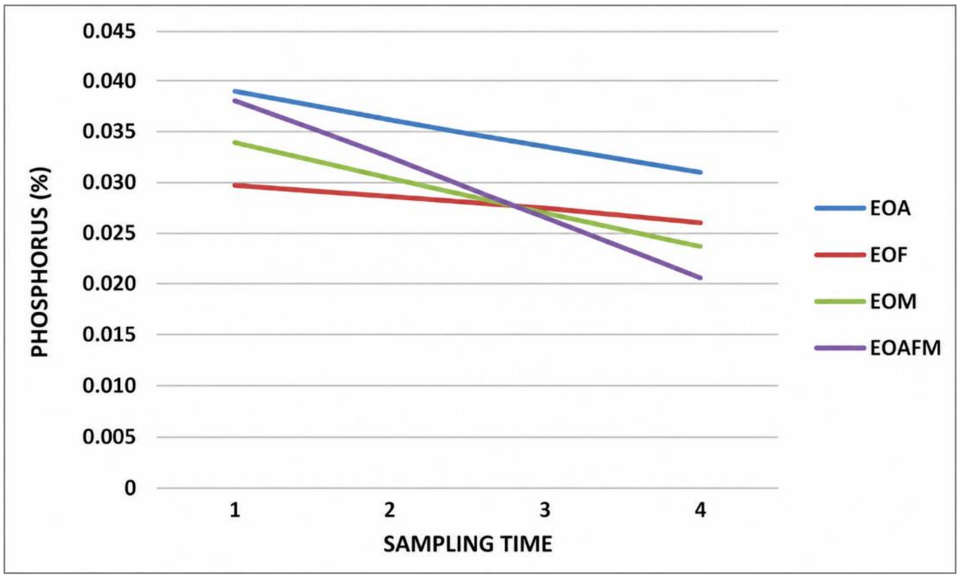

Figure 4. Phosphorus content values in four vermicomposts during four sampling periods

With respect to phosphorus in the vermicomposts evaluated, a decline in available phosphorus (P_2O_5) concentrations was observed in all four treatments (Figure 4), although the SMA treatment maintained comparatively higher values ($P > 0.05$). In all cases, the decrease in phosphorus concentrations can be explained by possible phosphorus fixation and a consequent reduction in phosphorus availability. The phosphorus content of the final vermicompost product was lower than that reported by Castillo *et al*. (2000), who found phosphorus concentrations ranging from 0.027% to 0.032%. Likewise, Castillo *et al*. (2010) reported that increases in phosphorus (P) content occur because earthworms ingest large amounts of phosphorus along with organic matter. This material is subsequently digested in the intestinal tract and further transformed through substantial microbial activity, resulting in elevated phosphorus concentrations in the excreted material. With regard to electrical conductivity (EC) and ash content, the EC values measured in the liquid extract of the vermicomposts are presented in Table 1. These values tended to increase throughout the study, and the treatments differed significantly in their interaction with time ($P < 0.05$). This behavior reveals one of the undesirable characteristics associated with vermicompost utilization, namely, the increase in soluble salt content.

The values obtained were moderately high, exceeding 4 dS m^{-1}, which is considered the upper limit of the low-salinity category for agronomic use according to the Mexican standard (NMX-FF-109-SCFI-2007). Another undesirable aspect was the accumulation of calcium, sodium, chloride, and sulfate, together with a decline in potassium concentrations, which is of particular importance from an agricultural perspective. Figure 5, which presents the mean values generated by the repeated-measures model, shows that all treatments exhibited very similar values at the end of the study. This finding indicates that salt accumulation may be a common characteristic of the vermicomposting treatments evaluated. The determination of ash content produced progressively increasing values (Table 2), with the SMB treatment differing significantly ($P < 0.05$) from the other treatments, followed by the SMABC treatment, which also included bean residues as a substrate. However, considering the potential impact that these salts may have on agricultural applications, salt accumulation was used as a criterion for selecting the treatment or treatments most likely to promote crop development according to the substrate added to sheep manure.

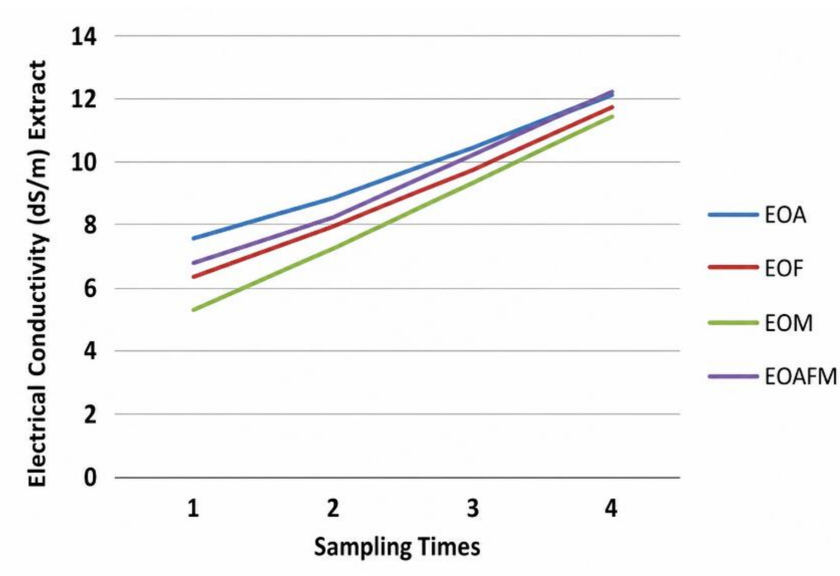

Figure 5. Electrical conductivity values in the saturation extract of vermicomposts throughout the study period

With respect to potassium content, a gradual decrease was observed in all treatments, with the SMA treatment exhibiting a greater decline than the remaining treatments and a significant treatment × time interaction ($P < 0.05$) (Table 1). In contrast to the findings reported by others (Lalander *et al*., 2015) who indicated that potassium concentrations increase during the vermicomposting process, the present study showed that continuous leaching resulted in a decrease in potassium content, with the SMC and SMABC treatments declining most rapidly.

Calcium accumulation was observed in all four treatments, with the SMABC treatment differing significantly ($P < 0.05$) from the others, followed by the SMC treatment. The increase in calcium content observed in the SMABC treatment was associated with the decline in available phosphorus, thereby promoting phosphorus fixation (Sanguino, 1961) which could not be detected by the analytical procedure employed because it measured only available phosphorus (P_2O_5). Likewise, calcium accumulation was also associated with bicarbonate concentrations, which tended to increase throughout the study. Chloride accumulation was also observed, with the SMB and SMC treatments exhibiting significantly higher values ($P < 0.05$). In this case, chloride accumulation may be considered undesirable with respect to the potential agricultural use of the vermicomposts evaluated in this study.

Regarding sulfate content, significant increases ($P < 0.05$) were observed in the SMA, SMB, and SMC treatments, whereas the SMABC treatment exhibited a decline. Another important change was observed in sodium content. The SMA and SMB treatments showed significant decreases ($P < 0.05$), whereas the SMC and SMABC treatments maintained relatively stable sodium concentrations throughout the study period ($P < 0.05$), although without exhibiting increases. Sodium content is of particular importance because of its tendency to strongly adsorb onto soil clay particles. Therefore, the most desirable vermicompost formulation is one that contains the lowest sodium concentrations. In the present study, the SMA treatment produced the lowest sodium values, followed by the SMB treatment. The remaining treatments (SMC and SMABC) did not decrease in sodium content and remained nearly constant throughout the experimental period.

The concentrations of major nutrients and soluble salts in the vermicomposts evaluated indicate that the greatest nitrogen contribution occurred in the SMABC treatment, possibly associated with a faster mineralization process than in the other treatments and related to changes in pH. However, the SMA treatment exhibited the highest phosphorus and potassium concentrations, although the magnitude of these elements was relatively low in all treatments. Regarding salts with potentially adverse effects on soils receiving the vermicomposts, the SMB treatment maintained the highest sodium concentrations, followed by the SMA treatment. The SMB treatment was also distinguished by its higher bicarbonate content, which may be associated with sodium accumulation. The SMABC treatment was characterized by the accumulation of calcium and chloride, the latter being considered potentially detrimental to plant growth. The SMC treatment tended to maintain a higher organic matter content that was mineralized more slowly, thereby providing a residual effect capable of improving soil physical properties. This treatment also exhibited the lowest bulk density (BD) values, although differences were not significant ($P > 0.05$). This response is associated with its greater organic matter content and with physical characteristics that are beneficial to soil quality. Bulk density exhibited significant differences in its interaction with time ($P < 0.05$), indicating that the mass of the material gradually declined as vermicomposting progressed. This response reflects a decrease in weight per unit volume and is associated with the transformation of the plant residues into vermicompost, producing a more porous material that occupies a greater volume while weighing less than the original substrate. When porosity was estimated, the SMC treatment produced the highest values, approaching 83.1%, followed by the SMA treatment with 82.4%.

The bulk density values observed in this experiment were within the range established by the Mexican Official Standard (NMX-FF-109-SCFI-2007), which indicates that higher bulk density results in reduced pore space for water and air movement, root growth and penetration, and consequently, plant development. Vermicompost contains a large number of micropores that enhance water retention and improve moisture conservation. Furthermore, the increased surface area facilitates root adhesion to the soil matrix, promoting aggregate formation and improving nutrient absorption efficiency (Polo *et al*., 2012).

Considering nitrogen production, the SMABC treatment achieved more rapid mineralization, favorable pH changes, and low C ratios. This treatment was also distinguished by its relatively high calcium and chloride concentrations. The SMA treatment maintained the highest phosphorus and potassium values, although the magnitude of these elements remained low across all treatments. The SMB treatment accumulated the highest sodium and bicarbonate concentrations, which could adversely affect soil quality. Finally, the SMC treatment exhibited the highest organic matter values, indicating slower mineralization and greater persistence in the soil, while also producing low bulk density values, a characteristic considered desirable for improving soil physical properties.

CONCLUSIONS

The SMABC treatment exhibited greater stability and a faster rate of mineralization. These characteristics provide a nutrient contribution to the soil that may be beneficial for agricultural applications. The SMA treatment maintained the highest phosphorus and potassium concentrations, although their magnitudes were relatively low for soil application. This treatment also exhibited sulfate accumulation. The SMB treatment showed the greatest accumulation of sodium and bicarbonates, as well as the lowest organic matter values, although its nitrogen contribution was not greater than that of the other treatments. The SMC treatment maintained its organic matter content for a longer period; therefore, its residual effect may be more effective in improving the physical properties of the soil.

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