RBCTI
Revista Brasileira de Ciência, Tecnologia e Inovação

DOI: https://doi.org/10.18554/rbcti.v9i1.7000

Research paper

Assessing the degradability of biodegradable-packaging base material through the insertion of organic solid waste deriving from composting process

Avaliação da degradabilidade de material base para embalagens biodegradáveis com a inserção de resíduos sólidos orgânicos a partir do processo de compostagem

Marcos Vinícius da Luz[1]; Carlos Casturino Bueno da Silva Cruz[2]; Juliana Bonametti Olivato[3]; Tatiane Bonametti Veiga[4]

[1]Environmental engineer, State University of the Center-West, Irati, Paraná, Brazil.
Orcid: 0009-0006-7183-512X. E-mail: marcosvinidaluz@gmail.com

[2]Master in Sanitary and Environmental Engineering, State University of the Center-West, Irati, Paraná, Brazil.
Orcid: 0009-0000-0985-3892. E-mail: carlosbuenoambiental@gmail.com

[3]Professor of the Pharmaceutical Sciences and the Food Science and Technology Undergraduate Course, State University of the Ponta Grossa, Ponta Grossa, Paraná, Brazil.
Orcid: 0000-0001-6463-6380. E-mail: jubonametti@gmail.com

[4]Professor of the Environmental Engineering Undergraduate Course, State University of the Center-West, Irati, Paraná, Brazil. Orcid: 0000-0002-6919-4013. E-mail: tatianeveiga@unicentro.br

ABSTRACT: The intensification of the use of plastic materials in recent decades has caused several environmental impacts, becoming direct incentives for research and development of alternatives that minimize the massive amount of plastics used by societies. In this context, so-called biodegradable materials emerge, with emphasis on starch-based compounds, which, although they have limited mechanical properties and low water resistance, allow the mixture with various reinforcing agents, in order to overcome the deficiencies for their application in larger scales without detracting from its focus on biodegradability. In this sense, the present study aimed to evaluate the biodegradability of a starch-based biopolymer, with the addition of different proportions of malt bagasse, this residue from the production process of beer; evaluating and monitoring parameters of the composting process of this mixture with organic solid waste. Biodegradation was determined from the visual assessment of the material, monitoring parameters such as pH, temperature, humidity and organic matter, being recorded in an electronic spreadsheet for descriptive analysis. The results obtained, when compared to the control composting unit, indicate a lower biological activity on the compost, consequently, a greater resistance to biodegradation. After three weeks of composting, it was difficult to identify the material and after four weeks, it was not possible to identify the biopolymer, indicating its biodegradation and incorporation into the substrate. It was observed that the material showed changes in its mechanical properties during composting. It is concluded that the material is totally biodegradable in all malt bagasse compositions, under composting conditions.
Keywords: Composting, biodegradable polymers, solid waste management, waste valorization.

RESUMO: *A intensificação do uso de materiais plásticos, nas últimas décadas, tem ocasionado diversos impactos ambientais, tornando-se incentivos diretos para pesquisa e desenvolvimento de alternativas que minimizem a massiva quantidade de plásticos utilizada pelas sociedades. Neste âmbito, despontam os materiais ditos biodegradáveis, com destaque aos compostos a base de amido, que, embora apresentem propriedades mecânicas limitadas e baixa resistência a água, permitem a mistura com agentes de reforço diversos, a fim de contornar as carências para sua aplicação em maiores escalas sem prejudicar seu foco na biodegradabilidade. Neste sentido, o presente estudo objetivou avaliar a biodegradabilidade de um biopolímero a base de amido, com adição de diferentes proporções de bagaço de malte, este, resíduo oriundo do processo produtivo da cerveja; avaliando e acompanhando parâmetros do processo de compostagem dessa mistura com resíduos sólidos orgânicos. A biodegradação foi determinada a partir da avalição visual do material, sendo monitorados parâmetros como pH, temperatura, umidade e matéria orgânica, sendo registrados em planilha eletrônica para análise descritiva dos dados. Os resultados obtidos, quando comparados a unidade de compostagem controle, indicam uma menor atividade biológica sobre o composto, consequentemente, uma maior resistência a biodegradação. Após três semanas de compostagem foi difícil a identificação do material e após quatro semanas, não era possível a identificação do biopolímero, indicando sua biodegradação e incorporação no substrato. Observou-se que o material apresentou alteração em suas propriedades mecânicas durante a compostagem. Conclui-se que o material é totalmente biodegradável em todas as composições do bagaço de malte, em condições de compostagem.*
Palavras-chave*: Compostagem, polímeros biodegradáveis, gestão de resíduos sólidos, valorização de resíduos.*

Revista Brasileira de Ciência, Tecnologia e Inovação

DOI: https://doi.org/10.18554/rbcti.v9i1.7000

INTRODUCTION

Scientific and economic development has led to significant evolution in human societies, and it enabled exponential population growth and longer life expectancy in the last century, as well as changes in the way people produce and consume resources, goods and services. Solid waste generation has also increased, both in quantity and diversity. More than 2.3 billion tons of municipal solid waste (MSW) are generated on a yearly basis, worldwide; MSW production *per capita* reaches 0.74 kg per person/ day. This amount reaches 81.8 million tons of MSW /year in Brazil, and it corresponds to approximately 3.55% of the global amount of generated MSW, whereas the average *per capita* of these solids is close to 1.04 kg per person/ day, a fact that turns it into a major issue in the modern world (Kaza *et al*., 2018; Abrelpe, 2022).

The implementation of the National Solid Waste Policy (PNRS), which was established by Law n. 12.305 and regulated by Decree n. 10.936 in 2022, was a major step forward in this sector (Brasil, 2010; 2022). PNRS differentiates concepts, such as solid waste management and management, and defines the non-generation, reduction, reuse, recycling and treatment of solid waste, as well as the environmentally appropriate final waste disposal, in order of priority (Brasil, 2010).

Plastic materials account for a significant amount of solid urban waste (MSW) generated by society daily; they are often found in the most diverse forms. Plastics are recyclable materials, but Brazil still does not show appropriate recycling rates; it is the fourth largest plastic waste generator in the world, right after the United States, China and India (Kaza *et al*., 2018).

The massive use of plastic materials in recent decades, in association with overall inadequate solid waste disposal, poses risks both to human health and to the environment because plastics' low degradability and consequent fragmentation intensifies the increasing presence of microplastics in the environment. In addition, bioplastics were recently identified in human blood; this pollutant enters the body through packaged food and contaminated meat intake or even through the inhalation or ingestion of contaminated water. The adversities associated with plastic waste, mainly with single-use plastic waste, can influence both research about, and the development of, more suitable solutions, such as biodegradable materials or biopolymers. Although developing biodegradable polymers remains the target of a growing market, it has been seen as promising alternative to plastic products in recent times, since innovative studies have been conducted in a growing market focused on biodegradable polymers' application in the packaging sector, where starch-based materials play major role in (Oksman; Skrifvars Selin, 2003; Tokiwa *et al*., 2009; Vartiainen; Vähä-Nissi; Harlin, 2014; Valapa; Pugazhenthi; Katiyar, 2016; Olivatto *et al*., 2018; Chollet *et al*., 2019; Sessini *et al*., 2019; Botelho, 2022).

Starch is widely produced by green plant species that use it as the main energy storage form. It is used in its polysaccharide form, which is found at high concentrations in reproductive structures like cereal grains. It has low cost and is easily degraded by the action of microorganisms (Muthuraj; Misra; Mohanty, 2017) when it is heated in water. Moreover, it could form foam in a process known as thermal expansion; the material resulting from this process presents features like those of some plastic types (Mello; Mali, 2014; Engel; Ambrosi; Tessaro, 2019; Ferreira; Molina; Pelissari, 2020).

It is necessary seeking biodegradability, as well as similar mechanical properties, affordable production costs and resistance to external agents, mainly to water, in order to

RBCTI
Revista Brasileira de Ciência, Tecnologia e Inovação
DOI: https://doi.org/10.18554/rbcti.v9i1.7000

use these materials for trading, reducing and, subsequently, replacing non-biodegradable plastic materials (Luz; Cruz; Veiga, 2022).

The simultaneous mixing and processing of biopolymers with different material types, such as reinforcing agents, compatibilizers, plasticizers, non-biodegradable polymers, among other additives, is a technique used to overcome some biopolymers' limitations and to improve their properties. These reinforcing materials comprise sugarcane bagasse, grape bagasse, asparagus peel and malt bagasse (which is one of the main ingredients used to produce beer, which, in its turn, is the world's most widely consumed alcoholic beverage) (Mello; Vergílio; Mali, 2013; Soykeabkaew; Thanomsilp; Suwantong, 2015; Khan *et al*., 2016; Arrieta *et al*., 2017; Bhasney *et al*., 2019; Cruz-Tirado *et al*., 2019; Engel; Ambrosi; Tessaro, 2019; Sessini *et al*., 2019; Ferreira; Molina; Pelissari, 2020; Oliveira; Souza; Magalhães-Guedes, 2022).

Beer makes significant direct and indirect contribution to the economy of many countries. Brazil is among the world's largest beer producers. Beer manufacturing generates large amounts of liquid effluents and solid waste, and it requires the adoption of environmentally appropriate treatment and disposal techniques (Tschope, 2001; Kochenborger, 2012; Mathias; Mello; Servulo, 2014; Barbosa, 2019).

The liquid and solid fractions are separated in the filtering process. Malt cake, which has high moisture, fiber and protein contents, is the main solid waste formed during this process. It is mostly fibrous, proteinaceous and lignocellulosic compound with significant nutritional capacity. Yet, it can be used as food supplement for animals, as energy source through direct burning or biogas production, as adsorbent material and as cell-immobilization support medium (Mussatto; Dragone; Roberto, 2006; Lima, 2010; Aliyu; Bala, 2011; Mello; Vergílio; Mali, 2013).

The simultaneous processing of biopolymers with lignin-based reinforcing agents, such as malt bagasse, can be an interesting alternative to help improving biodegradable polymers' mechanical qualities, as well as reducing their degradation rate. Consequently, it can provide this material with longer lifespan, although treatment techniques, such as composting, can also be used (Kale *et al*., 2007; Iovino *et al*., 2008; Fortunati *et al*., 2014; Yang *et al*., 2015; Valapa; Pugazhenthi; Katiyar, 2016; Kalita *et al*., 2019).

According to the NBR n. 13.591, published by ABNT, composting regards the biological decomposition of organic matter, under controlled conditions including the active degradation and maturation stages (ABNT, 1996). The aerobic degradation of the biodegradable organic matter found in the compost takes place in the composting process due to the action of microorganisms, mainly bacteria, fungi and actinomycetes, which release carbon dioxide and water. The generated product is a stable and sanitary compost used as fertilizer, and it enables the agronomic valorization of solid waste's organic fraction and prolongs the useful life of landfills (Kiehl, 1985; Domínguez; Edwards; Subler, 1997; Campitelli; Velasco; Ceppi, 2012).

Considering the foregoing, the aim of the current study was to assess the efficiency of the composting process applied to base material used to produce biodegradable packaging, based on different malt bagasse concentrations and on the incorporation of organic solid waste.

MATERIALS AND METHODS

Domestic compost bins (Figure 1) were set at Irati Campus, Midwestern State University (UNICENTRO), during the project's experimental stage, to analyze the

Revista Brasileira de Ciência, Tecnologia e Inovação

DOI: https://doi.org/10.18554/rbcti.v9i1.7000

physicochemical parameters of the composting applied to a base material used to produce biodegradable packaging. In order to do so, solid organic waste was incorporated to the investigated material and the parameters of the substrate obtained over a 90-day interval were monitored and recorded. These parameters were obtained from the aerobic process applied to the material inside the compost bins. This process was systematically and intensively carried out to regulate and stabilize the temperature and humidity inside these devices by carrying out daily manual interventions aimed at optimizing the ideal conditions for the aerobic decomposition of the investigated material.

Figure 1. Assembling the compost bins

Analyses were defined based on control parameters of the composting process, in compliance with the Soil Testing Methods Manual (Teixeira *et al*., 2017). The authors of the manual described the parameters necessary to assess the compost resulting from the composting process applied to the organic materials, which are set out in the Paraná Technical Note (Paraná, 2022). However, certain adaptations can be made to techniques and materials, depending on the availability of resources necessary to carry out the analysis.

Organic matter undergoes mineralization process during composting and its amount is reduced as degradation takes place (Kiehl, 1998). The methodology used to determine this parameter consisted in calculating the gravimetric difference between the dry sample (compost exposed to 105ºC, for 24 hours) and the one subjected to incineration in muffle furnace (at 550ºC, for 01 hour) (Teixeira *et al*., 2017). Organic matter was determined through Equation 1.

$$MO\ (\%) = \frac{(Mi - tara) - (Mf - tara)}{(Mi - tara)} x\ 100 \quad (1)$$

Wherein: tare corresponds to the tare weight of the crucible (in grams), Mi corresponds to initial mass –- i.e., the weight of the crucible added to the weight of the sample (in grams) after 24 hours in the oven -, and Mf refers to the final mass, which results from the weight of the crucible added to the weight of the sample (in grams) after 1 hour in the muffle furnace.

In addition, pH measurements were taken once a day based on using a potentiometer equipped with an electrode, which was immersed in the sample/distilled water mix (Teixeira *et al*., 2017). The aerobic composting process increased the pH value. The compost often remained acidic in the first few composting days, but it got close to neutrality as the

Revista Brasileira de Ciência, Tecnologia e Inovação
DOI: https://doi.org/10.18554/rbcti.v9i1.7000

composting stages passed (Kiehl, 1985). The optimum pH range for the final compost should range from 7.5 to 9.0 (Pereira Neto, 2007).

It is important emphasizing that temperature is a relevant parameter in composting processes, since it indicates microbiological activity in the compost and its maturation level. Temperature was checked, once a day, with a thermometer at depth ranging from 10 cm to 20 cm. It is worth highlighting that the optimum temperature during composting should range from 45°C to 65°C (Paraná, 2022).

The gravimetric difference between the mass of the initial sample and that of the sample dried in oven at 105°C, for 24 hours, was used to calculate moisture content (Equation 2). According to Pereira Neto (2007), moisture contents ranging from 40% to 55% are satisfactory for all processes.

$$U(\%) = \frac{(Mi - tara) - (Mf - tara)}{(Mi - tara)} x\ 100 \quad (2)$$

Wherein: tare corresponds to the tare weight of the crucible (in grams), Mi refers to the initial mass – i.e., the weight of the crucible added to the weight of the sample (in grams) -, and Mf corresponds to the final mass, which results from the weight of the crucible added to the weight of the sample (in grams) after 24 hours in the oven.

The biopolymer used in the current study was produced and provided by the Natural Polymers' Development and Application research group, which is linked to the State University of Ponta Grossa. The analyzed biopolymer resulted from three different concentrations of cassava starch (base material) and malt bagasse, which, in its turn, resulted from Pilsen-type beer production (10%, 5% and 0% malt bagasse in the mix).

Both the containers and the location were selected during the preparation stage, namely: commercial compost bin and greenhouse used to store the compost. Most green organic waste, vegetable scraps and peelings were provided by the university's restaurant which is located in the premises of Midwestern State University, Irati-Pr Campus. The rest of it derived from household organic waste that was manually fragmented by following particle size parameters ranging from 10 mm to 50 mm (in diameter), in compliance with the Paraná Technical Note for Municipal Solid Waste Composting (Paraná, 2022).

A control unit was used for comparison purposes, in addition to the composting unit comprising the biopolymer. A control unit was used for comparison purposes. Materials' concentrations were defined based on the composting unit dimensions in order to set up the compost bins. Volumetric measurement was adopted based on using the volume value, rather than the mass, to carry out the calculations. It was done by following the 70% dry organic waste: 30% green organic waste ratio. Moreover, 10% was defined as the biopolymer concentration forming the green organic waste volume to better represent the composting process. Pruning and weeding waste was used for the dry waste, but any microorganism inoculation type was adopted.

According to Brozio and Masek (2020) and to Paraná Technical Note (2022), degradation process efficiency also depends on the target material size, which is the reason why the green organic waste, such as the herein used biopolymer, was properly cut and mixed. The composting process began after the composting units were set up. Findings resulting from the composting units' monitoring process were duly recorded in electronic spreadsheet, in Microsoft® Excel® software, for subsequent descriptive data analysis purposes.

Revista Brasileira de Ciência, Tecnologia e Inovação

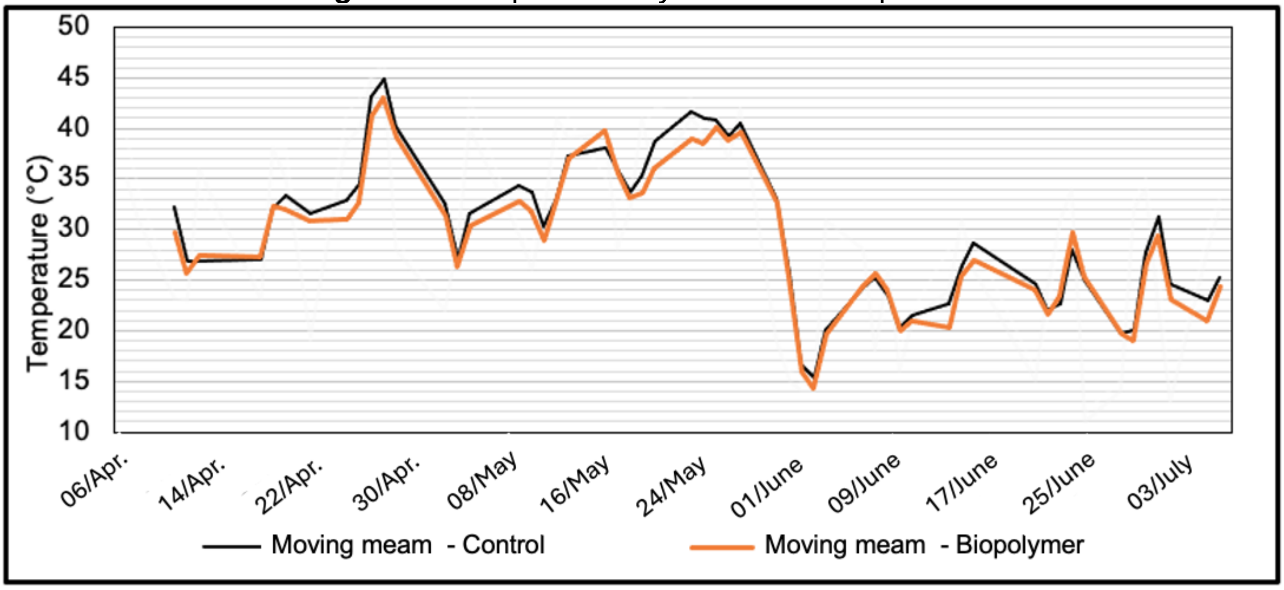
DOI: https://doi.org/10.18554/rbcti.v9i1.7000

RESULTS AND DISCUSSIONS

The composting process was monitored for 90 days, until compost stability was observed as the composting process progressed. The material recorded large volume reduction within approximately 1 month. Furthermore, it tended to form agglomerates in both composting units, as the process progressed, and it required continuously rotating and breaking up the agglomerates to achieve homogeneous substrate biodegradation.

Parameters, such as composting units' temperature, were susceptible to variations in external temperature due to lack of temperature control system in the greenhouse. The period the composting process was carried out in corresponded to fall and winter months, when there were recurrent temperature drops. Although the temperature was mild due to the features of the greenhouse the composting units were located in, it rose fast when there was sunlight. This process resulted in wide temperature range in the composting units, and it may have influenced the microbiological dynamics in them. The moving mean temperature recorded for the last three experimental days was used to better represent the temperature behavior, since the analysis carried out on a daily basis has evidenced high temperature variation over short periods-of-time (Figure 2).

Figure 2. Temperature dynamics in composters



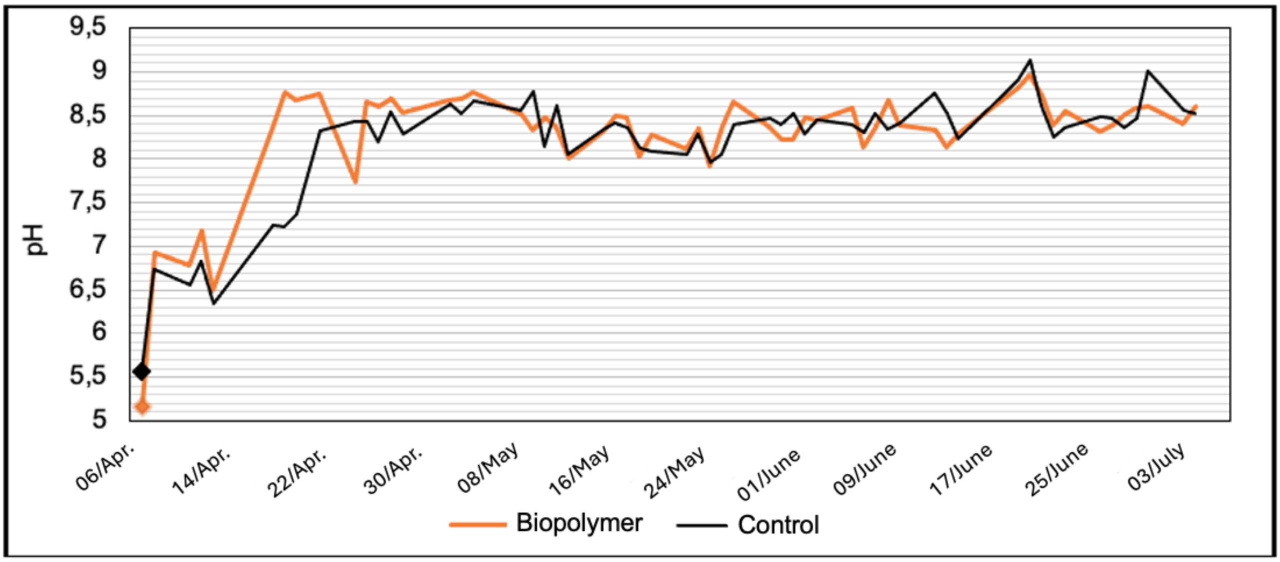
Maximum temperature peaks of 46.5°C and 45°C were recorded for both the control and biopolymer units, respectively – it happened between the 21st and 22nd day of composting. The control unit recorded 31 days with temperature higher than, or equal to, 30°C (34% of the total composting time), whereas the biopolymer unit presented this temperature range for 29 days (32%). Temperature higher than, or equal to, 40°C was recorded for 11 days (12%) in the control unit and for 9 days (10%) in the biopolymer unit. According to parameters defined by the Paraná Technical Note, the ideal temperature at the active degradation stage ranges from 45°C to 65°C (Paraná, 2022). However, it is worth emphasizing that the herein observed values were associated with beds in composting yards, whose larger dimensions enabled higher generated heat retention and higher resistance to external climatic influence. With respect to domestic compost bins, the small

RBCTI
Revista Brasileira de Ciência, Tecnologia e Inovação
DOI: https://doi.org/10.18554/rbcti.v9i1.7000

digester-box size made the process susceptible to temperature variation in the study site (Colón *et al*., 2010).

Moreover, pH, which is a composting-process chemical-behavior indicator referring to hydrogen ions' (H+) activity, was another parameter assessed in the current study. According to Pereira Neto (2004), acidic substrates lead to greater fungal development, which, in its turn, increase pH as fungi consume the organic matter. They also pointed out the ideal pH range for proper microorganisms' development, namely: from 5.5 to 8.0. In addition to the theoretical reference, there was white fungal hyphae development on both substrates in the compost bins, although to a lesser extent in the one holding the biopolymer. The pH, just like the temperature, also showed certain variation in values, as shown in Figure 3.

Figure 3. pH dynamics of compost bins



Based on values observed at the beginning of the composting process, the medium presented acidic pH (5.16 and 5.55 in the control compost bin and in the one holding the biopolymer, respectively) due to organic acids deriving from microbiological activity in the organic matter, which were found in larger amounts in the control compost bin. From the second day of the active composting stage onwards, the medium tended to alkalize, as evidenced by increased pH values, and it lasted until the third experimental week. After this time was over, pH got stabilized at 8.5, on average, until the end of the composting process. According to Jiménez and Garcia (1989) and Lacerda *et al*. (2020), this finding indicates that the compost has matured.

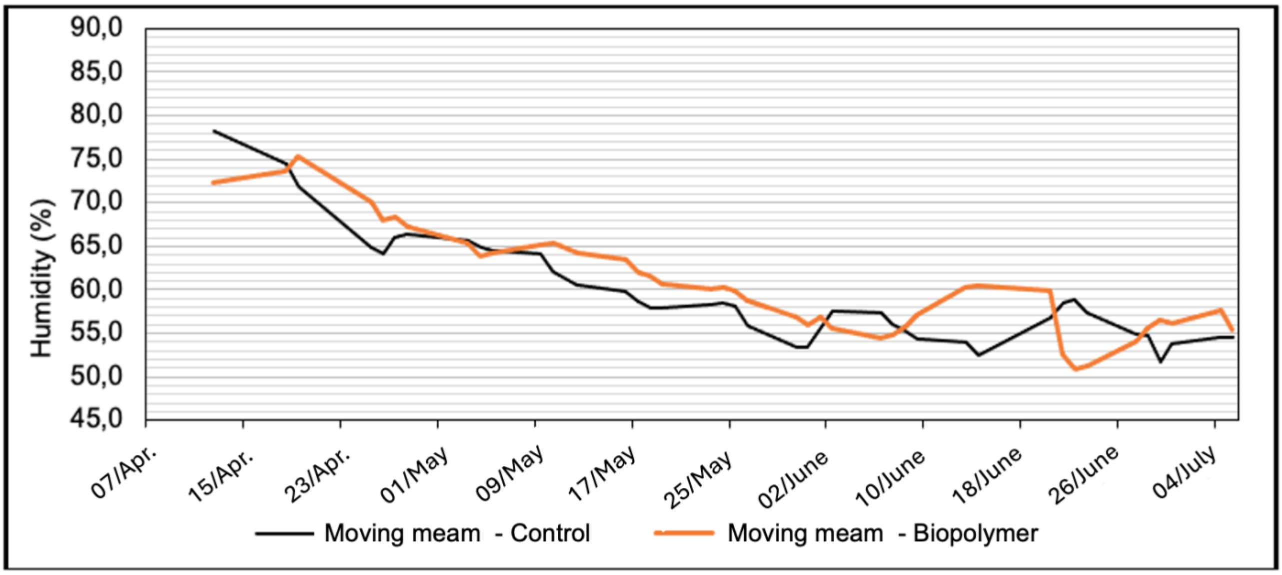
Based on the herein observed pH values, the alkalization process happened faster and was more intense in the biopolymer-free material, since it presented larger amounts of fresh organic waste, which was quickly and easily degraded. This finding pointed out that the biopolymer degradation by microorganisms was more complex.

Humidity was another relevant parameter in the composting process, given its straight influence on microbiological activity; humidity values lower than 20% led to the reduction or likely inhibition of organic matter degradation. It is worth emphasizing that humidity values higher than 60% impair aeration, promote anaerobic zones' formation and lead to unpleasant odors (Bidone; Povinelli, 1999). According to Kiehl (1998), there is higher prevalence of fungi acting in the substrate at humidity levels lower than 40%, as well as

RBCTI
Revista Brasileira de Ciência, Tecnologia e Inovação
DOI: https://doi.org/10.18554/rbcti.v9i1.7000

lower bacterial participation in organic matter degradation processes. The evolution of humidity levels herein observed in the compost bins is shown in Figure 4.

Figure 4. Humidity dynamics in compost bins



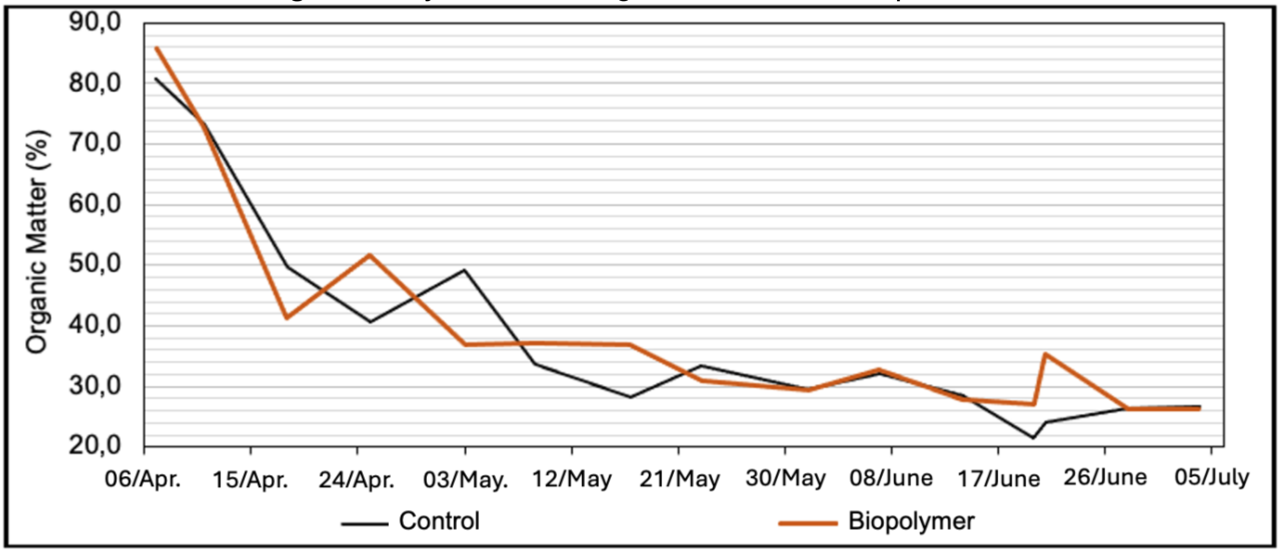
The humidity observed during the composting process presented downward trend, after a brief increase in both composting units at the initial composting days, which reached maximum peak of 85.05% humidity in the control unit and of 84.11% in the unit holding the biopolymer. The units were turned on a daily basis due to high humidity levels at the beginning of the process. Humidity values were close to 55%, on average, at the end of the composting process. The initial moisture content of the unit holding the biopolymer was lower than that of the control unit, 69.58% and 77.55%, respectively, given the features of the investigated material, which presented low moisture content. The mean moving temperature observed for the last three days was used to better represent the behavior of the data.

There was variation in humidity levels and downward trend as the process progressed in both composting units, mainly due to variations in external environment temperature and to interaction with humidity resulting from biodegradation processes, according to which, organic matter is converted into energy, carbon dioxide and water. There was increased humidity variation in the final composting stages. It may have happened due to the formation of regions with irregular substrate concentrations that showed different evaporation rates. These rates resulted in different humidity rates when they were collected for analysis purposes. The resulting moisture content observed for both units was close to 55% at the end of the composting process. This value was similar to the one described in the literature (Pereira Neto, 2007).

The organic matter found in the system was determined as the process progressed. It was done to assess the composting process dynamics. Samples were dried in oven to minimize humidity's influence. The behavior of organic matter values over the composting process is shown in Figure 5.

RBCTI
Revista Brasileira de Ciência, Tecnologia e Inovação
DOI: https://doi.org/10.18554/rbcti.v9i1.7000

Figure 5. Dynamics of organic matter in compost bins



The initial organic matter analysis was carried out 1 day after the beginning of the active composting stage. Results have evidenced microorganisms' action and recorded initial value of 80.85% for the control unit, whereas the unit holding the biopolymer recorded 85.84% within the same period. This finding has evidenced higher organic matter decomposition intensity in the control unit. The last analysis has shown significant organic matter reduction in both units: 26.55% in the control unit and 26.25% in the unit holding biopolymers. This composting process feature shows both the degradation and consumption of the organic matter found in the units, which was converted into biochemical energy, carbon dioxide and water. This behavior was reported in the literature and in other studies conducted in this field (Kiehl, 1998; Fonseca; Barcia; Veiga, 2021).

Malt bagasse addition to the starch-base material aimed at improving material's physical parameters. However, the biopolymer added with malt bagasse at both concentrations (5% and 10%) was mostly affected by contact with the medium, mainly by high humidity rates at the beginning of the tests. Yet, it showed higher disintegration of the material's outer layer. One of the hypotheses explaining this result may be associated with the material's higher roughness and, consequently, with its larger contact area with the medium. On the other hand, the malt bagasse-free material has shown better malleability and elastic behavior after 1-week composting due to its interaction with the medium, but no material detached from the biopolymer surface.

It was hard to identify the biopolymer at all malt bagasse concentrations after 3-week composting. It was no longer possible identifying the target material by the 4th composting week. Waste cohesiveness has also increased as the process went on.

CONCLUSION

Results in the herein proposed analyses have indicated that, although the values observed after the biopolymer was used in the composting processes were slightly divergent, they were similar and shared a common trend with the control composting unit. However, temperature and pH parameters led to lower microbiological activity; consequently, they evidenced higher complexity in the biodegradation of the tested materials. Although the unit holding the biopolymer recorded microbiological activity lower

RBCTI
Revista Brasileira de Ciência, Tecnologia e Inovação
DOI: https://doi.org/10.18554/rbcti.v9i1.7000

than that of the control unit, it was possible seeing the full degradation of the material inserted in the compostable medium.

The current study provided relevant information in compliance with the sustainable development principle set in the National Solid Waste Policy. Furthermore, all municipalities should include techniques focused on promoting composting at household and municipal levels in their Municipal Integrated Solid Waste Management Plans in order to boost waste recovery, since most of the waste generated by residents is organic and most of it is discarded along with biopolymers for municipal waste collection purposes.

Finally, although results presented in the current study have led to some reflections, the determination of material's mechanical features during the composting process, as well as the biological degradation effect on different compositions, have suggested that further in-depth studies about this dynamic should be carried out. The analysis applied to mechanical properties and biological degradation in composting process, from the holistic and integrated waste management perspective, heads towards the pursuit of sustainability and drives global efforts to build a more balanced and healthy future.

ACKNOWLEDGEMENT

The authors are grateful to Araucária Foundation for both the financial support and the grant provided to this research.

REFERENCES

ABRELPE - Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais. **Panorama dos resíduos sólidos no Brasil 2021/2022.** São Paulo, 2022.

ALIYU, S.; BALA, M. Brewer's spent grain: a review of its potentials and applications. **African Journal Of Biotechnology**, v. 10, n. 3, p. 324-331, 2011. DOI: https://doi.org/10.5897/AJBx10.006

ARRIETA, M.; SAMPER, M.; ALDAS, M.; LÓPEZ, J. On the Use of PLA-PHB Blends for Sustainable Food Packaging Applications. **Materials**, v. 10, n. 9, p. 1008, 2017. DOI: https://doi.org/10.3390/ma10091008

ABNT – Associação Brasileira de Normas Técnicas. **NBR 13.591**: **Compostagem - Terminologia**. Rio de Janeiro: ABNT, 1996.

BARBOSA, L. A. A. **Caracterização e análise do processo de tratamento de efluente de cervejaria para potencial reúso - comparação entre uma indústria de grande porte e uma cervejaria artesanal**. 2019. 81 f. Trabalho de Conclusão de Curso (Graduação em Engenharia Ambiental e Sanitária) – Centro Federal de Educação Tecnológica de Minas Gerais, Belo Horizonte, MG, 2019.

BHASNEY, S. M.; BHAGABATI, P.; KUMAR, A.; KATIYAR, V. Morphology and crystalline characteristics of polylactic acid [PLA]/linear low density polyethylene [LLDPE]/microcrystalline cellulose [MCC] fiber composite. **Composites Science And Technology**, v. 171, n. 1, p. 54-61, 2019. DOI: https://doi.org/10.1016/j.compscitech.2018.11.028

BIDONE, F. R. A.; POVINELLI, J. **Conceitos básicos de resíduos sólidos**. São Carlos: EESC/USP, 1999.

RBCTI
Revista Brasileira de Ciência, Tecnologia e Inovação
DOI: https://doi.org/10.18554/rbcti.v9i1.7000

BOTELHO, V. **Microplásticos da poluição podem contaminar o sangue por meio da alimentação e respiração**. Jornal da USP, 2022. Available at: https://jornal.usp.br/atualidades/microplasticos-da-poluicao-podem-contami-nar-o-sangue-por-meio-da-alimentacao-e-respiracao/. Access on: 22 May 2024.

BRASIL. Lei n. 12.305, de 02 de agosto de 2010. Institui a Política Nacional de Resíduos Sólidos. **Diário Oficial da União**: seção 1, Brasília, DF, p. 3, 03 ago. 2010.

BRASIL. Decreto n. 10.936, de 12 de janeiro de 2022. Regulamenta a Lei n. 12.305, que institui a Política Nacional de Resíduos Sólidos. **Diário Oficial da União**: seção 1, Brasília, DF, p. 2, 12 jan. 2022.

BROZIO, M. L.; MASEK, A. The Effect of Natural Additives on the Composting Properties of Aliphatic Polyesters. **Polymers**, v. 12, n. 9, p. 1856, 2020. DOI: https://doi.org/10.3390/polym12091856

CAMPITELLI, P.; VELASCO, M.; CEPPI, S. Characterization of humic acids derived from rabbit manure treated by composting-vermicomposting process. **Journal of Soil Science and Plant Nutrition**, v.12, n.4, p. 875-891, 2012. DOI: https://doi.org/10.4067/S0718-95162012005000039

CHOLLET, B.; CUESTA, J. M. L.; LAOUTID, F.; FERRY, L. Lignin Nanoparticles as A Promising Way for Enhancing Lignin Flame Retardant Effect in Polylactide. **Materials**, v. 12, n. 13, p. 2132, 2019. DOI: https://doi.org/10.3390%2Fma12132132

COLÓN, J; MARTÍNEZ-BLANCO, J; GABARRELL, X; ARTOLA, A; SÁNCHEZ, A; RIERADEVALL, J. *et al*. Environmental assessment of home composting, **Resources, Conservation and Recycling**, v. 54, n.11, p. 893-904, 2010. DOI: https://doi.org/10.1016/j.resconrec.2010.01.008 .

CRUZ-TIRADO, J. P.; VEJARANO, R.; TAPIA-BLÁCIDO, D. R.; ANGELATS-SILVA, L. M.; SICHE, R. The addition of sugarcane bagasse and asparagus peel enhances the properties of sweet potato starch foams. **Packaging Technology and Science,** v. 32, n. 5, p. 227-237, 2019. DOI: https://doi.org/10.1002/pts.2429

DOMÍNGUEZ, J.; EDWARDS, C.A.; SUBLER, S. A comparison of composting and vermicomposting. **Biocycle**, v.38, n.4, p.57-59, 1997.

ENGEL, J. B.; AMBROSI, A.; TESSARO, I. C. Development of biodegradable starch-based foams incorporated with grape stalks for food packaging. **Carbohydrate Polymers**, v. 225, n.1, p. 115234, 2019. DOI: https://doi.org/j.carbpol.2019.115234 .

FERREIRA, D. C. M.; MOLINA, G.; PELISSARI, F. M. Biodegradable trays based on cassava starch blended with agroindustrial residues. **Composites Part B: Engineering**, v. 183, p. 107682, 2020. DOI: https://doi.org/10.1016/j.compositesb.2019.107682 .

FONSECA, S.; BARCIA, M. K.; VEIGA, T. B. Avaliação dos parâmetros de processos de compostagem/ vermicompostagem para resíduos orgânicos com inserção de embalagens oxibiodegradáveis. **Revista Científica ANAP Brasil**, v. 14, n. 35, 2021. DOI: https://doi.org/10.17271/19843240143520212929

FORTUNATI, E.; RINALDI, S.; PELTZER, M.; BLOISE, N.; VISAI, L.; ARMENTANO, I. *et al.* Nano-biocomposite films with modified cellulose nanocrystals and synthesized silver nanoparticles. **Carbohydrate Polymers**, v. 101, n. 1, p. 1122-1133, 2014. DOI : https://doi.org/10.1016/j.carbpol.2013.10.055

RBCTI
Revista Brasileira de Ciência, Tecnologia e Inovação
DOI: https://doi.org/10.18554/rbcti.v9i1.7000

IOVINO, R.; ZULLO, R.; RAO, M. A.; CASSAR, L.; GIANFREDA, L. Biodegradation of poly(lactic acid)/starch/coir biocomposites under controlled composting conditions. **Polymer Degradation And Stability**, v. 93, n. 1, p. 147-157, 2008. DOI: https://doi.org/10.1016/j.polymdegradstab.2007.10.011

JIMÉNEZ, E. I.; GARCIA, V. P. Evaluation of city refuse compost maturity: a review. **Biological Wastes**, v. 27, n. 2, p. 115-142, 1989. DOI: https://doi.org/10.1016/0269-7483(89)90039-6.

KALE, G.; AURAS, R.; SINGH, S. P.; NARAYAN, R. Biodegradability of polylactide bottles in real and simulated composting conditions. **Polymer Testing**, v. 26, n. 8, p. 1049-1061, 2007. DOI : https://doi.org/10.1016/j.polymertesting.2007.07.006

KALITA, N. K.; NAGAR, M. K.; MUDENUR, C.; KALAMDHAD, A.; KATIYAR, V. Biodegradation of modified Poly(lactic acid) based biocomposite films under thermophilic composting conditions. **Polymer Testing**, v. 76, n. 1, p. 522-536, 2019. DOI: https://doi.org/10.1016/j.polymertesting.2019.02.021

KAZA, S.; YAO, L.; BHADA-TATA, P.; WOERDEN, V. F. **What a Waste 2.0**: A Global Snapshot of Solid Waste Management to 2050. Washington: World Bank, 2018. Available at: https://openknowledge.worldbank.org/handle/10986/30317. Access on: 05 Aug. 2022.

KHAN, B.; NIAZI, M. B. K.; SAMIN, G.; JAHAN, Z. Thermoplastic Starch: a possible biodegradable food packaging material-a review. **Journal Of Food Process Engineering**, v. 40, n. 3, p. 12447-12447, 2016. DOI : https://doi.org/10.1111/jfpe.12447

KIEHL, E.J. **Fertilizantes orgânicos**. Piracicaba: Editora Agronômica Ceres, 1985.

KIEHL, E.J. **Manual da Compostagem:** Maturação e Qualidade do Composto. 4. ed. Piracicaba: Escola Superior de Agricultura Luiz de Queiroz, 1998.

KOCHENBORGER, G. **Tratamento físico-quimico para efluente de cervejaria**. 2012. 41 f. Trabalho de Conclusão de Curso (Graduação em Engenharia Ambiental) – Universidade de Passo Fundo, Passo Fundo, RS, 2012.

LACERDA, K. A. P.; MORAES, J. V. Q.; SILVA, Y. G.; OLIVEIRA, S. L. Compostagem: alternativa de aproveitamento dos resíduos sólidos utilizando diferentes modelos de composteiras. **Brazilian Journal Of Development**, v. 6, n. 6, p. 40753-40763, 2020. DOI: https://doi.org/10.34117/bjdv6n6-567

LIMA, U. A. **Matérias-primas dos Alimentos**. São Paulo: Blücher, 2010. 402 p.

LUZ, M. V; CRUZ, C. C. B; VEIGA, T. B. Identificação e avaliação de fatores determinantes do processo de compostagem de materiais biodegradáveis: uma revisão sistemática. **Revista Científica ANAP Brasil**, v. 15, n. 36, 2022. DOI: https://doi.org/10.17271/19843240153620223364

MATHIAS, T. R. S.; MELLO, P. P. M.; SERVULO, E. F. C. Caracterização de resíduos cervejeiros. *In*: **XX Congresso Brasileiro De Engenharia Química**. Florianópolis, Santa Catarina, 2014.

MELLO, L. R. P. F.; MALI, S. Use of malt bagasse to produce biodegradable baked foams made from cassava starch. **Industrial Crops and Products**, v. 55, p. 187–193, 2014. DOI: https://doi.org/10.1016/j.indcrop.2014.02.015

RBCTI
Revista Brasileira de Ciência, Tecnologia e Inovação
DOI: https://doi.org/10.18554/rbcti.v9i1.7000

MELLO, L. R. P. F.; VERGÍLIO, R. M.; MALI, S. Caracterização Química e Funcional do Resíduo Fibroso da Indústria Cervejeira. **Biochemistry and Biotechnology Reports**, v. 2, n. esp (2013): Anais do III Simpósio de Bioquímica e Biotecnologia 2013, p. 191-194, 2013. DOI: https://doi.org/10.5433/2316-5200.2013v2n3espp191

MUSSATTO, S.I.; DRAGONE, G.; ROBERTO, I.C. Brewers' spent grain: generation, characteristics and potential applications. **Journal Of Cereal Science,** v. 43, n. 1, p. 1-14, 2006. DOI: https://doi.org/10.1016/j.jcs.2005.06.001

MUTHURAJ, R.; MISRA, M.; MOHANTY, A. K. Biodegradable compatibilized polymer blends for packaging applications: a literature review. **Journal of Applied Polymer Science**, v. 135, n. 24, p. 45726, 2017. DOI: https://doi.org/10.1002/app.45726

OKSMAN, K.; SKRIFVARS, M.; SELIN, J. F. Natural fibres as reinforcement in polylactic acid (PLA) composites. **Composites Science and Technology**, v. 63, n. 9, p. 1317–1324, 2003. DOI: https://doi.org/10.1016/S0266-3538(03)00103-9

OLIVATTO, G. P.; CARREIRA, R.; TORNISIELO, V. L.; MONTAGNER, C. C. Microplásticos: Contaminantes de Preocupação Global no Antropoceno. **Revista Virtual de Química**, v. 10, n. 6, p. 1968-1989, 2018. DOI: https://doi.org/10.21577/1984-6835.20180125

OLIVEIRA, C. R.; SOUZA, C. O.; MAGALHÃES-GUEDES, K. T. Compostos antioxidante presentes na cerveja e sua relação com a saúde humana. *In:* CORDEIRO, C. A. M.; EVANGELISTA-BARRETO, N. S.; SANCHES, A. G. (org.). **Ciência e tecnologia de alimentos**: o avanço da ciência no Brasil. Guarujá-SP: Científica Digital, 2022. cap. 6, p 70-85.

PARANÁ (Estado). Ministério Público do Estado do Paraná. Centro de Apoio Operacional às Promotorias de Proteção ao Meio Ambiente. **Nota Técnica**: Compostagem de Resíduos Sólidos Urbanos. Available at: https://www.mpma.mp.br/arquivos/ESMP/Nota_Tecnica_-_Compostagem.pdf. Access on: 05 Aug. 2022.

PEREIRA NETO, J. T. Compostagem: Fundamentos e métodos. *In:* **I Simpósio sobre compostagem**: ciência e tecnologia. Botucatu, São Paulo, 2004.

PEREIRA NETO, J. T. **Manual de Compostagem**: processo de baixo custo. Viçosa: UFV, 2007.

SESSINI, V.; ARRIETA, M. P.; RAQUEZ, J. M.; DUBOIS, P.; KENNY, J. M.; PEPONI, L. Thermal and composting degradation of EVA/Thermoplastic starch blends and their nanocomposites. **Polymer Degradation And Stability**, v. 159, p. 184-198, 2019. DOI: https://doi.org/10.1016/j.polymdegradstab.2018.11.025

SOYKEABKAEW, N.; THANOMSILP, C.; SUWANTONG, O. A review: Starch-based composite foams. **Composites Part A: Applied Science and Manufacturing**, v. 78, p. 246-263, 2015. DOI: https://doi.org/10.1016/j.compositesa.2015.08.014

TEIXEIRA, P. C. DONAGEMMA, G. K.; FONTANA, A.; TEIXEIRA, W. G. **Manual de Métodos de Análise de Solo**. 3. ed. Brasília, DF: Embrapa, 2017.

TOKIWA, Y.; CALABIA, B.; UGWU, C.; AIBA, S. Biodegradability of Plastics. **International Journal Of Molecular Sciences**, v. 10, n. 9, p. 3722-3742, 2009. DOI: https://doi.org/10.3390/ijms10093722

Revista Brasileira de Ciência, Tecnologia e Inovação

DOI: https://doi.org/10.18554/rbcti.v9i1.7000

TSCHOPE, E. C. **Microcervejarias e cervejarias**: a história, a arte e a tecnologia. São Paulo: Aden, 2001.

VALAPA, R.; PUGAZHENTHI, G.; KATIYAR, V. Hydrolytic degradation behaviour of sucrose palmitate reinforced poly (lactic acid) nanocomposites. **International Journal of Biological Macromolecules**, v. 89, p. 70–80, 2016. DOI: https://doi.org/10.1016/j.ijbiomac.2016.04.040

VARTIAINEN, J.; VÄHÄ-NISSI, M.; HARLIN, A. Biopolymer Films and Coatings in Packaging Applications - A Review of Recent Developments. **Materials Sciences and Applications**, v. 05, n. 10, p. 708–718, 2014. DOI: http://dx.doi.org/10.4236/msa.2014.510072

YANG, W.; FORTUNATI, E.; DOMINICI, F.; KENNY, J. M.; PUGLIA, D. Effect of processing conditions and lignin content on thermal, mechanical and degradative behavior of lignin nanoparticles/polylactic (acid) bionanocomposites prepared by melt extrusion and solvent casting. **European Polymer Journal**, v. 71, n. 1, p. 126-139, 2015. DOI: https://doi.org/10.1016/j.eurpolymj.2015.07.051

Received on: 2023/09/14
Approved on: 2024/05/17