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# EFFECT OF CHEMICAL INDICATORS AND RESPIRATORY ACTIVITY ON THE RESIDENCE TIME OF VERMICOMPOSTS

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## ABSTRACT

Vermicompost is considered an environmental quality to manage agricultural residues because it improves the structure, provides nutrients to the soil, and helps to mitigate the impact on the environment. The objective of this study was to know the residence time by applying a kinetic model of carbon mineralization, evaluating chemical and biological parameters obtained during the processing time of a vermicompost. Earthworms (*Eisenia fetida*) were used comparing different doses of residual sludge (LR) at 0, 10, 20 and 40 Mg, keeping constant the dose of domestic waste (RD) and cattle manure (EV) at a ratio of 1:1 (dry basis). An AxB factorial design was used, where A represented the LR dose and B the type of residues (RD and EV); thus, eight treatments with nine replicates were compared. The pH, organic matter (MO), total nitrogen, C/N ratio, respiratory activity, C mineralization, and residence time were determined. The results of the treatments indicate a slightly alkaline trend. MO was different among treatments, with higher percentage of MO in EV and LR with 40 Mg of LR (28.92 ± 10.78 %, $F_{(7,88)} = 2.63$, $p \leq 0.01$). The percentage of total N was low, but the treatment containing 40 Mg of LR and RD (1.04 ± 0.62 %, $F_{7,88} = 3.87$, $p < 0.01$) stood out. C/N ratios < 20, indicating stability, were recorded in the treatments with LR and EV. The vermicompost obtained by 40 Mg of LR and EV complied with a minimum residence time (less than 70 days) during its processing, which makes it a highly recommendable option for application in agriculture.

**Keywords**: stabilization, half-life, organic amendment, carbon kinetics.

## INTRODUCTION

The growing interest in the use of soil amendments, such as manures, composts, vermicomposts and biochar, is due to their significant contribution in improving soil structure and the ability to provide nutrients for sustainable agriculture, aligned with the 2030 Agenda for Sustainable Development of the United Nations, where

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vermicompost plays a key role in mitigating environmental impact (Abbott *et al*., 2018; Kauser and Khwairakpam, 2022). Coupled with the interest in environmentally friendly composts, there is societal concern about solid waste generation and reducing its impact on the environment. An integrated management of this type of waste can be carried out, including its reduction, reuse, recycling, thermal energy recovery, and adequate waste confinement (Dümenci *et al*., 2021; Tan *et al*., 2021; Vorobeva *et al*., 2022).

Amendments in organic agriculture offer valuable alternatives by utilizing a wide range of available organic wastes, such as manures, domestic wastes, and residual sludge. The latter are employed due to their contribution of nutrients and organic matter, either directly or after stabilization (Doan *et al*., 2013; Abbott *et al*., 2018; Rékási *et al*., 2023). One solution to waste is vermicomposting, which consists of a bioxidative process in which the earthworm plays a key role and is considered a clean, sustainable, and effective technology to recycle organic waste (Das *et al*., 2022; Ugak *et al*., 2022; Chen *et al*., 2023). Vermicompost shortens the stabilization time of organic matter and supplies nutrients such as phosphorus, nitrogen, calcium, and magnesium. It also increases moisture holding capacity, microbial activity, and stable organic matter to the soil, increasing crop yields (Das *et al*., 2021; Mahapatra *et al*., 2022; Chen *et al*., 2023; Gebrehana *et al*., 2023). Vermicompost must meet minimum requirements for its production, whose raw material (diverse waste) is generated by agricultural, forestry and livestock activities, as long as they are biodegradable, do not affect the quality of the final product, and represent no risk to human health and the environment, according to the Mexican standard (DOF, 2007). The present study responds to the need to understand the vermicomposting process and its relationship with chemical and biological parameters. This understanding is essential to maximize the efficiency of vermicompost and its capacity to oxidize agricultural residues effectively, so it must adhere to the maturity and stability of the product.

Maturity shows to what extent the composting process is completed, while stability refers to a particular state of organic matter, specific stage, or decomposition of organic matter, and is assessed with parameters such as pH, total nitrogen, organic matter, C/N ratio, electrical conductivity, bulk density, moisture content, among others. It can also be assessed using biochemical parameters such as enzyme activity, respiration, and mineralization, which are indicators of process dynamics (Nikaeen *et al*., 2015; Mahapatra *et al*., 2022).

The usefulness of this research is to know some chemical and biological parameters, among them the respiratory activity, frequently used as an index of soil microbial activity. The metabolic activity of soil microorganisms is determined by quantifying $CO_2$, whose emission increases in the presence and activity of earthworms because they promote the decomposition and stabilization of the substrate (Chen *et al*., 2023). Similarly, the support of mathematical models with predictions in the operation is required to help optimize costs, calculate time in process efficiency, and extrapolate its effects in the agricultural field (Dümenci *et al*., 2021). The work by Sharma *et al*. (2021)

validates the maturity of a vermicompost by applying a response surface model (RSM) and artificial neural network (ANN) with flower residues and cow dung, considering C/N ratio and $CO_2$ evolution rate as maturity parameters.

The use of kinetic models of carbon mineralization using zero, first and second order differential equations help to predict the degradation of organic matter and its evolution, as well as the residence time or maturation during the process, relying on the respiratory activity expressed as the rate of $CO_2$ decomposition (Denes *et al*., 2015; Ugak *et al*., 2022).

The hypothesis of this research is that residence time in vermicompost production, together with the application of a kinetic model of carbon mineralization and the measurement of chemical and biological parameters play a critical role in the quality and efficiency of vermicompost. The relationship between the factors and the composition of the waste used is presumed to influence the final outcome of the vermicompost. Therefore, the objective is to determine the optimum residence time for vermicompost production, using *Eisenia fetida* earthworms and evaluating doses of 0, 10, 20 and 40 Mg $ha^{-1}$ of residual sludge (LR), keeping constant the domestic waste (RD) and cattle manure (EV) in the process. This analysis is based on the measurement of chemical and biological parameters to identify the most effective dose and its agricultural use.

## MATERIALS AND METHODS

### Experimental site location

The study was carried out in the laboratory of the Faculty of Sciences of the Universidad Autónoma del Estado de México (UAEMex) located at km 15.5 of the Toluca-Ixtlahuaca highway, State of Mexico, Mexico (19° 24′ 32″ N, 99° 41′ 20″ W).

### Sampling of solid waste

The organic wastes collected were: cow manure (EV) obtained from the post of the Veterinary Faculty of the UAEMex; domestic waste (RD) taken from the cafeteria of the University campus "El Cerrillo" UAEMex; and residual sludge (LR) collected from the filter press of the municipal wastewater treatment plant Toluca Norte of the company Operadora de Ecosistemas S. A. C. V. The samples were characterized by recording the pH values, amount of organic matter (MO), organic carbon, C/N ratio, and concentration of different elements (Table 1).

### Vermicomposting

Plastic tubs or containers of 20 x 30 x 20 cm (width x length x height) were used, perforated at the base for oxygen circulation and in each one of them a mesh was used at the top to avoid worm escape. In each tub the worm (*Eisenia fetida*) was added with a feeding preference of organic matter, validating indicators of sexual maturity: individuals of a faint red color, well developed clitellum, average size of 4 to 6 cm

**Table 1**. Chemical characteristics of organic wastes used in vermicomposting (M ± DE).

| Parameter | Domestic waste (RD) | Bovine manure (EV) | Residual sludge (LR) |
|---|---|---|---|
| pH | 6.8 ± 0.3 | 7.4 ± 0.6 | 7.1 ± 0.4 |
| **MO** (%) | 18.5 ± 0.2 | 23.3 ± 0.7 | 30.4 ± 0.4 |
| C orgánico (%) | 10.7 ± 0.6 | 13.5 ± 0.9 | 17.6 ± 0.7 |
| C/N | 28.5 ± 1.2 | 16.5 ± 1.5 | 9.5 ± 1.1 |
| N (%) | 1.1 ± 0.6 | 2.4 ± 0.8 | 4.1 ± 1.2 |
| K (%) | 0.9 ± 0.5 | 1.2 ± 0.7 | 1.4 ± 0.6 |
| Ca (mg kg$^{-1}$) | 11.5 ± 3.7 | 9.2 ± 2.8 | 10.4 ± 2.7 |
| Mg (mg kg$^{-1}$) | 0.6 ± 0.1 | 0.9 ± 0.1 | 1.0 ± 0.2 |
| Cu (mg kg$^{-1}$) | 130.0 ± 2.9 | 235.0 ± 6.8 | 490.0 ± 9.9 |
| Zn (mg kg$^{-1}$) | 75.0 ± 1.4 | 65.0 ± 1.9 | 115.0 ± 1.5 |
| Cd (mg kg$^{-1}$) | 3.0 ± 0.6 | 2.0 ± 0.3 | 2.0 ± 0.76 |
| Ni (mg kg$^{-1}$) | 25.0 ± 1.7 | 17.0 ± 1 | 82.0 ± 1.1 |
| Cr (mg kg$^{-1}$) | 50.0 ± 0.6 | 47.0 ± 0.3 | 124.0 ± 0.6 |
| Pb (mg kg$^{-1}$) | 54.0 ± 0.8 | 31.0 ± 0.1 | 99.0 ± 0.5 |

M: mean; SD: standard deviation; MO: organic matter.

and weight of 0.5 g per individual. Twenty adult earthworms per kg of substrate were included, as reported by Gupta and Garg (2008).

To evaluate the stability of the vermicompost, combinations of different types of organic wastes were carried out using an AxB factorial experiment. This study was developed under a completely randomized design that included eight treatments and nine replicates for each of them. The design included the following treatments: T1 = cattle manure (EV) + earthworms; T2 = EV + residual sludge (LR) 10 Mg + earthworms; T3 = EV + LR 20 Mg + earthworms; T4 = EV + LR 40 Mg + earthworms; T5 = domestic residue (RD) + earthworms; T6 = RD + LR 10 Mg + earthworms; T7 = RD + LR 20 Mg + earthworms; T8 = RD + LR 40 Mg + earthworms. The variables considered were: type of waste (animal and domestic); residual sludge; and doses of 0, 10, 20 and 40 Mg. The definition of the levels mentioned above is because they are values that do not exceed the standard for the use of residual sludge.

Substrate sampling was carried out for each treatment every 15 d, up to 90 d. Substrate samples were carefully stored in plastic bags for subsequent laboratory analysis. Two reloads of 3.5 kg of organic waste were made at days 45 and 75 to guarantee the necessary food supply for the earthworms throughout the experiment.

## Variables evaluated

### Chemical variables: pH, MO, total N and C/N ratios

The samples were dried at room temperature, homogenized, ground and sieved for chemical analysis in the laboratory. The C/N ratio was obtained by dividing the concentration of organic C and total nitrogen.

### Biological variables: respiratory activity

Samples for the study of respiration and mineralization were taken at 15 and 75 d. They were then stored in plastic bags at a temperature of 4 °C, ensuring their conservation until the kinetics were carried out.

### Chemical and biological analysis of the vermicompost

The parameters determined in the laboratory were: pH using a potentiometer (inoLab® pH 7110, Mexico), total nitrogen (NT) using the Kjeldahl method (Bremner and Mulvaney, 1982), organic carbon (CO) (Walkley and Black, 1934) and the C/N ratio, all based on the Mexican standard (DOF, 2007). Respiratory activity was measured by the method of Kassem and Nannipieri (1995).

### Mineralization model to determine residence time

The mineralization process was determined, which required the respiratory activity data to generate a kinetic model that considers the available carbon, represented by the first order differential equation (Equation 1) proposed by Ugak *et al*. (2022).

$$\frac{dC}{dt} = -KC \qquad (1)$$

where $dC/dt$ is the mineralization rate, K is the mineralization constant, and C is the residual carbon concentration.

Numerical calculations yield the residence time or so-called half-life ($t_{1/2}$), which compares the time that must elapse for the potentially mineralizable fraction to decrease its concentration by half (Equation 2). The value 0.693 represents the inverse of ln 2 and is obtained by calculating the half-life by solving the associated differential equation. This operation was carried out using the carbon mineralization rate data.

$$t_{1/2} = \frac{0.693}{K} \qquad (2)$$

### Experiment design and statistical analysis

An AxB factorial design was used, where factor “A” is the three doses of LR used (10, 20 and 40 Mg ha$^{-1}$) and a control, and factor “B” is the two types of residues (EV and RD), giving a total of eight treatments with nine replicates each. The data of the chemical variables were subjected to an analysis of variance and the means were compared by Tukey’s test ($p \leq 0.05$) in the statistical package Statgraphics Centurion XV (Statgraphics.net, Madrid, Spain). In addition, the respiratory activity and mineralization of mineralized C were plotted.

## RESULTS AND DISCUSSION

During the 90-d vermicomposting process, the following parameters were evaluated: pH, MO, total N and C/N ratio, respiration, mineralization, and residence time.

### Chemical results during vermicomposting process

Significant differences in pH were recorded between treatments with and without LR addition ($F_{(7, 88)} = 3.58$, $p \leq 0.02$). The treatment containing 40 Mg of LR and EV, as well as the two treatments without LR addition (EV (7.29 ± 0.23) and RD (7.2 ± 0.24) presented a neutral behavior, although the other treatments that included different doses of LR, EV and RD showed a slightly alkaline behavior with pH values between 7.39 ± 0.21 and 7.63 ± 0.27 (Table 2).

It is possible to affirm that the treatment that included EV and 40 Mg of LR (T4) shows a beneficial potential for agriculture based on this parameter. The Mexican standard (DOF, 2007) establishes a pH range between 5.5 and 8.5 that makes it suitable for use in agriculture. Authors such as Sharma and Garg (2017) and Hassan *et al.* (2022) have shown that vermicompost produced from household waste and horse, cow and buffalo manures has a pH range of 7.2 to 7.3, thus showing beneficial neutrality levels for plant development. The treatments with these pH values distinguish them notably from the others. The dynamics shown by pH in vermicomposting is attributed to the production of $CO_2$ and the accumulation of organic acids produced by the microorganisms, and is related to changes in the nitrogen balance. These effects are probably influenced by the presence of earthworms in the vermicomposting process (Hait and Tare, 2011).

**Table 2**. Average values and standard deviation of pH, organic matter (MO) concentration, N and C/N ratio of the different treatments used for vermicomposting.

| Treatments | pH | MO (%) | N (%) | C/N |
|---|---|---|---|---|
| T1 | 7.29 ± 0.23c | 20.32 ± 9.21c | 0.29 ± 0.09d | 22.36 ± 13.58b |
| T2 | 7.52 ± 0.30ab | 20.03 ± 7.05c | 0.37 ± 0.16d | 25.33 ± 13.3b |
| T3 | 7.53 ± 0.25ab | 22.18 ± 9.20b | 0.89 ± 0.96b | 16.78 ± 5.66c |
| T4 | 7.24 ± 0.38c | 28.92 ± 10.78a | 0.51 ± 0.34c | 19.88 ± 8.39c |
| T5 | 7.20 ± 0.24c | 16.56 ± 6.14d | 0.47 ± 0.15c | 37.83 ± 10.37ab |
| T6 | 7.41 ± 0.25abc | 18.70 ± 8.78cd | 0.80 ± 0.04b | 37.40 ± 18.61b |
| T7 | 7.39 ± 0.21bc | 19.00 ± 11.42cd | 1.04 ± 0.62a | 23.87 ± 9.42bc |
| T8 | 7.63 ± 0.27a | 15.64 ± 5.73d | 0.46 ± 0.06cd | 48.86 ± 11.63a |

Means with different letters per column represent statistical difference (Tukey $p \leq 0.05$). F: Fisher; *p*: probability. AxB: interaction of A (LR dose) and B (type of residue). Treatments contained combinations of cow manure (EV), earthworms (L), residual sludge (LR) and domestic waste (RD). T1: EV and L; T2: EV and 10 Mg LR; T3: 20 Mg LR and L; T4: 40 Mg LR and L; T5: RD and L; T6: RD and 10 Mg LR; T7: RD and 20 Mg LR; T8: RD and 40 Mg LR.

Significant differences ($F_{(7, 88)} = 2.63$, $p \leq 0.01$) in organic matter (MO) concentration were observed among the different treatments. The type of residue played a crucial role in these differences, highlighting those containing LR and EV, which exhibited a higher concentration of MO, significantly different with RD. For 10 Mg of LR, a value of 20.03 ± 7.05 % was recorded (T2), while for 20 Mg of LR it was 22.18 ± 9.2 % (T3) and for 40 Mg of LR it reached 28.92 ± 10.78 % (T4). In contrast, those without LR and only with EV presented a value of 20.32 ± 9.21 % (T1), and those containing RD showed 16.56 ± 6.14 % (T5). Treatments combining LR and RD, such as 40 Mg LR with 15.64 ± 5.73 % (T8), 10 Mg LR with 18.7 ± 8.78 % (T6), and 20 Mg LR with 19 ± 11.42 % (T7), exhibited different MO concentrations without showing differences (Table 2). The combination of EV and 40 Mg of LR (T4) stood out for its higher MO concentration, in contrast to the MO concentration found in the mixture of RD and 40 Mg of LR.

The average MO concentration at the end of all treatments was 20.17 ± 9.27 %, a value that agrees with the study by Ghaffari *et al*. (2022) and the Mexican standard (DOF, 2007), which indicates an acceptable range of MO between 20 and 50 %, confirming that the results obtained comply with the recommended standards. A lower percentage of MO in the treatment containing only RD is due to substrate decomposition promoted by the earthworm and mineralization activated by the microorganisms, which coincides with Das *et al*. (2022), Chen *et al.* (2023), and Gebrehana *et al*. (2023). Similarly, reports by Wang *et al*. (2021), Mahapatra *et al*. (2022), and Rékási *et al*. (2023) specified that stable organic residues contribute nutrients such as nitrogen, phosphorus, and potassium to the soil in organic and inorganic forms. However, nitrogen in its organic form is converted to greenhouse gases, which may result in its loss.

Significant differences were observed in the total nitrogen percentage among treatments ($F_{(7,88)} = 3.87$, $p \leq 0.01$), highlighting those composed of LR and RD, with higher values of 0.47 ± 0.15 (T5), 0.8 ± 0.04 (T6) and 1.04 ± 0.62 % (T7). In second place, there were the treatments with LR and EV, recording 0.37 ± 0.16 (T2), 0.89 ± 0.96 (T3) and 0.51 ± 0.34 % (T4). Treatments containing only RD (0.46 ± 0.06 %, T8) and EV (0.29 ± 0.09 %, T1) also showed significant differences in their nitrogen levels, although with low values (Table 2).

These results underline the significant influence of the combination of LR and RD on nitrogen percentages, followed closely by the synergy between LR and EV. Specifically, the combination of RD and 20 Mg of LR showed the highest nitrogen percentage, while the lowest concentration was recorded in the EV-only treatment. The importance of carefully considering the composition of the materials used is highlighted, as it can have a significant impact on the availability of nitrogen in the agricultural system.

Although the average value is below the Mexican standard (DOF, 2007), which has a range between 1 and 4 % N, only T7 met it (1.04 ± 0.6 % N), which was made with LR 20 Mg and RD. Studies by Ahmed and Deka (2022), Cai *et al.* (2022), Das *et al*. (2021, 2022), and Kauser and Khwairakpan (2022) explain that the addition of nitrogenous mucous substances, decomposing tissues, hormones and enzymes promote the metabolic activity of the earthworm and the production of humic and fulvic acids that occur during the vermicomposting process.

The C/N ratio derived from the quotient between the percentage of carbon and nitrogen exhibits significant differences ($F_{(7, 88)} = 3.58$, $p \leq 0.002$) among treatments, influenced by the amount of LR and the type of residue. The highest C/N ratios are those containing LR and RD, recording 48.86 ± 11.6 for treatment T8 and 37.4 ± 18.1 for T6, including also the one containing only RD, with 37.8 ± 10.3. On the other hand, the treatments containing LR and EV presented lower values in the C/N ratio. Ratios of 25.3 ± 13.3 were recorded for the treatment with 10 Mg of LR, 16.7 ± 5.6 for that with 20 Mg of LR, and 19.8 ± 8.3 for that with 40 Mg of LR. This group also includes the treatment containing only EV, with a ratio of 22.3 ± 13.3.

These results highlight the significant influence of the amount of LR residues and the type of residue on the C/N ratio, which plays a crucial role in understanding the decomposition dynamics and nutrient availability in the evaluated systems. Importantly, the composite treatment with 40 Mg of LR and EV exhibits the best chemical stability in terms of C/N ratio, which positions it as an adequate and suitable option for use in agricultural practices. These results provide valuable information to optimize residue management strategies and improve soil quality.

The C/N ratio is often used to evaluate the stability of compost (Chen *et al*., 2023). Authors such as Katakula *et al*. (2021) and Dümenci *et al*. (2021) mention that a C/N ratio less than 20 indicates good quality vermicompost, since soluble MO is biodegradable and contains stable high molecular weight compounds, but if the C/N ratio is high, N is deficient to produce bacterial protein and the growth of organisms that decompose organic matter is reduced. Also, Das *et al*. (2021) and Gebrehana *et al*. (2023) explain that the quality of nutrients and the earthworm species present in the waste influence the C/N ratio, which is an important factor in favoring the growth rate of earthworms.

### Respiration, carbon mineralization and carbon residence time

The respiratory activity in the treatments represented by factors "A" and "B" shows a similar behavior between them. Likewise, the respiratory activity at the initial time (15 d) (Figure 1A) is higher compared to that observed in the treatments for the final time (75 d) (Figure 1B). In the first time, the respiratory activity values vary from 640.21 to 814.68 mg $CO_2$ 100 $g^{-1}$ soil. On the other hand, at the final time, values ranging from 475.98 to 659.01 mg $CO_2$ 100 $g^{-1}$ soil were recorded.

Respiratory activity at the initial time was notably higher in those treatments containing RD and LR, registering a value of 741.7 ± 48 mg $CO_2$ 100 $g^{-1}$ soil. In contrast, treatments with a combination of EV and LR presented a lower respiratory activity, with an average of 616.8 ± 8.6 mg $CO_2$ 100 $g^{-1}$ soil. A similar pattern was observed at the final time, where the treatments with RD and LR exhibited higher respiratory activity, reaching a value of 631.4 ± 29 mg $CO_2$ 100 $g^{-1}$ soil. In contrast, the mixture of EV and LR showed a lower respiratory activity, with an average of 516.29 ± 70 mg $CO_2$ 100 $g^{-1}$ soil. This variation can be attributed to the presence of a consortium of microorganisms derived from the waste residues and the vermicomposting process, which is in agreement with Suthar (2009).

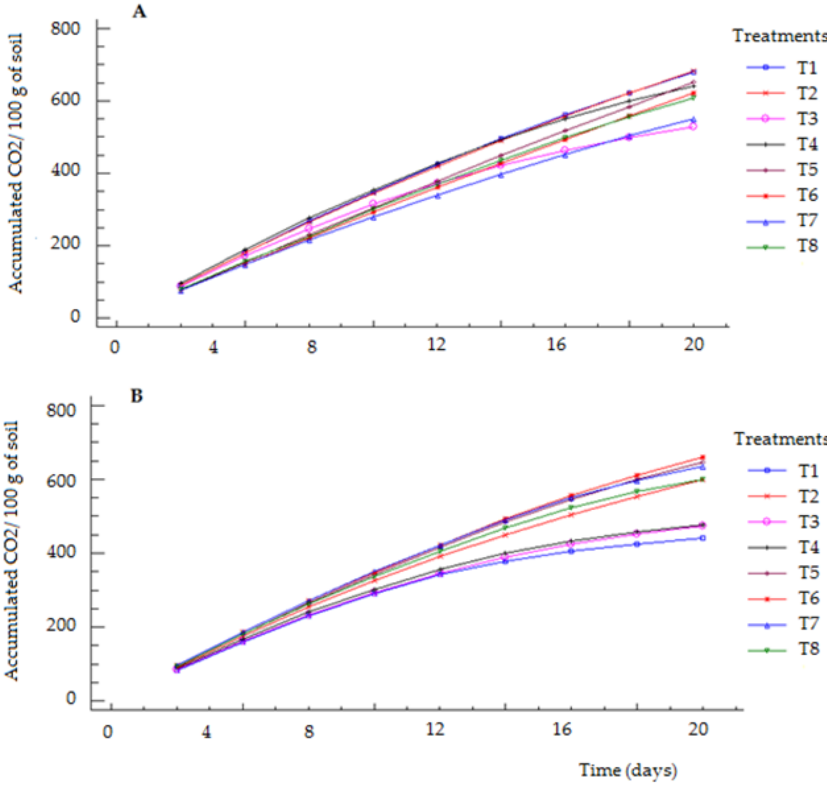

**Figure 1** .$CO_2$ evolution of the vermicompost in the eight treatments. A: at 15 d of incubation; B: at 75 d. Treatments contain combinations of cow manure (EV), worm castings (L), residual sludge (LR) and domestic waste (RD): T1 EV and L; T2 EV and 10 Mg of LR; T3 20 Mg of LR and L; T4 40 Mg of LR and L; T5 RD and L; T6 RD and 10 Mg of LR; T7 RD and LR; and T8 RD and 40 Mg of LR.

It is worth mentioning that the respiratory activity was ascending at the beginning of the vermicomposting process, which is due to an accelerated degradation of the MO and the continuous feeding of the substrate by the earthworm, coinciding with Gómez-Brandón *et al*. (2022) and Chen *et al*. (2023). On the other hand, the respiratory activity of the treatments reaches a maximum and begins to stabilize, which is due to the decrease in respiratory activity due to the loss of available carbon sources and the presence of compounds rich in lignin and cellulose (Gusain and Suthar, 2020).

## Carbon mineralization in the vermicompost

A significant change in carbon mineralization was observed in the treatments containing EV and LR; these mineralized at a faster rate compared to those containing RD and LR from day eight onwards. At this point, the rate of mineralization showed the following sequence: T4 ($K2 = -12.2 \times 10^{-3}$) > T3 ($K2 = -11.1 \times 10^{-3}$) > T1 (K2 = -10.8

x $10^{-3}$) > T2 (K2 = -7.5 x $10^{-3}$). This change possibly suggests a transition from labile to recalcitrant carbon after day eight, which slowed carbon degradation in all treatments. With respect to treatments T5, T6, T7 and T8, which included RD and LR residues, a significant change was identified as of day 10. The mineralization rate sequence in this case was as follows: T8 (K2 = -7.59 x $10^{-3}$) > T7 (K2 = -7.37 x $10^{-3}$) > T5 (K2 = -6.81 x $10^{-3}$) > T6 (K2 = -6.57 x $10^{-3}$). This variation is probably related to the amount of organic matter present in each treatment (Figure 2).

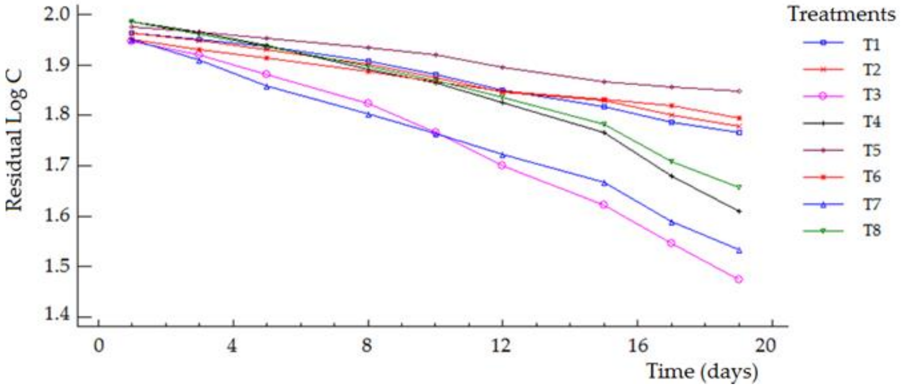

**Figure 2.** Carbon mineralization rate curves at 75 d of incubation of the treatments. Treatments contained combinations of cow manure (EV), worm castings (L), residual sludge (LR) and domestic waste (RD): T1 EV and L; T2 EV and 10 Mg of LR; T3 20 Mg of LR and L; T4 40 Mg of LR and L; T5 RD and L; T6 RD and 10 Mg of LR; T7 RD and LR; and T8 RD and 40 Mg of LR.

As incubation time progressed, the treatments gradually entered a stage of stability, where the easily degradable material began to be depleted, thus decreasing degradation activity and carbon dioxide release (Alvarez and Alvarez, 2000). In terms of mineralization rate, treatments T1, T3 and T4 demonstrated a higher rate compared to those involving RD and LR, with T4 predominating. Chen *et al*. (2023) recommended that in order to quantify the direct and indirect contributions of earthworm in carbon mineralization, it is necessary to consider a feeding model containing cow dung and stubble residues and relate it to the respiration model.

## Carbon residence time of the mathematical model

The half-life of the mineralized organic carbon of each treatment was determined, focusing mainly on the K values at 60 d. Based on this information, a classification into three groups was carried out, considering the residence time. The first group covers the interval of t < 70 d, where T3 (57 d), T4 (62 d) and T1 (64 d) are included. The second group comprises the interval of 70 < t < 100 d, consisting of T2, T8 (91 d) and T7 (92 d). Finally, the third group encompasses those with t > 100 d, being represented by T5 (105 d) and T6 (102 d) (Table 3).

**Table 3**. Values of carbon mineralization constants and half-life at day 75 of the vermicomposting process in the treatments.

| Treatments | Mineralization constants K1 and K2 | | Residence time ($d^{-1}$) |
|---|---|---|---|
| | $K_1$ ($d^{-1}$) ($10^{-3}$) | $K_2$ ($d^{-1}$) ($10^{-3}$) | |
| T1 | -5.60 | -10.80 | 64 |
| T2 | -15.50 | -7.58 | 91 |
| T3 | -8.90 | -11.10 | 62 |
| T4 | -8.65 | -12.20 | 57 |
| T5 | -10.80 | -6.81 | 102 |
| T6 | -7.58 | -6.57 | 105 |
| T7 | -11.10 | -7.37 | 94 |
| T8 | -12.20 | -7.59 | 91 |

$K_1$ and $K_2$: kinetic constants of carbon mineralization. Treatments contained combinations of cow manure (EV), worm castings (L), residue sludge (LR) and domestic residue (RD): T1 EV and L; T2 EV and 10 Mg of LR; T3 20 Mg of LR and L; T4 40 Mg of LR and L; T5 RD and L; T6 RD and 10 Mg of LR; T7 RD and LR; and T8 RD and 40 Mg of LR.

With the purpose of validating the optimum residence time for vermicompost production, it is observed that the treatments containing EV and LR (T3 and T4) and only EV (T1) allow obtaining vermicompost in less than 70 d. Among these treatments, the one that incorporates 40 Mg of LR and EV (T4) stands out, achieving a time of 57 d and exhibiting ideal chemical and biological qualities for its use in agriculture. Therefore, it is considered that the T4 treatment is not only efficient in producing vermicompost in a reduced time, but also suitable for its application in agricultural soils and environmental improvement.

The model used to determine residence times proves to be practical and useful for predicting the duration of the vermicomposting process, which agrees with Dümenci *et al*. (2021) and Chen *et al*. (2023), who emphasized that mathematical models optimize the process and reduce costs, which benefits agricultural producers.

## CONCLUSIONS

Regarding pH, all treatments are slightly alkaline, which suggests the efficacy of the process in pH regulation. The concentration of organic matter in the treatments is considered adequate according to the Mexican standard, with a higher percentage in T4 and T3, and the influence of the ingredients on the quality of the vermicompost is highlighted. The percentage of N in the treatments was low according to the standard, but its stability was reflected in the C/N ratio, which was only fulfilled for the doses of 20 and 40 Mg of residual sludge and cow manure.

Respiratory activity was more dynamic in the treatments with domestic waste and residual sludge than those containing cow manure and residual sludge. In terms of mineralization rate and residence time, the vermicompost with 40 Mg and cow manure (T4) had an optimal processing time (less than 70 days) and met the standards, which makes it suitable for agriculture, while the other treatments may have another vocation, either as forestry or restoration use.

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