Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X

http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

REVISTA AIDIS

de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica.

BIODEGRADABLE MATERIAL FORMULATED WITH OAT HULLS IN THE COMPOSTING PROCESS OF HOUSEHOLD ORGANIC WASTE AND TREE PRUNING

Rafaela Gasparotto Moser [1]
Ana Paula Bilck [2]
Fábio Yamashita [3]
Leonardo Galice Chies [4]
Pedro Henrique Presumido [5]
* Ramily M. A. O. Meneses [6]
Roger Nabeyama Michels [7]
Tatiane Cristina Dal Bosco [8]

Recibido el 25 de mayo de 2021. Aceptado el 8 de noviembre de 2021

Abstract
With attractive research and development of new biodegradable polymers and their packaging applications, there is a need to address their environmental performance. This study aimed to compare the compostability of biodegradable materials (BM) produced with cassava starch, glycerol, poly (lactic) acid, with and without oat hulls to compost organic waste and also to evaluate if the BM influenced the compost process and its final product. The composting was carried out in 100 L reactors, 30 L of which were occupied with household organic waste and 66 L with tree pruning. The process was monitored for 60 days using the following parameters: temperature, C/N ratio, total organic carbon, total nitrogen, pH, electrical conductivity, series of solids, humidity, and reduction in mass and volume. At the end of the experiment, the degradation of the BM was analyzed by scanning electron microscopy (SEM). In the SEM images, cracks, voids, and irregular surfaces were observed, which did not exist in the BM before composting. The degradation of BM occurred, and their presence did not interfere in the composting process or the final compost's quality.

Keywords: biodegradation, biodegradable packaging, compost quality, scanning electron microscope, solid waste management.

[1] Departamento de Engenharia Ambiental, Universidade Tecnológica Federal do Paraná (UTFPR). Londrina, Paraná, Brasil.
[2] LabMult - Central de Análises, Universidade Tecnológica Federal do Paraná (UTFPR). Pato Branco, Paraná, Brasil.
[3] Departamento de Ciência e Tecnologia de Alimento (DCTA), Universidade Estadual de Londrina (UEL). Londrina, Paraná, Brasil.
[4] Departamento de Engenharia de Produção, Universidade Tecnológica Federal do Paraná (UTFPR). Londrina, Paraná, Brasil.
[5] Chemical Engineering Department, Faculty of Engineering University of Porto. Porto, Portugal.
[6] Departamento de Engenharia Ambiental, Universidade Tecnológica Federal do Paraná (UTFPR), Brasil.
[7] Departamento de Engenharia Mecânica, Universidade Tecnológica Federal do Paraná (UTFPR). Londrina, Paraná, Brasil.
[8] Departamento de Engenharia Ambiental, Universidade Tecnológica Federal do Paraná (UTFPR). Londrina, Paraná, Brasil.
* *Corresponding author*: Departamento de Engenharia Ambiental, Universidade Tecnológica Federal do Paraná (UTFPR). Av. dos Pioneiros, 3131, Jardim Morumbi, Londrina, Paraná, Brasil. Email: ramilymeneses@gmail.com

http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

Introduction

The generation of solid urban waste in 2020 was 79.6 million tons, and it is possible to project an increase of 50% in 2050 (ABRELPE, 2020). Plastics production has quadrupled in the last 50 years and can double in the next 20 years, causing significant problems for the marine and terrestrial ecosystems (Luo *et al.*, 2019). Improving solid waste management is considered an environmental challenge, and there is a particular focus on reducing consumption, reducing waste, and transforming waste into resources (Ghinea *et al.*, 2019).

In this context, the difficulty of recycling conventional plastic materials has promoted the development of biodegradable materials that are becoming increasingly important, as they can be produced from renewable sources or raw materials (Kale *et al.*, 2007) such as starch, poly (lactic) acid (PLA), oat hulls (Furlan *et al.*, 2012; Debiagi *et al.*, 2013), sugarcane bagasse (Tita *et al.*, 2002), and coffee husks (Machado *et al.*, 2010).

Oat hulls are a residue of the agribusiness that, in addition to being generated in large quantities, have no economic value and must be disposed of appropriately. The use of oat hulls to reinforce biodegradable materials and to reduce their costs is an alternative destination. These reinforced materials with oat hulls can reduce their cost and can be used to produce biodegradable bags, films, and packaging for quick disposal with better mechanical properties (Peixoto *et al.*, 2019; Brito *et al.*, 2011).

About 50% of urban solid waste disposal in plastic trash bags is organic (CEMPRE, 2017), and according to the Panorama of Solid Waste in Brazil, around 170 kg of organic waste per person are generated each year (ABRELPE, 2020). According to Law 12.305/2010, which institutes the National Solid Waste Policy, composting should be the priority strategy for treating organic waste (Brasil, 2010), which transforms organic matter into a more humidified final product. However, plastic trash bags are difficult to compost like household organic waste and tree pruning because they are not biodegradable, and they need to be removed before starting the composting process. The replacement of those bags by biodegradable ones would reduce the time and costs of composting because they can be biodegraded in landfills and composting piles/reactors (Kale *et al.*, 2007).

This paper aims to compare the compostability of biodegradable materials produced with starch, glycerol, PLA, with and without oat hulls in composting process of household organic waste and tree pruning and also to evaluate if they influenced the compost process and it´s final product.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

Materials and methods

Composting test: Experimental configuration, production, and characterization of biodegradable material and organic waste

The composting process lasted 60 days, between April and June 2017, and the methodology was based on NBR 15448-2: 2008 - Degradable plastic packaging and/or from renewable sources, part 2: Biodegradation and composting - Requirements and test methods.

The experiment was carried out at the greenhouse of the Federal Technological University of Paraná, Câmpus Londrina, Brazil, where there is a roof and waterproof floor, to simulate the process carried out in municipal composting facilities where the organic wastes arrive packaged in plastic bags. Then they are crushed and mixed with tree pruning since tree pruning is a waste commonly generated by municipalities and requires an environmentally appropriate destination.

The organic wastes used in this experiment came from a large restaurant in Londrina (simulating household organic wastes) and the Municipality of Londrina (trees pruning).

The formulation of the biodegradable materials (Table 1) was based on Silva *et al.* (2020a) and used cassava starch (General Mills Brasil Alimentos Ltda, Paranavaí, Brazil), poly (lactic acid) (PLA) REVODE® 201- Zhejiang Hisun Biomaterials Co, China), micronized oat hulls (SL Alimentos-Mauá da Serra, Paraná, Brazil) (4.64 g 100 g^{-1} ash, 3.95 g 100 g^{-1} protein, 2.12 g 100 g^{-1} of lipid, 23.13 g 100 g^{-1} of cellulose, 26.25 g 100 g^{-1} of hemicellulose and 3.80 g 100 g^{-1} of lignin) and glycerol (Dinâmica Química Ltda, Brazil). The cassava starch and oat hulls were used because of their low cost compared with pure PLA, and the glycerol was used as a plasticizer (SILVA *et al.*, 2020a).

Table 1. Formulation of composted biodegradable materials.

Formulation	Cassava Starch (g 100g^{-1})	Glycerol (g 100g^{-1})	PLA (g 100g^{-1})	Oat hull (g 100g^{-1})
1	45	15	40	0
2	35	15	40	10

The starch, glycerol, PLA, and oat hull were mixed according to the proportions shown in Table 1 and extruded in a single-screw extruder (BGM, model EL-25, Brazil) to produce cylindrical strands. The extruder had a screw diameter (D) of 25 mm, a screw length (L) of 750 mm (L/D ratio of 30), and a screw speed of 35 rpm, four heating zones, and a matrix with two 2 mm holes. The temperature profile was set at 90/150/150/140 °C. After processing, the cylindrical strands were cut into 5 cm long pieces (biodegradable material - BM) to perform the composting tests. This size of the BM is used to allow more contact of the material with the solid waste and to allow a larger contact surface.

http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

Composting was carried out in 100 L reactors by mixing organic waste (household organic waste and tree pruning) and biodegradable material (BM), resulting in three treatments with the same volume. T_0 treatment was used as a blank (control) because it did not contain any BM. T_1 and T_2 treatments contained biodegradable material without and with oat hulls, respectively. Each treatment was performed in duplicate, totaling six experimental units. The disposition of treatments in the greenhouse was randomized (Figure 1).

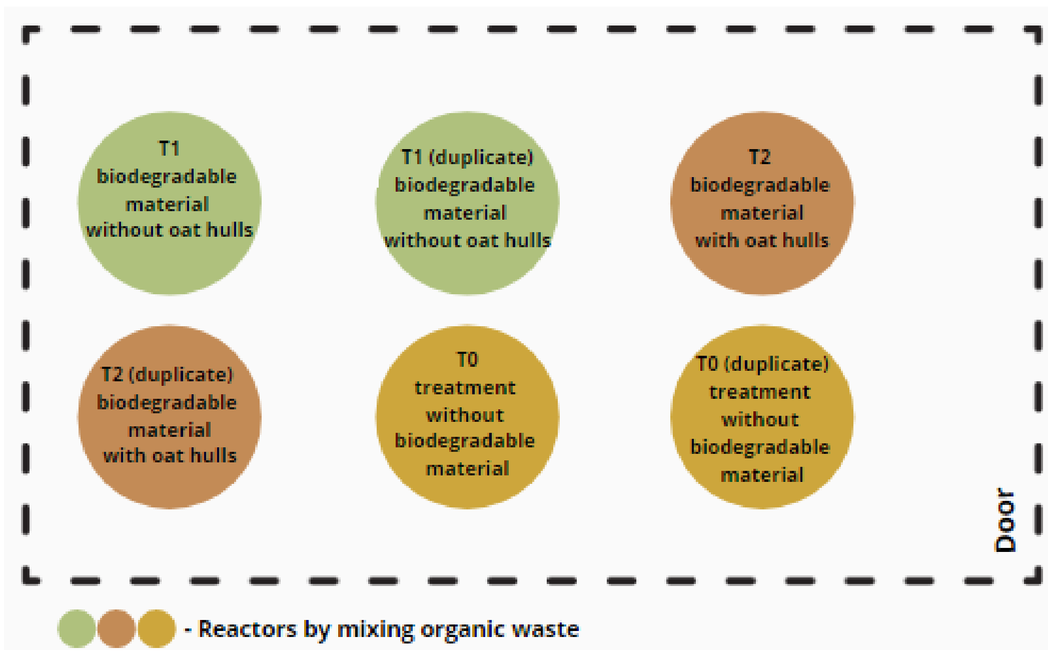

Figure 1. Arrangement of treatments in the greenhouse.

For the calculation of the initial C/N ratio, the characterization of the residues was necessary to determine the composition of total nitrogen (TN), total organic carbon (TOC), humidity, series of solids (fixed solids, volatile and total solids), specific mass, pH and electrical conductivity. These analyzes were made at the Sanitation Laboratory of UTFPR Campus Londrina, and the results are described in Table 2.

The pH and conductivity were measured using the methodology proposed by Tedesco *et al.* (1995). The series of solids and moisture content was determined by the American Public Health Association methodology (APHA, 2012). TN was determined by the methodology proposed by Malavolta *et al.* (1997), and the TOC content was estimated from the equation proposed by Carmo and Silva (2012) (Equation 1).

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica.
ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

Table 2. Initial characteristics of organic waste.

Parameter	Tree Pruning	Household Organic Waste
Electrical conductivity (µS cm^{-1})	620	1296
pH	7.4	4.47
Apparent density (kg L^{-1})	0.256	0.688
Moisture (%)	42.31	80.08
Total solids (%)	57.69	19.92
Volatile solids (%)	91.71	96.16
Fixed solids (%)	8.29	3.84
Total organic carbon (%)	36.91	38.80
Total nitrogen (%)	1.91	2.31

$$TOC = (0.425 * VS) - 2.064$$ **Equation (1)**

Where:
TOC = Total Organic Carbon;
VS = Volatile Solids.

From the results of the organic waste characterization (Table 2), the equation proposed by Kiehl (1985) was used to define the residues proportions to start the process with an appropriate C/N ratio (Equation 2).

$$\frac{C}{N} = \frac{(X * Nn) - Cm}{Cc - (X * Nc)}$$ **Equation (2)**

Where:
X = initial Carbon/Nitrogen ratio
Nn = % Nitrogen of the Household Organic Waste.
Cm = % Carbon of the Household Organic Waste.
Cc = % Carbon of the Tree Pruning.
Nc = % Nitrogen of the Tree Pruning.

The result from Equation 2 is given in dry mass. So it was necessary to transform this data into a wet mass. The residue moisture was used to this conversion. The conversion from mass to volume was done using the residues apparent density.

According to the organic waste characterization (Table 2), it was not possible to meet the C/N ratio of 30:1, considered ideal to start the composting process (Kiehl, 1985), because this proportion was impracticable to assembly the reactors and to homogenize the wastes, it means that it would be necessary too much tree pruning. Other studies have also reported good performances in composting organic materials with C/N ratios below 19:1 (Sbizzaro *et al.*, 2017; Silva *et al.*, 2020a). Thus, other C/N ratios were tested, such as 19:1, 18.5:1, and 18:1 (Table 3).

ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

Table 3. Reactor composition for different C/N ratios.

Ratio C/N	Household Organic Waste		Tree Pruning	
	Capacity (L)	Capacity (%)	Capacity (L)	Capacity (%)
19:1	11	11.5%	85	88.5%
18.5:1	30	31%	66	69%
18:1	47	49%	49	51%

The C/N ratio of 18.5:1 was chosen because the ratio of approximately 1.8 L of tree pruning to 1 L of household organic waste was considered the most suitable for waste homogenization. In this way, the reactors were composed of approximately 30 L of household organic waste and 66 L of tree pruning (96 L total). In addition, 400 g of biodegradable material were placed in treatment T_1 and T_2.

Experimental conditions and monitored composting parameters.

The organic wastes had the appropriate granulometry (KIEHL, 1985) since they came from food scraps and tree pruning, which were crushed at the time of collection.

The assembly of the reactors was done by superimposing alternate layers of each waste totalazing three layers of tree pruning and two layers of household organic wastes. The first and last layers were tree pruning to avoid the bad smell and the proliferation of vectors in the first weeks of composting (Pereira Neto, 1998). In T_1 and T_2 treatments, the biodegradable materials (BM) were incorporated with the organic residues inside the reactor.

Two BM samples were wrapped in a net nylon packaging and placed in each reactor to facilitate the visualization of their degradation and their location in the reactor. The porosity of these packagings allowed the BM to contact the microorganisms and other compost in the process (Taiatele Júnior *et al.*, 2020).

During the process, temperature, pH, electrical conductivity, humidity, fixed solids, volatile solids, TOC, TN, aeration, volume, and mass reductions were monitored.

The temperature was monitored with the aid of an automated data collection system. Five sensors were inserted in each reactor, and their positioning inside the reactor took place at strategic points to record the temperature at different points to observe temperature variations. These sensors were connected to an Arduino board equipped with a data logger system (datalogger) together with an RTC (Real Time Clock) that provided the time of data acquisition. Data were stored every 10 minutes and recorded on an SSD card (Dal Bosco *et al.*, 2020).

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

Aeration was performed by manual overturns, which took place every three days, but the first overturning was only carried out after seven days. The humidity was controlled by a hand test (Nunes, 2009) when overturning, but there was no need to add water during the process. When overturning the BM into the nylon net were mixed with the tree pruning and the household organic waste.

The volume reduction was measured using a non-deformable container. The material was weighed at the beginning and the end of the process to calculate the mass reduction. The mass of water was discounted according to the moisture data so that it was possible to compare the differences between the initial and final dry mass. The analysis frequency of each parameter is described in Table 4.

Table 4. Frequency of monitoring the composting parameters.

Parameter	Frequency
Temperature	Every 10 minutes
Moisture	Every 3 days
Aeration	Every 3 days
pH	Biweekly
Electrical conductivity	Biweekly
Total solids	Biweekly
Fixed solids	Biweekly
Volatile solids	Biweekly
Total nitrogen	Biweekly
Total organic carbon	Biweekly
Mass reduction	Finale
Volume reduction	Finale

Monitoring of biodegradable materials (BM): Scanning Electron Microscopy (SEM)

The microstructure of the BM surface was observed by Scanning Electron Microscopy (SEM) before being placed in the reactors and at the end of the composting process.

The samples were immersed in liquid nitrogen for rapid freezing and, later, were fractured with the aid of stainless-steel clamps. Then, these samples were left in a desiccator with calcium chloride for 48 hours to remove moisture. The samples were then sputter-coated with gold in a BAL-TECSCD 050 Sputter Coater. SEM images were obtained by a FEI, Quanta 200 (USA). This analysis aimed to verify changes in the microstructure of BM resulting from the composting process.

Statistical analyzes

The analysis of the variance of the average temperature data was made considering a split-plot design. The analyses were divided by periods because the data did not show homogeneity of

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

variances when considering the entire period. For the C/N ratio, TOC, TN, pH, electrical conductivity, series of solids, and volume reduction parameters, the Scott-Knott test was performed at 5% of significance to compare the means of each treatment.

Result and discussions

Biodegradation of biodegradable materials in compost: physical-chemical analysis

The biodegradable materials (BM) were incubated for about 60 days under composting conditions in direct contact with the other wastes. The microorganisms present in composting carry out an exothermic process: while degrading the waste, they release heat, causing an increase in temperature in the medium (Bidone and Povinelli, 1999). Thus, temperature variations occur during the process, generally in phases: thermophilic, mesophilic, and maturation (Kiehl, 2002). Figure 1 summarizes the temperature data from the period of feedback control. At the beginning of the composting process, the average temperature presented by the treatments was 40 °C, which indicates that the process was in balance, as according to Fernandes and Silva (1999), if the temperature is not around 40 °C in the first days, it is a sign that some parameters are out of control.

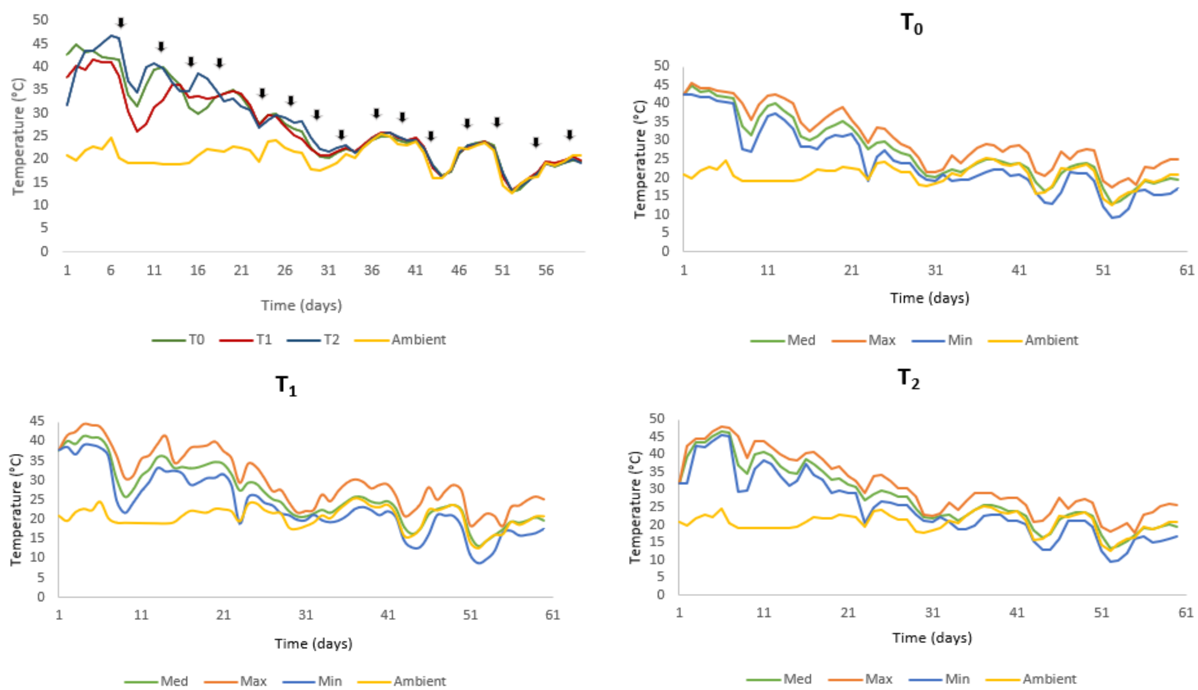

Figure 2. Average temperature during the composting process.

Note: T_0 - tree pruning + household organic waste, T_1– tree pruning + household organic waste + biodegradable material without oat hulls, T_2 - tree pruning + household organic waste + biodegradable material with oat hulls. ↓ Manual aeration.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

The thermophilic phase, the phase with the highest temperature (above 40), and microbiological activity (Trautmann and Olynciw, 2005), occurred in the first 11 days, with a variation of 40 °C to 45 °C. The mesophilic phase, which has temperatures in the range of 40 to 20 °C, lower rate of microbial activity, and reduced oxygen demand (Massukado, 2008; Kiehl, 1985), lasted 26 days, with an average final temperature of 25 °C. Approximately 40 days after the beginning of the process, the maturation phase started and lasted until the end of the composting process. In this phase, the process temperature follows the ambient temperature (Barreira, 2005) (Figure 2).

When analyzing the levels of total organic carbon, total nitrogen, and C/N ratio between treatments T_0, T_1, and T_2, it is possible to notice that there is no statistical difference over time. Thus, the addition of biodegradable materials in the composting process did not interfere with these parameters (Figure 3).

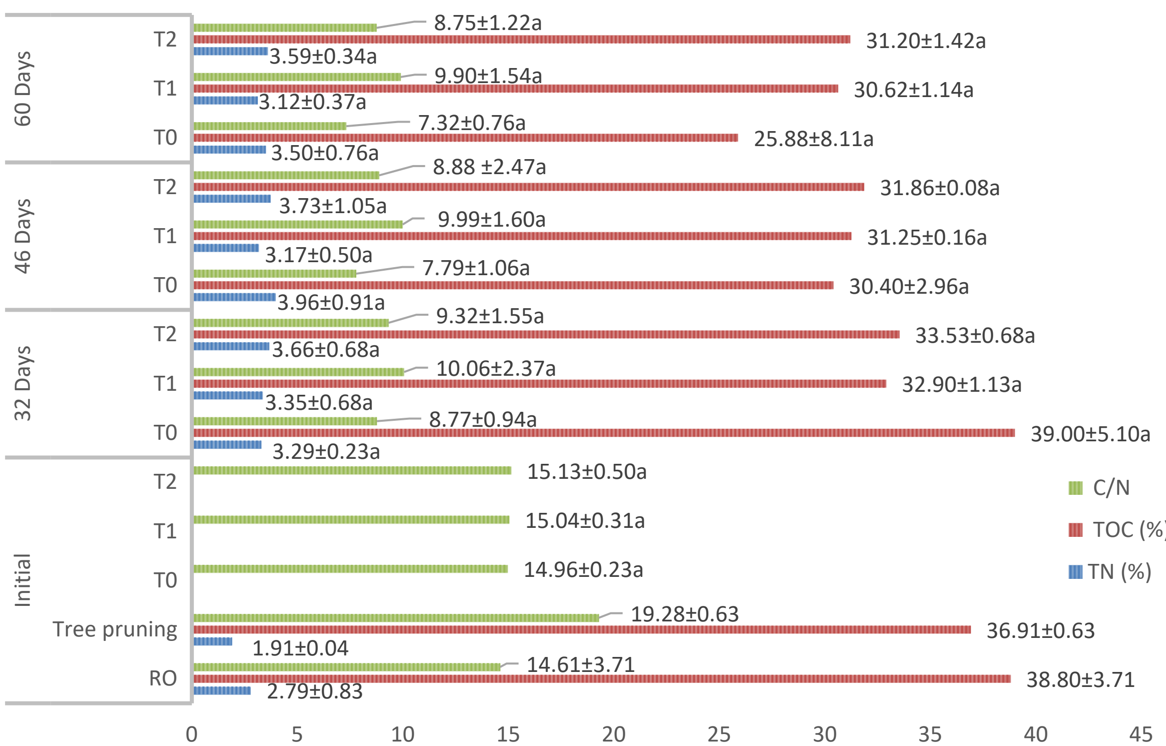

Figure 3. Total organic carbon content, total nitrogen, and initial C/N ratio of residues after 32, 46, and 60 days of composting treatments.

Note: RO - household organic waste, T_0 - tree pruning + household organic waste, T_1– tree pruning + household organic waste + biodegradable material without oat hulls, T_2 - tree pruning + household organic waste + biodegradable material with oat hulls, TOC - total organic carbon, TN - total nitrogen. Average levels ± standard deviation. Different letters in the same column and the same period represent a significant difference (p <0.05) by the Scott-Knott test.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X

http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

The C/N ratio decreased during the process due to the organic matter degradation by microorganisms, through carbon mineralization, despite the initial C/N ratio not being those proposed by Kiehl (2004), 25:1 and 35:1. According to MAPA Normative Instruction 61 of 2020, the C/N ratio of organic compost must have a maximum value of 20:1, Organic Carbon (OC) a minimum amount of 15%, and Total Nitrogen (TN), a minimum value of 0.5%. In this way, the compost produced in this study could be marketed as agricultural fertilizer since only the parameters C/N, OC, and TN (MAPA, 2020) are observed.

The pH was followed as a function of time (days) and is reported in Table 5. In the initial analyses of the wastes, the household organic waste had a pH of 4.5 and the tree pruning pH of 7.0. According to Valente et al. (2009), organic materials have an acidic pH, which justifies the pH of the initial organic waste. After 18 days of composting, the treatments showed pH with less acidity, which was maintained in the analyses of 32 days, 46 days, and 60 days. It was expected that the pH could increase during the composting process since an acidic medium indicates a lack of maturation of the compost (Oliveira et al., 2008). The statistical analysis presented in Table 5 proves that the BM inserted in the T_1 and T_2 treatments did not influence the pH parameter since there was no significant difference between the treatments ($p> 0.05$).

Table 5. Statistical analysis for pH and electrical conductivity values.

Period	Treatment	pH	Conductivity (µS.cm^{-1})
18 days	T_0	8.29a±0.34	3830a±42
	T_1	8.36a±0.35	3520a±934
	T_2	9.11a±0.11	5027a±1990
32 days	T_0	8.65a±0.13	4385a±375
	T_1	8.83a±0.18	4145a±559
	T_2	8.72a±0.10	3320a±339
46 days	T_0	8.60a±0.27	5055a±417
	T_1	8.28a±0.76	5975a±219
	T_2	8.51a±0.36	4640a±254
60 days	T_0	9.30a±0.36	5980a±99
	T_1	9.27a±0.18	6325a±1577
	T_2	8.96a±0.66	4910a±2475

Note: T_0 - tree pruning + household organic waste, T_1– tree pruning + household organic waste + biodegradable material without oat hulls, T_2 - tree pruning + household organic waste + biodegradable material with oat hulls. Different letters in the same column and the same period represent a significant difference ($p <0.05$) by the Scott-Knott test.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X

http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

Pereira Neto (2007) states that composting can be carried out in a pH range of 4.5 to 9.5. Thus, during all collections, the pH variation was in accordance with the literature. For organic fertilizers to be used in agriculture, the pH must be between 7 and 9, recommends for the inoculum, so it creates a favorable ambient for developing the microorganisms. It is worth mentioning that other factors need to be checked before using the compost and that it also depends on the purpose of its destination (MAPA, 2020).

In the initial wastes analysis, the tree pruning had an electrical conductivity (EC) of 620 µS cm^{-1}. The initial EC of household organic waste was higher, approximately 1300 µS cm^{-1}. The EC of all treatments increased during the process due to the increased salt concentration caused by the material degradation and due to the fact that the reactors are closed systems, it does not allow such large dispersion of the leachate, as occurs in composting piles, for example.

The BM did not influence the EC since there was no significant difference between treatments ($p > 0.05$).

Throughout the process, the humidity of the three treatments compost was close to the initial moisture of the organic residues. No water was added to the reactors since the humidity was always above 64.75% (Table 6). At the end of the process, the moisture content of the compost was approximately 65%. According to MAPA Normative Instruction 61/2020, the maximum moisture value for mixed organic fertilizer and solid organic compost from household waste must be 50% (MAPA, 2020). Thus, the compost obtained in this experiment had values close to those required by the Legislation.

Table 6. Statistical analysis for solids series values.

Period	Treatment	Moisture (%)	Total solids (%)	Volatile solids (%)	Fixed solids (%)
Initial	Tree pruning	42.30±8.63	57.70±8.63	91.71±1.38	8.29±1.38
	RO	80.08±4.24	19.92±4.24	96.16±0.60	3.84±0.60
32 days	T_0	75.39±3.35a	24.61±3.35a	73.09±12.01a	26.91±12.00a
	T_1	74.08±4.69a	25.92±4.69a	82.27±2.66a	17.73±,2.66a
	T_2	73.98±1.31a	26.02±1.31a	83.75±1.62a	16.24±1.62a
46 days	T_0	75.34±0.33a	24.66±0.34a	76.40±6.97a	23.60±6.97a
	T_1	66.10±1.41a	33.90±1.41a	78.40±0.39a	21.59±0.39a
	T_2	70.31±5.74a	26.69±5.74a	79.84±0.17a	20.16±0.17a
60 days	T_0	66.02±1.79a	33.98±1.79a	70.82±12.67a	29.18±12.65a
	T_1	65.39±3.66a	34.60±3.67a	76.92±2.68a	23.08±2.68a
	T_2	64.75±5.86a	35.25±5.86a	78.28±3.34a	21.72±3.34a

Note: RO - household organic waste, T_0 - tree pruning + household organic waste, T_1– tree pruning + household organic waste + biodegradable material without oat hulls, T_2 - tree pruning + household organic waste + biodegradable material with oat hulls. Average levels ± standard deviation. Different letters in the same column and the same period represent a significant difference ($p < 0.05$) by the Scott-Knott test.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

The BM did not influence the humidity, total solids, volatile solids, and fixed solids, as there was no significant difference between treatments (p> 0.05) (Table 6), especially at the end of the process.

Mass and volume reduction of the wastes at the end of the compost process, considering the initial mass and volume of the reactors

One of the main advantages of carrying out composting is reducing the mass and volume from the initial waste, allowing to obtain a final product with good fertilizing characteristics (Orrico Junior *et al.*, 2011). All treatments had similar volume reductions, ranging between 78.1% (T2) and 79.2% (T0). This considerable reduction was expected since organic waste tends to decrease its volume during composting processes, and it can be considered that all treatments obtained equal volume reductions in the Scott-Knott comparison at 5% significance (p = 0,81). Therefore, BM did not influence this parameter (Figure 4). The mass reductions were expressive, varying between 59.1% (T_0) and 75.59% (T_2), with statistical equality, at 5% significance, between the three treatments (Figure 4). Taiatele (2017), when composting tree pruning, organic restaurant waste and biodegradable materials achieved volume reductions close to 50%. Likewise, Demetrio *et al.* (2016) achieved a 60% reduction in volume after 42 days of composting with tree pruning and organic waste from a restaurant.

The mass reduction is directly linked to the microbes' consumption of organic carbon (C-organic) in the compost. These heterotrophic microbes use C-organic as an energy source to degrade organic matter, and consequently, there is a reduction in the mass of the compost material. During the composting process, CO2 will be released by the activity of heterotrophic microbes through their respiration. Generally, the global warming potential of these emissions is not considered in the environmental impact of composting operations, as these emissions are used by plants in photosynthesis (IPCC, 2006 - Intergovernmental Panel on Climate Change (IPCC) (2006).

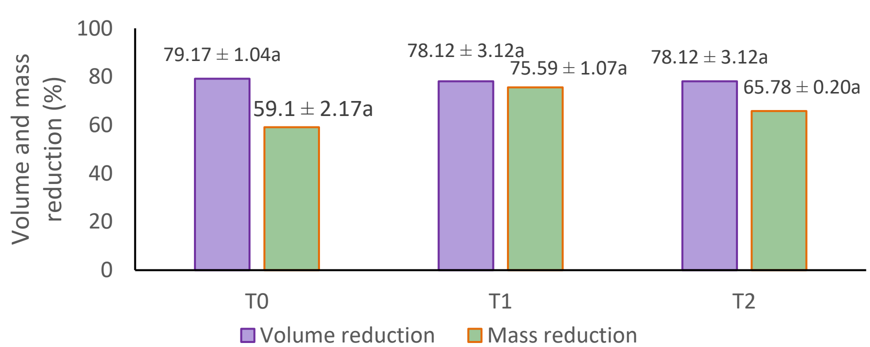

Figure 4. Average reduction in volume and mass of the reactors at the end of the composting process and statistical comparison by the Scott-Knott test at the level of 5% significance.

Note: T_0 - tree pruning + household organic waste, T_1 – tree pruning + household organic waste + biodegradable material without oat hulls, T_2 - tree pruning + household organic waste + biodegradable material with oat hulls.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X

http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

Microstructural characterization

Biodegradation of the biodegradable materials (BM) at the beginning and the end of the composting process were visually inspected (Figure 5), and it was possible to distinguish the BM from the rest of the waste at the end of the composting process.

Figure 5. Biodegradation of biodegradable materials at the beginning and the end of the composting process.
Note: T_1- biodegradable material without added oat hull, T_2- biodegradable material with added oat hull.

From the visual inspection of the BM, some observations can be highlighted: (i) the BM without the addition of oat hulls became opaquer; (ii) after the composting process, the BM became fragile and brittle; and (iii) the BM with oat hulls became less brittle because the oat hulls reinforced the polymer structure (Debiagi *et al.*, 2010). The length of the BM containing the oat hull was reduced to 0.5 cm more than the BM without oat hulls (Figure 5). The shape changes in the first days can be attributed to the distortion due to the temperatures (45 ± 5 °C) in the compost pile being very close to the PLA's glass transition temperature (Vouyiouka; Papaspyrides, 2012).

Comparing the length reduction of the materials, the BM with the addition of oat hulls reduced approximately 3.5 centimeters, higher than the BM without oat hulls, which reduced 3 centimeters. The decrease in the material length is a consequence of reducing the mass and volume due to the composting process. The decline in weight and volume increases the concentration of nutrients and reduces the need for space for storage and transport of waste. These results prove that the addition of oat husks into the BM was beneficial for the composting of domestic organic waste.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

SEM images of the cryofracture surfaces from the studied materials are presented in Figure 6. Before composting, the T_2 material showed a uniform surface, without visible voids or cracks (Figure 6a). After composting, the microstructures of the T_2 material were altered, and an irregular surface, cracks, and holes were observed. Silva *et al.* (2020a) composted PLA and starch biodegradable materials and observed cracks, pickles, and irregular surfaces early in the composting process. This change in the material's surface makes it more susceptible to biodegradation due to increased surface area and water permeation, accelerating hydrolysis (Flynn *et al.*, 2020).

a) b) c)

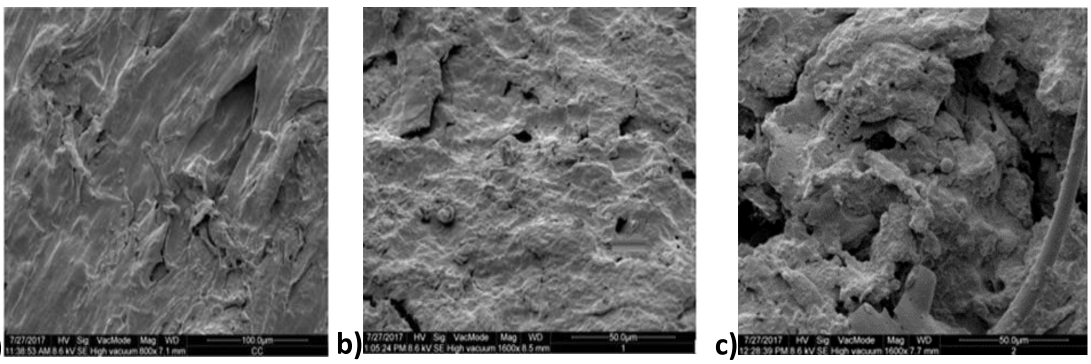

Figure 6. Scanning Electron Microscopy images of biodegradable materials with and without oat hulls, before and after composting.

Note: (a) surface of the biodegradable material with oat shell before composting, (b) surface of the biodegradable material without oat shell after composting, (c) surface of the biodegradable material with oat shell after composting.

Conclusion

Formulations based on plasticized PLA blends were successfully disintegrated under composting conditions in less than 60 days, stating their biodegradable character. It is possible to conclude that the biodegradable materials studied did not interfere with the composting process. The addition of oats did not change the behavior of the monitored parameters, thus allowing these biodegradable materials to be used as primary conditioners for solid organic waste. The degradation of biodegradable materials submitted to the composting process was also notable.

The final compound showed a reduction in mass and volume in all treatments. Although the reductions in volatile solids were satisfactory, the C/N, TOC, TN, and final pH ratios were within the standard required by MAPA, the electrical conductivity was high, which requires attention for the use of the compost in certain cultures. The humidity in the three treatments was above the maximum limit proposed by MAPA, requiring some drying process if commercialization was intended.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

References

ABRELPE (2020) *Panorama dos Resíduos Sólidos no Brasil 2020*. São Paulo – SP. [2020]. Acess on Dec. 26, 2020. Available in: https://abrelpe.org.br/panorama-2020

APHA, A.-W. (2012) *Standard methods for the examination of water and wastewater*. 22 ed. Washington: American Public Health Association.

Barreira, L. P. (2005) *Avaliação das usinas de compostagem do estado de São Paulo em função do composto e processos de produção***.** 2005. 204f. Tese (Doutorado em Saúde Ambiental) Universidade de São Paulo, São Paulo.

Bidone, F.R.A., Povinelli, J. (1999) *Conceitos Básicos de Resíduos Sólidos*. São Carlos: EESC/USP, Projeto REENGE.

Brasil (2010) *Lei Federal n° 12.305 de 02 de agosto de 2010*. Institui a Política Nacional dos Resíduos Sólidos, altera a Lei no 9.605, de 12 de fevereiro de 1998; e dá outras providências.

Brito, G. F., Agrawal, P., Araújo, E. M., Melo, T. J. A. (2011) Biopolímeros, Polímeros Biodegradáveis e Polímeros Verdes. *Revista Eletrônica de Materiais e Processos (REMAP)*, **6**(2), 127-139.

Carmo, D. L. d., Silva, C. A. (2012) Métodos de quantificação de carbono e matéria orgânica em resíduos orgânicos. *Revista Brasileira de Ciência do Solo*, **36**(4), 1211-1220.

CEMPRE. *Compromisso Empresarial para Reciclagem*. (2017) Acess on Jan. 01, 2021. Available in: http://cempre.org.br/artigo-publicacao/ficha-tecnica/id/10/composto-urbano

Dal Bosco, T. C., Michels, R. N., Bertozzi, J., Taiatele Junior, I., Hashimoto, E. M. (2020) The ideal frequency of temperature data collection in compostability experiments on domestic organic residues. *Environmental Technology*, **41**(9), 1160-1166.

Debiagi, F., Mali, S., Grossmann, M. V. E., Yamashita, F. (2010) Efeito de fibras vegetais nas propriedades de compósitos biodegradáveis de amido de mandioca produzidos via extrusão. *Ciência e Agrotecnologia***, 34**(6), 1522-1529.

Demetrio, L. F. F., Nakagawa, D. H., Pinto, A. L. de S., Presumido, P. H., Bertozzi, J., Michels, R. N., Dal Bosco, T. C., Prates, K. V. M. C. (2016) *Compostagem Em Pequena Escala De Resíduos Sólidos De Restaurante Universitário Associado A Poda De Árvores***.** In: XIII CONGRESSO NACIONAL DE MEIO AMBIENTE DE POÇOS DE CALDAS 2016, Poço de Caldas.

Fernandes, F., Silva, S. M. C. P. (1999) *Manual prático para a compostagem de biossólidos.* Londrina: PROSAB - Programa de Pesquisa em Saneamento Básico.

Flynn A., Torres, L. F., Hart-Cooper W., Mccaffrey, Z., Glenn, G. M., Wood, D. F., Orts, W. J. (2020) *Evaluation of biodegradation of polylactic acid mineral composites in composting conditions*. **137**(32), 48939.

Furlan, L. G., Duarte, U. L., Mauler, R. S. (2012) Avaliação das propriedades de compósitos de polipropileno reforçados com casca de aveia. *Química Nova*, **35**(8), 1499-1501.

Ghinea, C., Apostol, L. C., Prisacaru E., Leahu, A. (2019) Development of a model for food waste composting. *Environmental Science and Pollution Research*, **26**(4), 4056-4069.

IPCC – Intergovernmental Panel on Climate Change. (2006) Guidelines for National Greenhouse Gas Inventories. Available in: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>. Acess on September 15, 2021.

Kale, G., Auras, R., Singh, S. P., Narayan, R. (2007) Biodegradability of polylactide bottles in real and simulated composting conditions*. Polymer Testing*, **26**, 1049-1061, 2007.

Kiehl, E. J. (1985) *Fertilizantes orgânicos*. Piracicaba: Editora Agronômica Ceres Ltda., 1985.

Kiehl, E.J. (2002) *Manual da Compostagem:* Maturação e Qualidade do Composto. 3ªed. Piracicaba, 173p. 2002.

Luo, Y., Zelenika, I., Zhao, J. (2019) Providing immediate feedback improves recycling and composting accuracy. *Journal of Environmental Management*, **232**, 445-454.

Machado, A. R. T., Martins, P. F. Q., Fonseca, E. M. B., Reis, K. C. Compósitos biodegradáveis a base de polihidroxibutirato-hidroxivalerato (PHB-HV) reforçados com resíduos do beneficiamento do café. *Revista Matéria*, **15**(3), 400-404, 2010.

Revista AIDIS de Ingeniería y Ciencias Ambientales:
Investigación, desarrollo y práctica. ISSN 0718-378X
http://dx.doi.org/10.22201/iingen.0718378xe.2022.15.2.79575
Vol. 15, No.2, 773-788
6 de agosto de 2022

Malavolta, E., Vitti, G. C., Oliveira, S. A. (1997) *Avaliação do estado nutricional das plantas: princípios e aplicações*. 2ª ed. Piracicaba: Potafos.

MAPA, Ministério da Agricultura, Pecuária e Abastecimento (2020) Instrução Normativa nº 61, de 8 de julho de 2020. Estabelece as regras sobre definições, exigências, especificações, garantias, tolerâncias, registro, embalagem e rotulagem dos fertilizantes orgânicos e dos biofertilizantes, destinados à agricultura. *Diário Oficial da União República Federativa do Brasil*, Brasília, DF, 8 jul. 2020. Acess on April 24, 2021.

Massukado, L. M. (2008) *Desenvolvimento do processo de compostagem em unidade descentralizada e proposta de software livre para o gerenciamento municipal dos resíduos sólidos domiciliares.* 2008. 204 f. Tese (Doutorado em Ciências da Engenharia Ambiental) - Universidade de São Paulo, São Carlos.

Nunes, M. U. C. (2009) Compostagem de resíduos para produção de adubo orgânico na pequena propriedade. *Embrapa Tabuleiros Costeiros-Circular Técnica (INFOTECA-E)*

Oliveira, E.C.A. de; Sartori, R.H., Garcez, T.B. (2008) *Compostagem*. Disciplina: Matéria Orgânica do Solo (LSO-897) Programa de Pós-Graduação em Solos e Nutrição de Plantas, Escola Superior de Agricultura Luiz de Queiroz, Universidade de São Paulo, Piracicaba, 19 pp.

Orrico Junior, M. A. P., Orrico, A. C. A., Junior, J. de L., Sampaio, A. A. M., Fernandes, A. R. M., de Oliveira, E. A. (2012) Compostagem dos dejetos da bovinocultura de corte: influência do período, do genótipo e da dieta*. R. Bras. Zootec*., Viçosa, **41**(5), 1301-1307. Acess on Dec. 25, 2020. Available in: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1516-35982012000500030&lng=en&nrm=iso

Peixoto, T. S., Yamashita, F., Bilck, A. P., Carvalho, G. M., Grossmann, M. V. E. (2019) Crosslinking starch/oat hull mixtures for use in composites with PLA. *Polímeros: Ciência e Tecnologia*, **29(3)**, e2019040.

Pereira Neto, J. T. (1998) *Lixo urbano no Brasil: descaso, poluição irreversível e mortalidade infantil.* Ação Ambiental, Viçosa, 8-11.

Pereira Neto, J.T. (2007) *Manual de Compostagem: processo de baixo custo*. UFV. Viçosa. 81 pp.

Sbizzaro, M; Dal Bosco, T. C., Prates, K. V. M. C., Presumido, P. H., Pereira, D. C., Sampaio, S. C. (2017) Vermicompostagem de dejeto de ovinos e bovinos com palha de cana-de-açúcar a partir de diferentes relações iniciais de C:N. *Gaia Scientia*, **11**(1)

Shi, B., Palfery, D. (2010) Enhanced Mineralization of PLA Meltblown Materials Due to Plasticization. *Journal of Polymers and the Environment*, **18**(2), 122-127.

Silva, D. L., Paulista, L. O., Presumido, P. H., Bertozzi, J. Yamashita, F., Bilck, A. P., Dal Bosco, T. C. (2020a) Influence of Oat Hulls on Biodegradation of Biopolymer from Polylactic Acid. *U.Porto Journal of Engineering***, 6**(1), 1-10.

Taiatele Junior, I., Dal Bosco, T. C., Bertozzi, J., Michels, R. N., Mali, S. (2020) Biodegradability assessment of starch/glycerol foam and poly (butylene adipate-co-terephthalate)/starch film by respirometric tests. *Brazilian Journal of Food Technology*, **23**.

Tedesco, M. J., Gianello, C., Bissani, C. A., Bohenen, H. Volkweiss, S. J. (1995) *Análises de solo, plantas e outros materiais*. 2ª ed. Porto Alegre: Departamento de Solos da UFRGS.

Tita, S. P. S., Paiva, J. M. F. de; Frollini, E. (2002) Resistência ao impacto e outras propriedades de compósitos lignocelulósicos: matrizes termofixas fenólicas reforçadas com fibras de bagaço de cana-de-açúcar. *Polímeros: Ciência e Tecnologia*, **12**(4), 228-239.

Trautmann, N., Olynciw, E. (2005) Compost Microorganisms – The Phases of Composting. In: *Cornell Composting, Science & Engineering*. Acess on Dec. 25, 2020. Available in: http://compost.css.cornell.edu/microorg.html

Vouyiouka, S. N., Papaspyrides, C. D. (2012) 4.34 - Mechanistic Aspects of Solid-State Polycondensation. *In*: Matyjaszewski, K. e Möller, M. (Ed.) *Polymer Science: A Comprehensive Reference*. Amsterdam: Elsevier, 857-874.