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3D-printed polylactic acid biopolymer and textile fibers: comparing the degradation process

Biopolímero ácido polilático impresso em 3D e fibras têxteis: um comparativo do processo de degradação

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ABSTRACT

With the advancement of sustainable actions in the textile industry, biodegradable polymers are considered a potential solution to environmental problems generated by plastic waste. In particular, renewable polyesters, such as polylactic acid (PLA), are the most promising bioresorbable materials for application in consumer areas, such as the textile industry, which is one of the largest segments responsible for waste generation. Based on these considerations, the objective was to investigate the degradability of 3D-printed PLA biopolymer, compared to the degradability of natural and synthetic textile fibers (cotton and polyester). The comparison was carried out with samples of materials degraded in soil and exposed to the weather for 120 days. Significant results were obtained for mass loss, as follows: 13.4% PLA; 8.9% cotton/flat, and 3.84% polyester/flat. As for the loss of area, the results were 46.5% for PLA; 15.4% for cotton/knit; and 6.25% for polyester/knit. The composition of the analyzed materials is one of the factors that can determine the period of degradation, since natural fiber fabrics present faster decomposition due to the presence of microorganisms. Another point to highlight is the material construction, as the knitted fabric is more unstable compared to flat fabric, its bonds tend to break more easily resulting in a different degradation process for flat, knit, and non-woven materials.

Keywords: degradability; additive manufacturing; fabric.

RESUMO

Com o avanço de ações sustentáveis na indústria têxtil, os polímeros biodegradáveis são vistos como potencial solução para os problemas ambientais gerados por resíduos plásticos. Os poliésteres renováveis como o ácido polilático (PLA), particularmente, constituem os materiais bioreabsorvíveis mais promissores para aplicações nas áreas de consumo, como a indústria têxtil, um dos maiores segmentos responsáveis pela geração de resíduos. Com base nessas considerações, objetivou-se investigar a degradabilidade do biopolímero PLA impresso em 3D, comparado à degradabilidade das fibras têxteis naturais e sintéticas (algodão e poliéster). O comparativo foi realizado por meio de amostras dos materiais degradadas em solo e expostas às intempéries por 120 dias. Foram obtidos resultados significativos para a perda de massa, sendo: 13,4% PLA; 8,9% algodão/plano e 3,84% poliéster/plano. Já para a perda de área se obtiveram 46,5% PLA; 15,4% algodão/malha e 6,25% poliéster (malha). Observou-se que a composição dos materiais analisados é um dos fatores que pode determinar o período de degradação, pois os tecidos com fibras têxteis oriundas de fontes naturais apresentam decomposição mais rápida em razão da presença de microrganismos. Outro ponto a destacar é a construção dos materiais: observou-se que pelo fato de a malha ser mais instável comparada ao tecido plano, suas ligações tendem a se romper com mais facilidade, resultando em um processo de degradação diferente para os materiais plano, malha e não tecido.

Palavras-chave: degradabilidade; manufatura aditiva; tecido.

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Introduction

In the current scenario, the search for sustainable development in the textile sector has become possible in terms of the environmental value added to the products, which includes the raw materials used in the manufacturing process to create actions and materials that contribute to this process, involving discussions that permeate the entire textile chain, mainly the manufacture of fabrics (Niinimäki, 2015).

According to Fletcher and Grose (2011), given the exploitation of material from petrochemical fibers in the clothing sector, one of the starting points for sustainable innovation in fashion is the substitution of raw materials, aiming to bring benefits to the environment, and economic contribution to the sector, increasing the sales volume.

The raw material most used in clothing is associated with impacts on the sustainability of fashion, "climate change; adverse effects on water and its cycles; chemical pollution; loss of biodiversity; excessive or inappropriate use of non-renewable resources; waste generation; negative effects on human health; and harmful social effects for producing communities" (Fletcher and Grose, 2011, p. 12).

Although new textile fibers appear that will compose new products, all of them, in some way, end up affecting ecological and social systems, but these impacts differ from one fiber to another in terms of the type and scale at which it will be applied in productions.

Krosofsky (2021) states that the degradation of biodegradable fabrics refers to those with easy decomposition and natural occurrence due to the presence of microorganisms. In this sense, the biodegradability of fabrics is directly proportional to the content of chemical products present in them. Thus, one of the ways to minimize damage to the environment is the use of biodegradable raw materials.

As fabrics considered non-biodegradable are composed of synthetic and petroleum-derived raw materials, from the production process to the disposal of the material, toxic substances will be released into the environment, polluting the air, water and soil, in addition to microplastics present in the ocean, given the slow decomposition (Fletcher and Grose, 2011).

Therefore, Armstrong et al. (2015) points out that initiatives for the production of sustainable materials in the textile industry have contributed to technological development, as a way of providing new perspectives to the fashion industry, through more efficient production techniques and raw materials.

Therefore, interest in issues associated with waste generation and opportunities has led "to the development of a new type of biodegradable polyester fiber (sometimes called a biopolymer) that includes fibers made from PLA. PLA fibers are made from sugars derived from crops, usually corn, by a rotational molding process, similar to conventional petroleum-derived polyester" (Fletcher and Grose, 2011, p. 17). Fibers from PLA are renewable and biodegradable but only decompose under conditions provided by an industrial composting station (Fletcher and Grose, 2011).

Therefore, in addition to the use of new fibers, the emphasis on technological development and the gradual adoption of emerging technologies in the production system, such as the insertion of new means of manufacturing, in which 3D printing has been increasingly present in the manufacturing of clothing textiles, it is necessary to develop studies about the degradation process of these new textiles used in the clothing industry, being them, the 3D-printed non-woven using PLA filaments in flexible and rigid forms, compared to the degradation of fabrics composed of natural and synthetic fibers.

The 3D-printed non-woven, as it is known by the textile industry, is built by flat, flexible, and porous structures, from the direct accumulation of layers of fibers or textile filaments, in the form of a veil or mesh. Its formation is done in bonded layers of the material, forming a combination of fibers, through mechanical, chemical, and thermal processes (Kuhn and Minuzzi, 2015).

Due to this, according to Kim et al. (2019), 3D printing changes the configuration of the textile material that is known until then - the weaving of the yarn into the warp and weft. In this new textile construction, the fabric is obtained by joining the geometries with flexible connectors that result in the repetition of the pattern and fabric formation (Kim et al., 2019).

In this sense, for Perry (2018), 3D textile printing has been a sustainable alternative due to the raw material and its transformation process into the fabric, when compared to the use of textiles made of natural and synthetic fibers that encompass different manufacturing sectors, from the cultivation of fibers to the product, the fabric.

Thermoplastics include polymers and resins that can be used in liquid, solid, gaseous, or powder form, as well as other materials made from natural and synthetic fibers, which include cotton, nylon polymers, and leather. These are due to advances that have required the introduction of textile fibers in the manufacture of 3D-printed products (Vanderploeg et al., 2017).

In view of the foregoing, 3D printing is a means of contributing to reducing the environmental impact of the textile industry due to the manufacture of biodegradable raw materials, such as non-woven printed in PLA biopolymer, which follows a shorter life cycle model, compared to printing with other polymers (Yap and Yeong, 2014).

Among the biopolymers, the most used in 3D printing is poly (lactic acid) (PLA), one of the most commercially produced biopolymers, accounting for 25% of global production. In addition, it contains properties similar to common polymers but offers additional benefits, such as organic recycling and reduced decomposition time (Besko et al., 2017).

Furthermore, according to Vanderploeg et al. (2017), PLA can be degraded under various environmental conditions, such as natural environments in soil, water, and composting conditions, biotically or abiotically. The degradation process of polymeric surfaces results from interfacial interactions with microorganisms and depends on factors, such as hydrophobicity, moisture, and nutrients, so that microorganisms adhere, colonize and form biofilms on the material. As a result, fungal hyphae penetrate the material and cause a decrease in its mechanical stability (Dambrós et al., 2014).

In line with the perspective of advances in technological and sustainable growth in the textile industry, such actions are aimed at the adoption of the 17 Sustainable Development Goals (SDGs), based on their three dimensions, economic, social, and environmental, which aim to stimulate actions in the main areas of importance for the survival of humanity and the planet (ONU, 2015).

Sustainability standards allied to the SDGs emerge as an alternative for regulation and the search for more conscious practices, guided by SDG 9, which operates in the industry, innovation, and infrastructure, and SDG 12 with a focus on responsible consumption and production, both focused on actions encompassing the raw materials sector (Salcedo, 2014).

In this sense, this study aimed to monitor the degradation process of textiles used in the clothing industry, namely, 3D-printed non-woven using flexible and rigid PLA filaments, compared to the degradation of natural and synthetic fabrics. Thus, collaborating with the reduction of waste generated during the textile manufacturing process, promoting non-woven printed with degradable biopolymer, as a sustainable alternative for the production of textile fabric.

Material and Methods

For the research development, a practical experiment was carried out to test the degradation process of non-woven samples printed in PLA and natural and synthetic fiber fabrics to make a comparison of the data obtained. Figure 1 presents the methodological procedure for this research.

Sample collection and preparation

In the development of the research, three distinct geometries were defined for degradability tests, and each geometry was printed in duplicate (Chart 1).

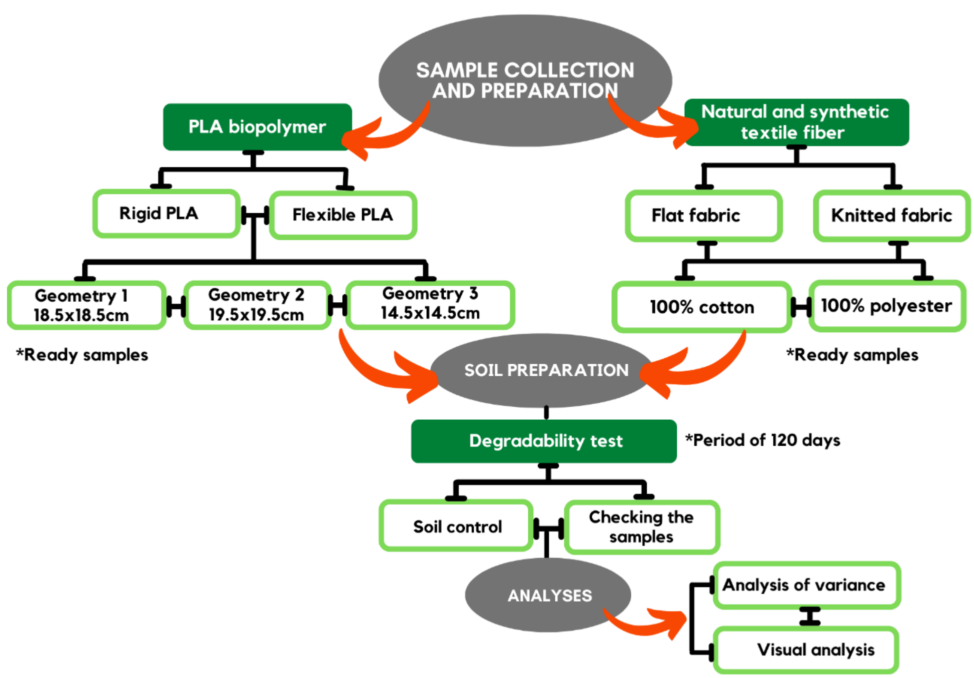

Figure 1 – Flowchart of the methodology used for degradation of flexible and rigid PLA biopolymer samples, natural and synthetic fiber fabrics.

Chart 1 – Parameters used for printing triangular, square and floral samples3D printing of PLA biopolymer.

Geometry	Platform	Print time (hours)	Type	PLA/1.75mm	Size
1 - Triangular	Thingiverse	8	Textile knit	Rigid/flexible	18.5 × 18.5 cm
2 - Square	Thingiverse	8	Textile knit		19.5 × 19.5 cm
3 - Floral	Myminifactory	1h33min	Lace		14.5 × 14.5 cm

Complementary to Chart 1, Figure 2 illustrates the geometries of the 3D-printed samples used for degradability analysis. The definition of the geometries was carried out considering the availability of files in stl format with the geometry already built for downloads on digital platforms, such as Thingiverse, since the focus of the study is the analysis of the degradability of the material (printed fabric).

The printing of the group of samples was performed on a Createbot Mini (FDM) printer, at 210°C, for an estimated 35 hours of printing, using an *stl file and 500g filament for printing each sample. They also worked with samples of fabrics made of natural and synthetic fibers, in a flat and knit structure (Chart 2).

For fabrics with natural and synthetic fibers, 50 cm samples of each material were obtained from the local market. Each sample was cut in straight wire measuring 10 × 10 cm, with the aid of scissors, and weighed on a precision scale, model BL320H.

Samples were recorded with a cell phone camera, on a flat surface in an illuminated environment. Samples were labeled with nylon thread, containing their composition and structure, in the numerical sequence from 1 to 3 in the respective samples.

Soil preparation

A mixture of two types of soil was prepared, red latosol and vegetal soil, to obtain soil properties close to the real ones.

The plastic containers were purchased at the local market, with measures of 49.5 cm × 18.5 cm × 16.7 cm and a capacity of 9 L. They were labeled in sequence from 1 to 10, to allow sample identification.

Each container received 5 kg soil, 50% of which was red latosol, taken from the garden of an educational institution in the Northwest of the state of Paraná with coordinates latitude 23º -23’43” S, longitude 51º -51’91” W; and 50% of vegetal soil acquired in an agricultural shop. For soil homogenization, both were passed through a sand sieve and added to the containers, they had no contact with the soil, and were exposed to the weather.

Degradability test

Samples were buried in the soil mixture for 120 days (Figure 3), identified with labels in numerical order, and separated according to their structure and composition.

Soil control

During the test period (120 days), the soil was analyzed weekly for pH through a sample of 10 g soil, stored in a glass beaker, dispersed in 200 mL distilled water, and homogenized by stirring in Fisaton shakers, Model 752A Series 221794 (Figure 4A). Afterward, the pH was measured with the aid of indicator paper, on Merck slides, immersed in the solution for 30 s, and compared with the color available in the box.

Chart 2 – Parameters used for fabrics made of natural and synthetic fibers such as tricoline, oxfordine, comfort knit, and helanca.

Triplicate samples (natural and synthetic fiber fabrics)			
Structure	Composition	Size	Description
Flat	100% Algodão	10 × 10 cm	Tricoline
	100% Poliéster		Oxfordine
Knit	100% Algodão		Comfort knit
	100% Poliéster		Helanca

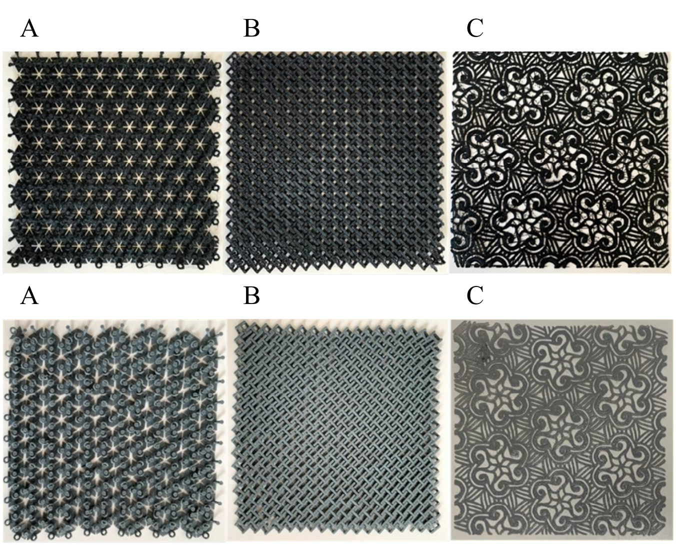

Figure 2 – Samples of 3D-printed PLA biopolymer on flexible and rigid material, respectively: (A) Geometry 1; (B) Geometry 2; (C) Geometry 3

Figure 3 – Containers used for burying PLA biopolymer samples and natural and synthetic textile fibers.

Moisture was controlled by means of the weight of the soil + container, in which, on day 0 of the experiment, they were individually weighed without the samples, to periodically check the weight. When the soil lost water by evaporation, rainwater was added to the container until it could return to its initial weight (5 kg) (Figure 4B).

Checking the samples

During the tests, samples were photographed, weighed, and measured at intervals of 30, 60, 90, and 120 days. Samples were taken from the soil, washed in running water, and dried in the sun. Then, photographs were taken with a cell phone camera (Figure 5A), the measurements were taken with the aid of a ruler and then weighed on a Shimadzu, BL320H precision scale (Figure 5B).

From the data obtained during the experiment, sample degradation was obtained in terms of loss of mass and area by experimental design. A randomized design resulting from the composition of samples was used, being 100% cotton and 100% polyester (flat and knitted), flexible and rigid PLA biopolymer printed in 3D (geometries from 1 to 3).

For the Analysis of Variance, the Statistica 12 software was used, to identify differences in the process of mass and area degradation of the 10 treatments, according to Tukey's test at a level of 5%.

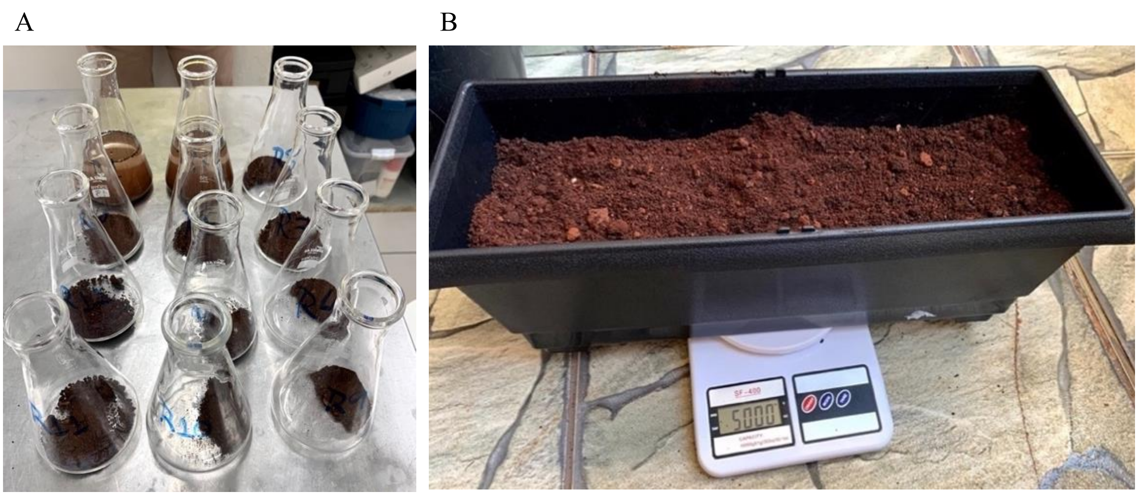

Figure 4 – (A) Preparation of soil samples present in the containers for analysis and pH control; (B) Control of the weight of the soil used for burying the samples.

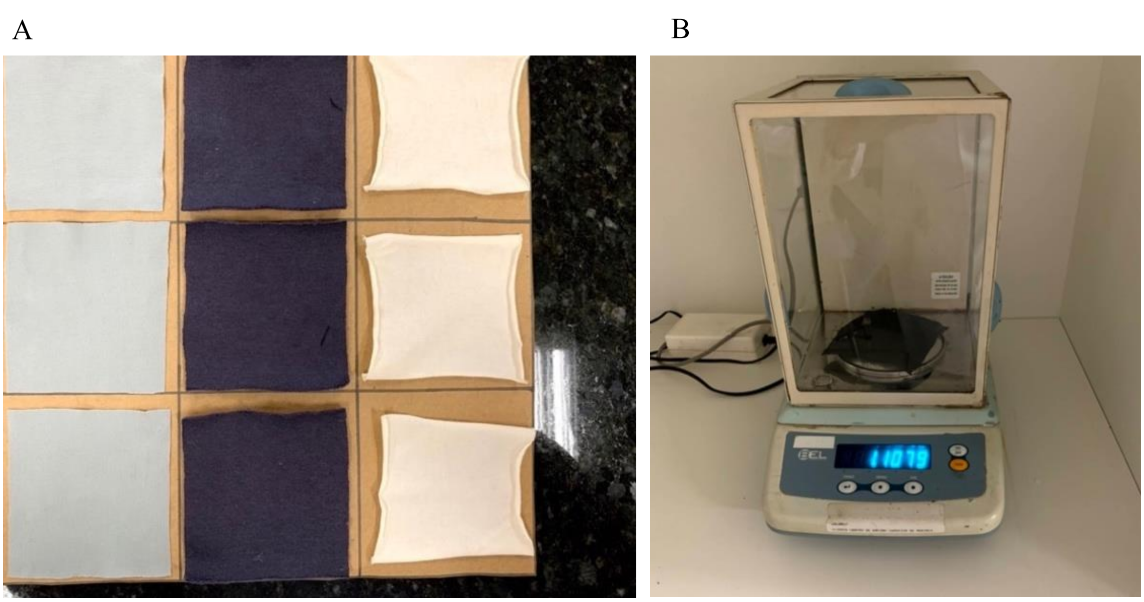

Figure 5 – (A) Sample registration; (B) weighing on a Shimadzu BL320H precision scale.

Finally, a descriptive analysis was carried out through the characterization of treatments, based on the photographic records made.

Results and Discussion

Throughout the test period, that is, during the 120 days in which the samples were in contact with the soil, the pH of the soil remained constant, between 6.5 and 7.0. The pH influences the number of fungi and bacteria present in the soil, being these the agents of degradation.

3D-printed PLA polymer

The analyses of the 3D-printed PLA biopolymer samples showed a loss of mass in the flexible PLA samples during the experiment. In 30 days, the flexible PLA samples showed a gain of mass, which can be explained by the presence of soil in their structure during weighing. In the final period (120 days), there was a loss of 6.2% compared to the initial mass, Figure 6A.

The degradation process of the flexible PLA biopolymer showed no damage to the sample structure (Figure 7). The rigid PLA samples (Figure 8A) showed a lower mass loss when compared to flexible PLA.

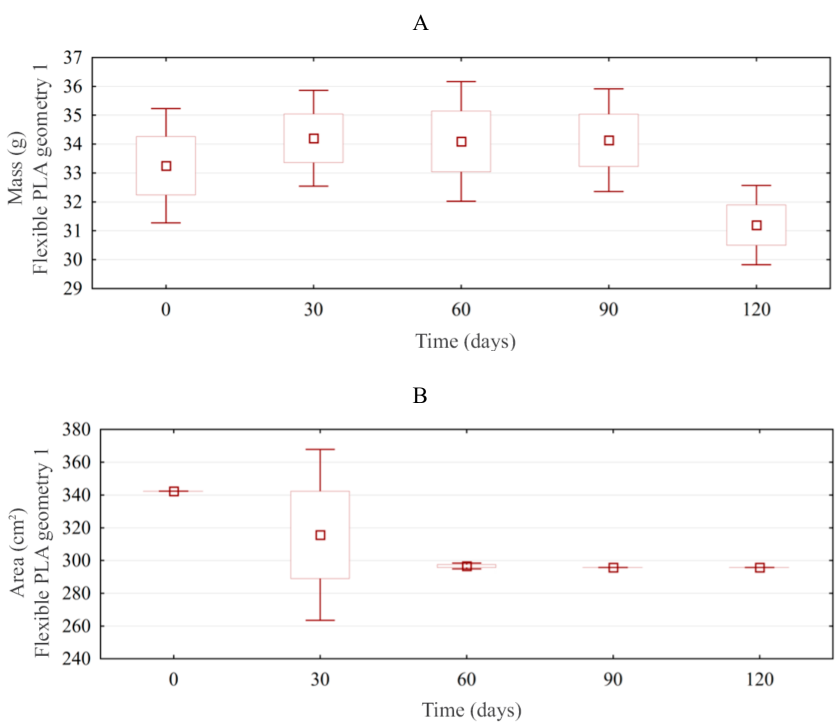

Figure 6 – Analysis of the (A) loss of mass (g) and (B) area (cm²) by degradation of 3D-printed flexible PLA biopolymer (geometry 1) buried for 0, 30, 60, 90, and 120 days.

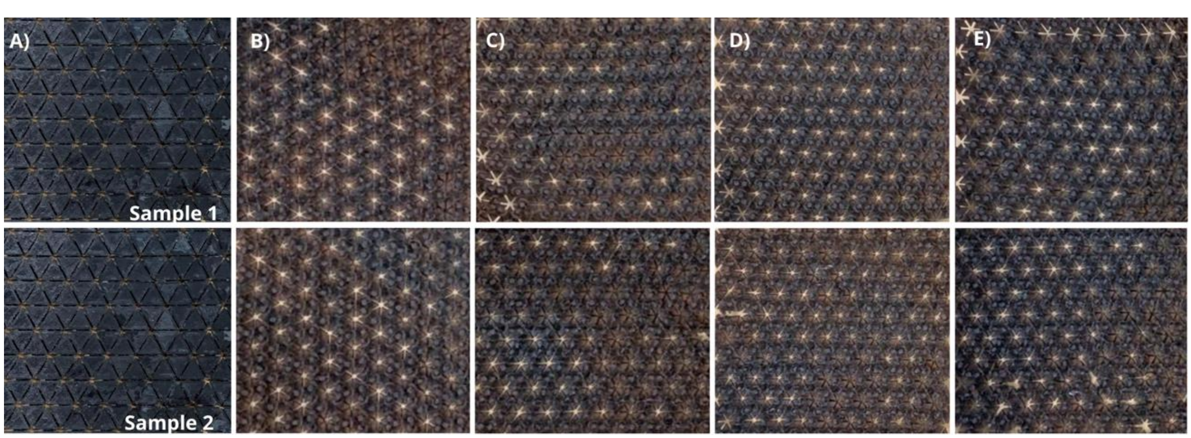

Figure 7 – Degradation process of 3D-printed flexible PLA biopolymer samples (geometry 1) buried for (A) 0, (B) 30, (C) 60, (D) 90, and (E) 120 days.

Figure 9 presents the degradation process of the rigid PLA biopolymer during the experiment, showing the damage of burying the samples.

In the study proposed by Rajesh et al. (2019), for a period of 90 days, there was an area loss of 5.56% for PLA+25% sisal (non-treated) and 15.20% for PLA + 25% sisal (treated). In the present study, the mass loss was 6.07% (flexible PLA) and 10.55% (rigid PLA) in the same period, with an area loss of 13.58% (flexible PLA) and 5.35% (rigid PLA). However, the addition of sisal can accelerate the degradation process.

This data can be justified due to the difficulty in performing the complete cleaning of the samples, without soil residues that could influence the data obtained during weighing.

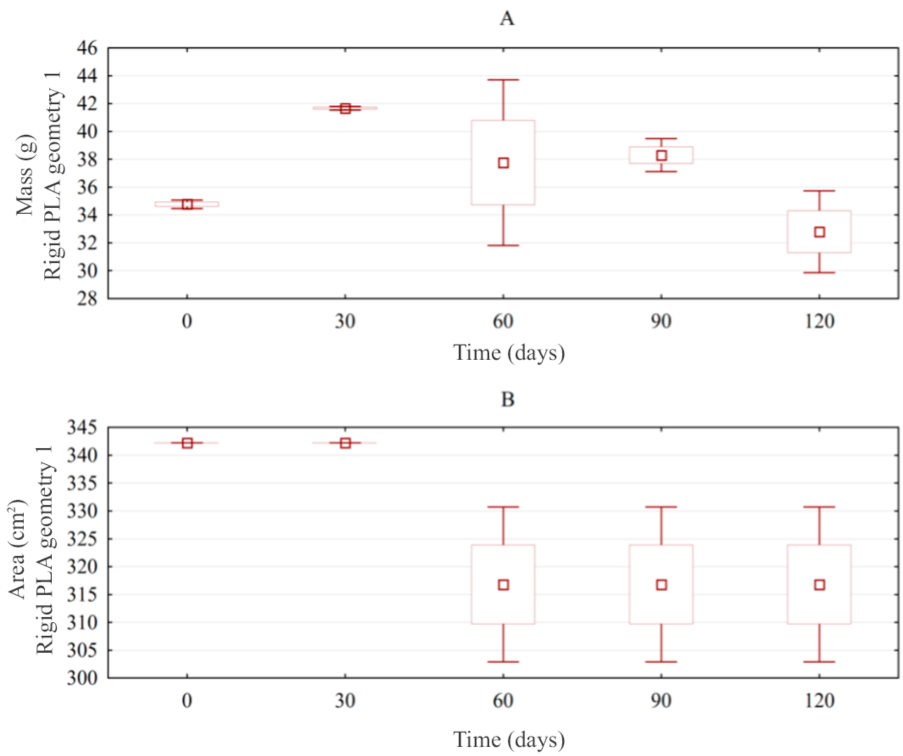

Figure 8 – Analysis of the (A) loss of mass (g) and (B) area (cm²) by degradation of 3D-printed rigid PLA biopolymer (geometry 1) buried for 0, 30, 60, 90, and 120 days.

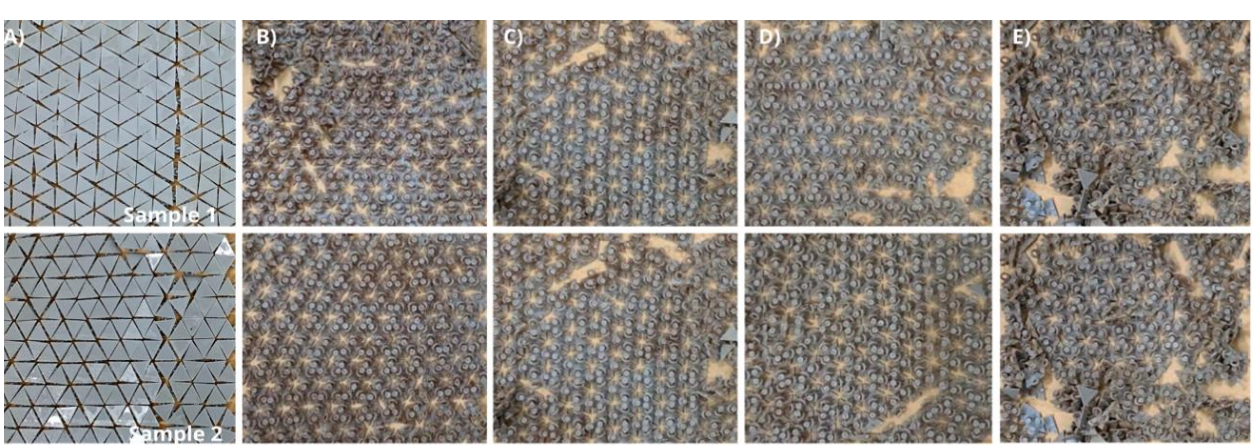

Figure 9 – Degradation process of 3D-printed rigid PLA biopolymer samples (geometry 1) buried for (A) 0, (B) 30, (C) 60, (D) 90, and (E) 120 days.

Considering the result obtained in the degradation of the non-woven printed in geometry 2 on flexible PLA, a small loss of mass of 3.38% was found throughout the experiment (Figures 10A and 10B), compared to the loss obtained in geometry 1.

In the degradation of the flexible PLA printed in geometry 2, there was no visible damage from degradation (Figure 11).

As for rigid PLA, a loss of 2.35% initial mass was observed, as can be seen in Figure 12A), and a loss of 19.25 cm^2 of its initial area (Figure 12B).

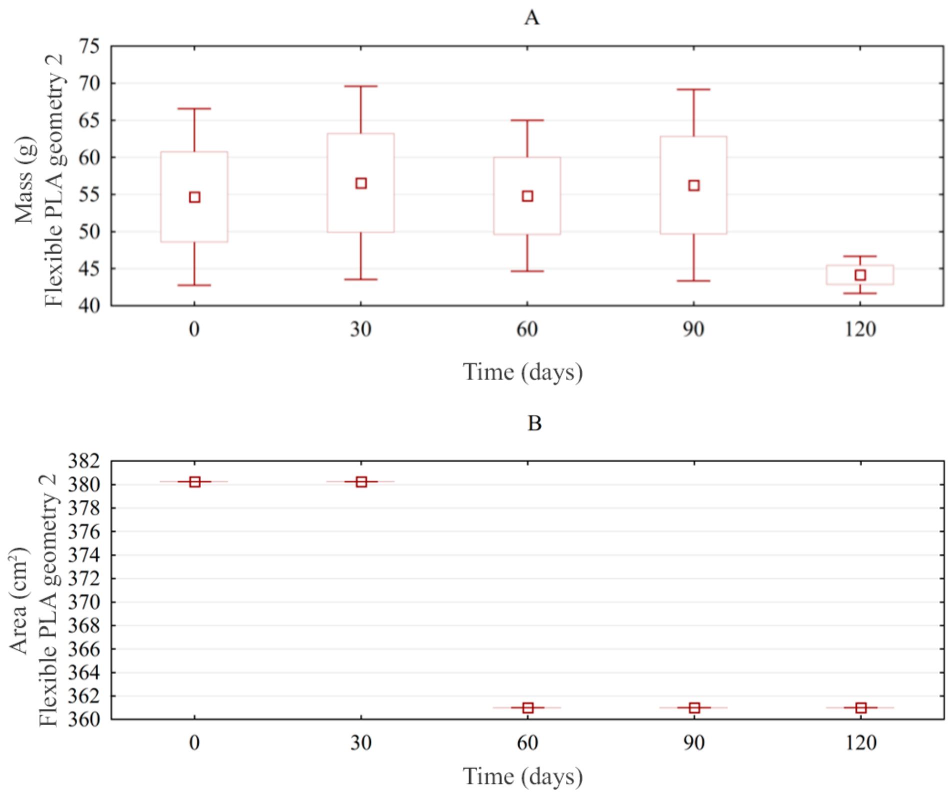

Figure 10 – Analysis of the (A) loss of mass (g) and (B) area (cm^2) by degradation of 3D-printed flexible PLA biopolymer (geometry 2) buried for 0, 30, 60, 90, and 120 days.

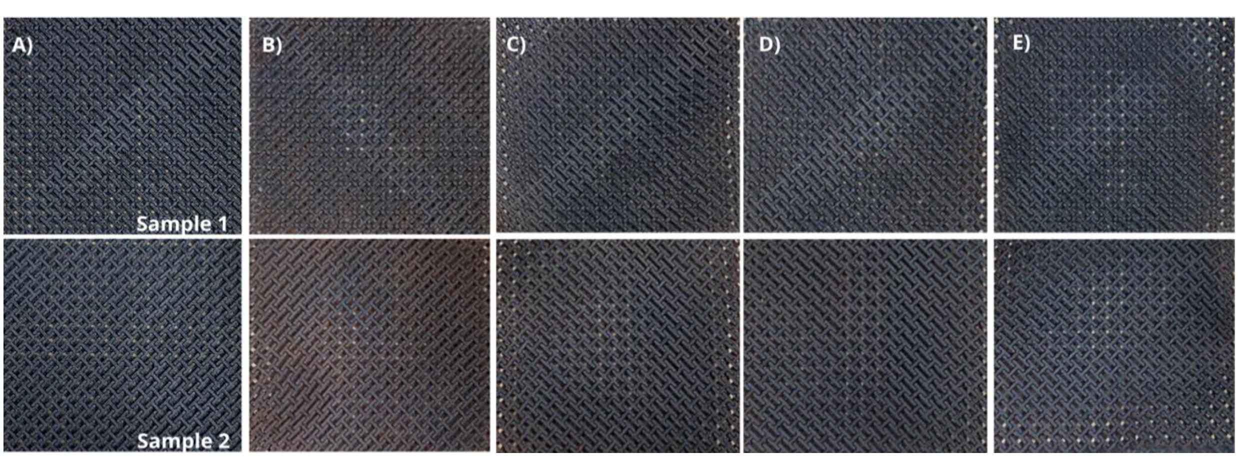

Figure 11 – Degradation process of 3D-printed flexible PLA biopolymer samples (geometry 2) buried for (A) 0, (B) 30, (C) 60, (D) 90, and (E) 120 days.

Figure 13 shows that degradation was lower because there were no changes in the sample structure.

As a comparison, in the study proposed by Rajesh et al. (2019), over a period of 90 days, the degrading PLA showed an area loss of 5.56% for PLA + 25% non-treated sisal and 15.20% for PLA + 25% treated sisal. In the same period, there was also a significant loss of area, in which the flexible PLA had a 5.06% loss and the rigid PLA 5.56% compared to the initial area. The difference in the percentage of mass loss in the same period for both studies can also be explained by the PLA composition of the sample used by the aforementioned authors, which contained 25% sisal fiber in the composition.

By observing the non-wovens printed in geometry 3 using rigid and flexible PLA, during the experiment, there was a loss of mass and area, except for the area of rigid PLA. In the period of 30 days, the non-woven printed with flexible PLA showed an increase in mass,

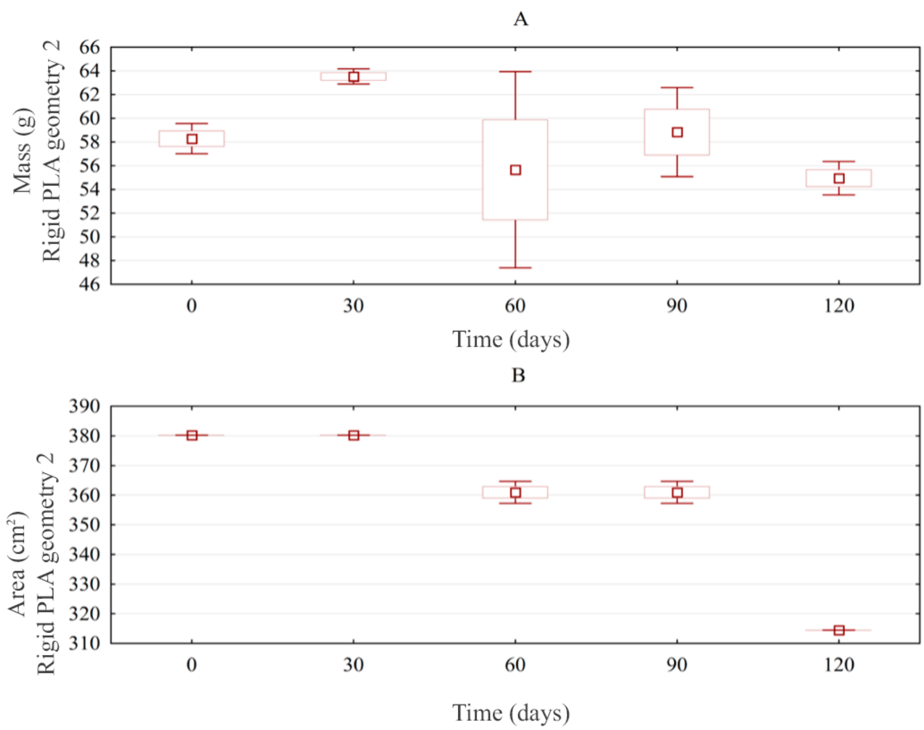

Figure 12 – Analysis of the (A) loss of mass (g) and (B) area (cm²) by degradation of 3D-printed rigid PLA biopolymer (geometry 2) buried for 0, 30, 60, 90, and 120 days.

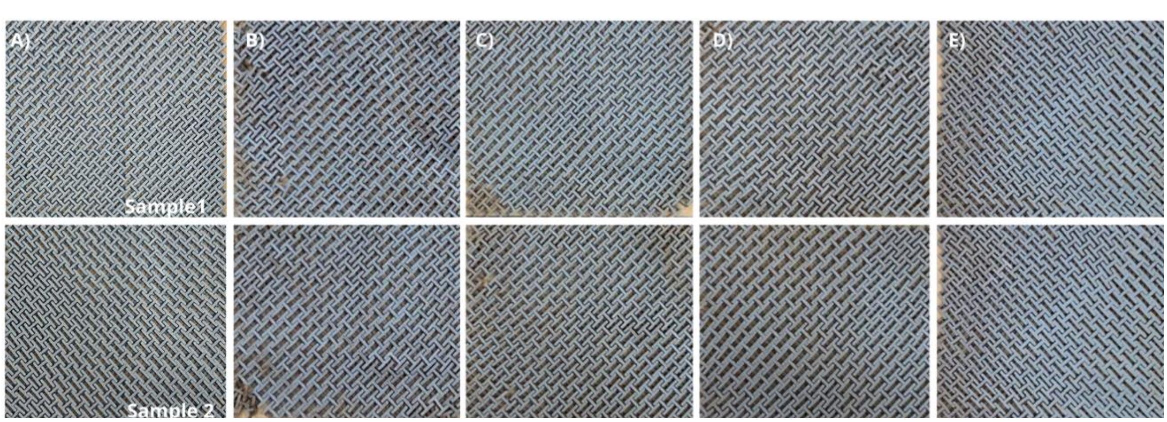

Figure 13 – Degradation process of 3D-printed rigid PLA biopolymer samples (geometry 2) buried for (A) 0, (B) 30, (C) 60, (D) 90, and (E) 120 days.

At the end of the period (120 days), it was observed that the smallest mass (5.48g) represents a loss of 2.3%, equivalent to 0.13g initial mass. As for the area, there was a loss from 90 days onwards, and until the end of the period, it remained stable. However, when comparing the initial with the final mass, it was possible to observe a loss of 2.17, as shown in Figures 14A and B.

In Figure 15, even after removing the soil from the samples, there were still soil remnants. This residual soil stiffened the samples and impaired their structure, which could influence the degradation analysis, as it did not allow for accurate measurement of the area.

As for geometry 3 printed using rigid PLA, there was a mass gain at 60 days, which can be explained by the sample disintegration

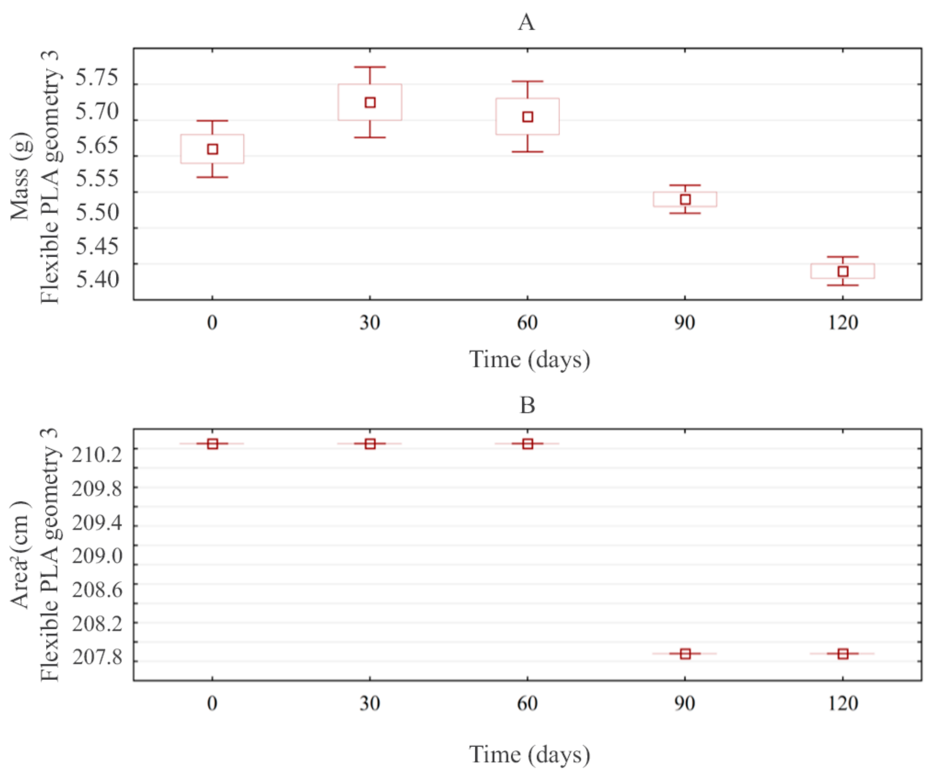

Figure 14 – Analysis of the (A) loss of mass (g) and (B) area (cm²) by degradation of 3D-printed flexible PLA biopolymer (geometry 3) buried for 0, 30, 60, 90, and 120 days.

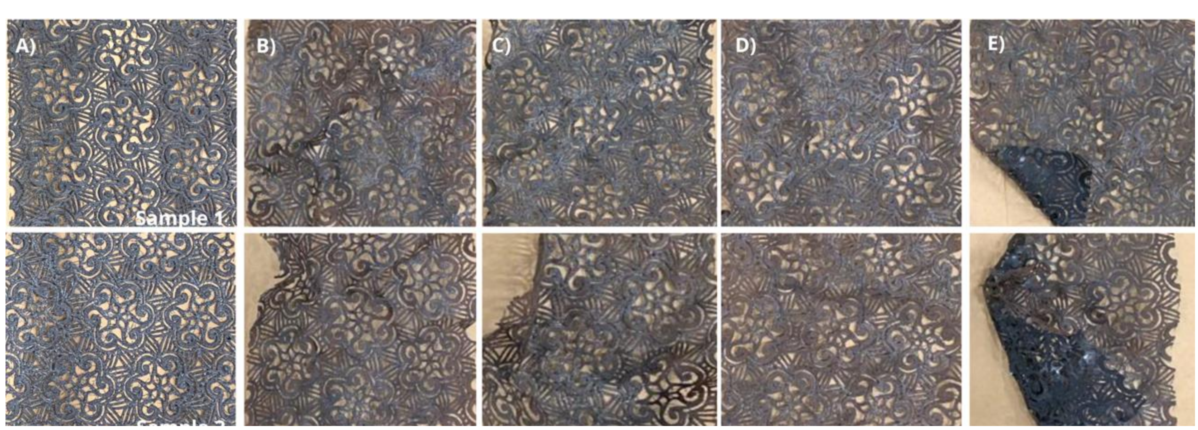

Figure 15 – Degradation process of 3D-printed flexible PLA biopolymer samples (geometry 3) buried for (A) 0, (B) 30, (C) 60, (D) 90, and (E) 120 days.

and possibly containing parts from another sample. At the end of the period (120 days), there was a loss of 0.77g, equivalent to 12.1% initial mass, considering that it was the sample that lost the most mass (Figure 16).

Regarding the area, it cannot be measured at the end of the period, because after 30 days the buried samples disintegrated, which made it impossible to make the final measurement of the sample, as can be seen in Figure 17.

According to Rajesh et al. (2019), for a period of 90 days, the degrading PLA showed a loss of 5.56% for PLA + 25% non-treated sisal and 15.20% for PLA+25% treated sisal. However, during the same period, in the present study, there was an area loss equivalent to 0.35% (flexible PLA) and 2.67% (rigid PLA), also presenting an area loss of 2.14 cm^2 equivalent to 1.01% initial area. The PLA used in the present study is considered as free of textile fibers, which is not the case with the PLA analyzed by Rajesh et al. (2019), who reported a significant mixture (25%) with a natural textile fiber.

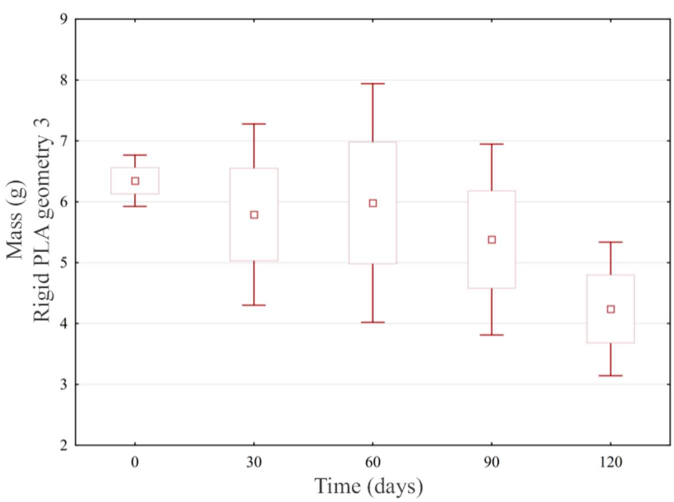

Figure 16 – Analysis of the (A) loss of mass (g) by degradation of 3D-printed rigid PLA biopolymer (geometry 3) buried for 0, 30, 60, 90, and 120 days.

In addition to the 3D-printed samples with flexible and rigid PLA biopolymer, in three different geometries, natural and synthetic textile fibers (cotton and polyester) were analyzed to draw a comparison.

Natural textile fibers: 100% cotton flat and knitted fabric

When analyzing flat and knitted fabrics with a composition of 100% cotton, it was possible to observe that over 120 days there was a loss of mass and area. At 30 days, the flat fabric showed a gain in mass, which can be explained by the moisture and soil residue present in samples during weighing. At 120 days, its mass was reduced by 8.9% compared to its initial mass. As for the area, there was a gradual reduction that resulted in a loss of 11.65% at the end of the period, this was because the fabric contains natural fibers, as can be seen in Figure 18.

Figure 19 shows the degradation process of the 100% flat cotton fabric samples. It is possible to observe the reduction in fabric area, where, samples 1 and 3 showed a large reduction in width on day 60 and day 30, respectively. After both periods, there was a loss of 1cm for the width of samples 1 and 2, and in sample 3 the loss was 2cm for the period from 60 to 90 days, remaining stable until the end of the period.

According to Figure 19, fabric samples had crumpled structures, which may have influenced the measurements of their size. In addition, another factor influencing this reduction is the fabric structure starting to defiber.

Regarding the 100% cotton knit, an increase in mass was found on day 30 compared to its initial weight, probably due to the moisture absorbed by the sample. At 120 days after the onset of the experiment,

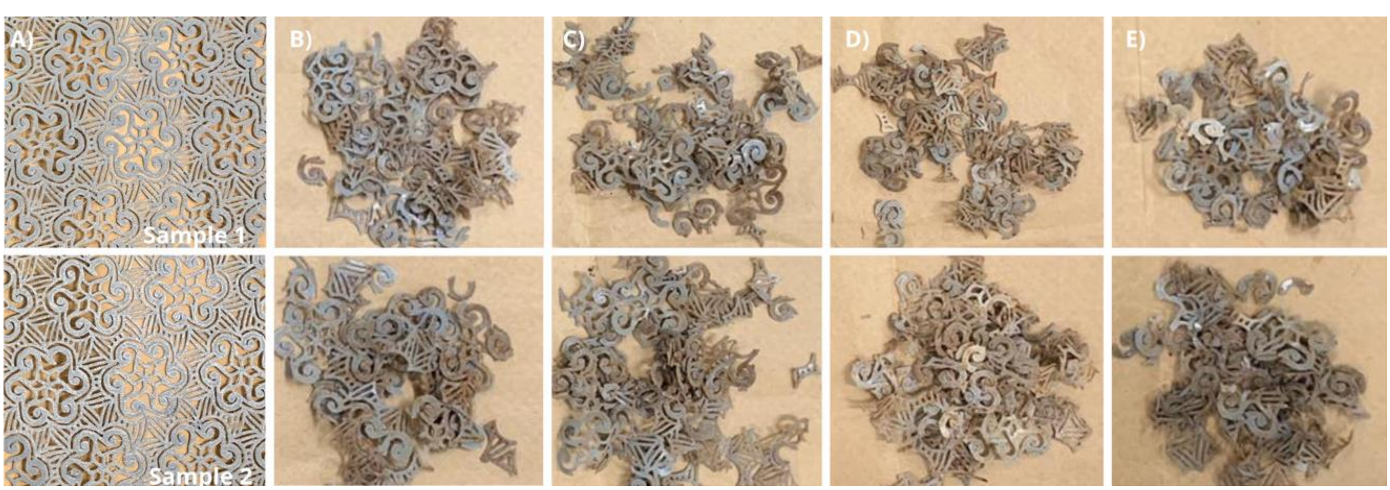

Figure 17 – Degradation process of 3D-printed rigid PLA biopolymer samples (geometry 3) buried for (A) 0, (B) 30, (C) 60, (D) 90, and (E) 120 days.

there was a loss of mass, however, this loss was greater than that observed in the flat fabric. Concerning the area, the result was also significantly greater than for the flat fabric, as the knitted fabric presents the shrinkage factor (Figure 20).

In view of this, it is observed that the weft of the fabric can influence the reduction in area, as the knit tends to curl, and the flat fabric to defiber in contact with the soil, humidity, and exposure to the sun (Mazibuko et al., 2019).

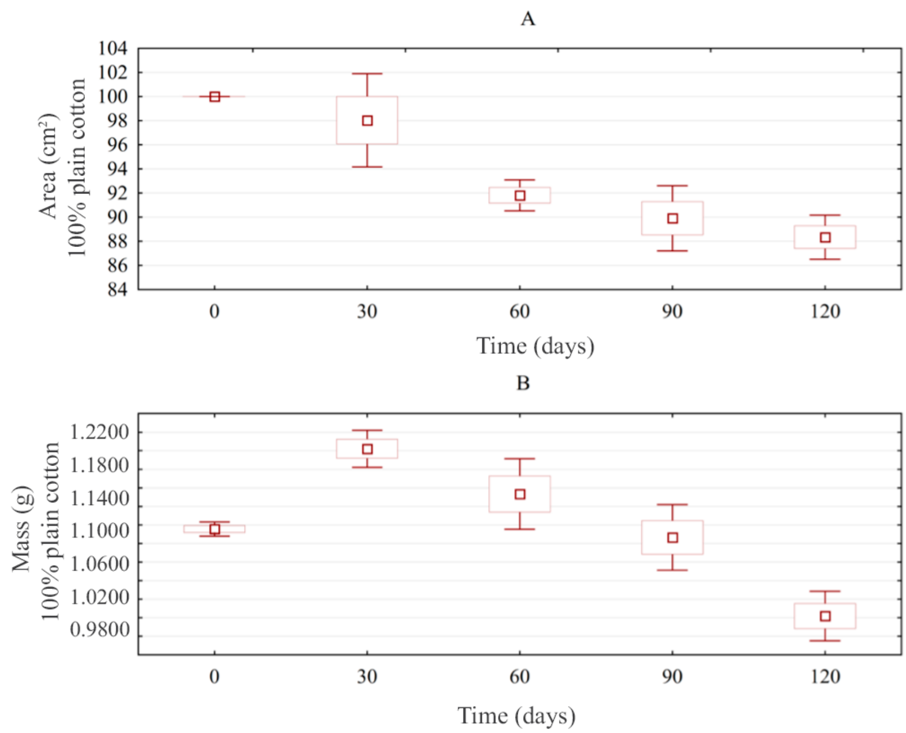

Figure 18 – Analysis of the (A) loss of mass (g) and (B) area (cm²) by degradation of natural textile fibers of 100% cotton (flat fabric) buried for 0, 30, 60, 90, and 120 days.

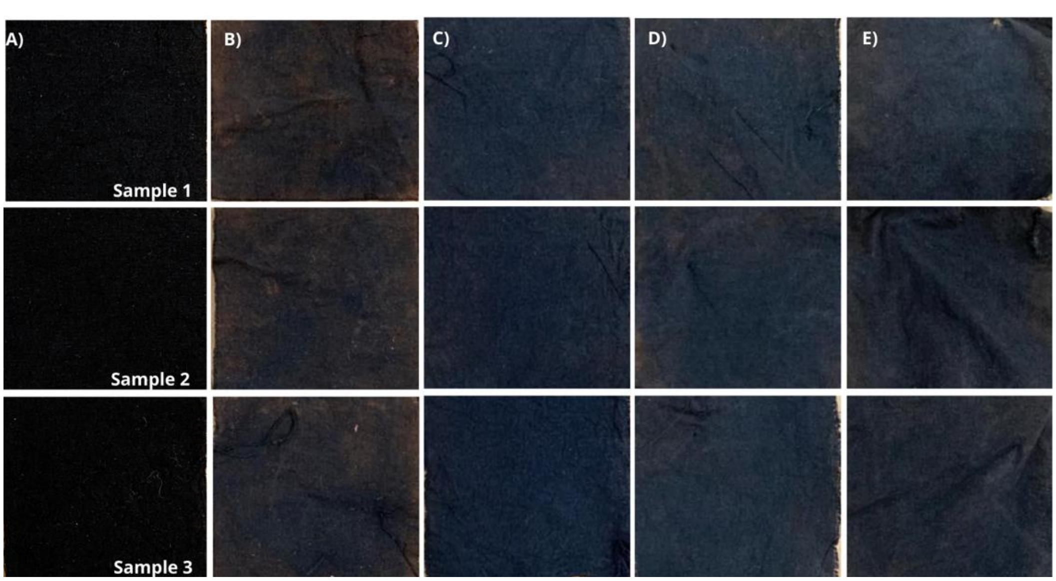

Figure 19 – Degradation process of 100% cotton (flat) natural fiber fabric samples buried for (A) 0, (B) 30, (C) 60, (D) 90, and (E) 120 days.

Konell et al. (2020) examined the degradation of clothing residues in soil for 60 days, and observed a loss of 70.64% for 100% flat cotton fabrics. In this study, for this same type of fabric, there was no loss of mass in the period of 60 days, although there was a loss of area (15.40%). This can be explained by the fact that the methodology used by the aforementioned authors differs from the one adopted in this study concerning the frequency of moisture control (weekly) and the soil exposure to real climatic conditions.

In addition to this factor, Konell et al. (2020) added water to the soil every day whenever the weight of the container fluctuated, which made the environment more humid. While in the present study the soil was exposed to the climatic conditions of the Northwest region of the state of Paraná, and the soil was moistened only once a week to correct the initial weight of the container (5 kg).

When evaluating the results for 100% cotton knitted fabrics, according to Konell et al. (2020), during the period of 60 days, a loss of 76.67% initial mass of the fabrics was observed. In the present study, there was no loss of mass, but there was a loss of area (15.40%) at the end of the experiment, which may also be associated with differences between the methodologies of the studies, and the type of fabric used by the authors, in which no commercial characteristics are presented, other than its composition, which may influence its degradation process.

According to Mazibuko et al. (2019), the loss of area presented by samples may indicate shrinkage of the fabric due to contact with the soil and the climatic conditions, such as great exposure to high temperatures on hot days, and immersion in rainwater, which occurred during the experiment. Textile exposure to ultraviolet rays is a factor that directly influences its degradation, resulting in loss of area and color, as can be seen in Figure 21.

Samples of 100% cotton knitted fabric showed significant changes in their structure after 60 days, with distortions in height and width, and tears along their length (Figure 21). Samples 1 and 3 at 60 days had a reduction of 1 cm in width. The samples again showed a loss of 1.2 cm (sample 1) in the period of 90 days, remaining stable until the end of the experiment, and for sample 3, there was a loss only at the end of the experiment, also corresponding to 1.2 cm of the measure taken at 60 days.

In studies proposed by Milošević et al. (2017), the biodegradability of cotton fibers was analyzed by the soil burial test, with compostable soil, and in a controlled environment following the ASTM 5988-03 standard test. Both tests were performed with 100% cotton and 50% cotton 50% PET fabrics, the 100% cotton samples showed better degradability due to visible damage to the fabric structure.

The test took place at an interval of 46 days, and on day 32 there was the greatest loss of mass, 17% initial weight. This was gradually intensified, and after 25 days, large holes could be seen in the fabrics, evidencing the severe disintegration of the cotton fabric after one month (Mazibuko et al., 2019).

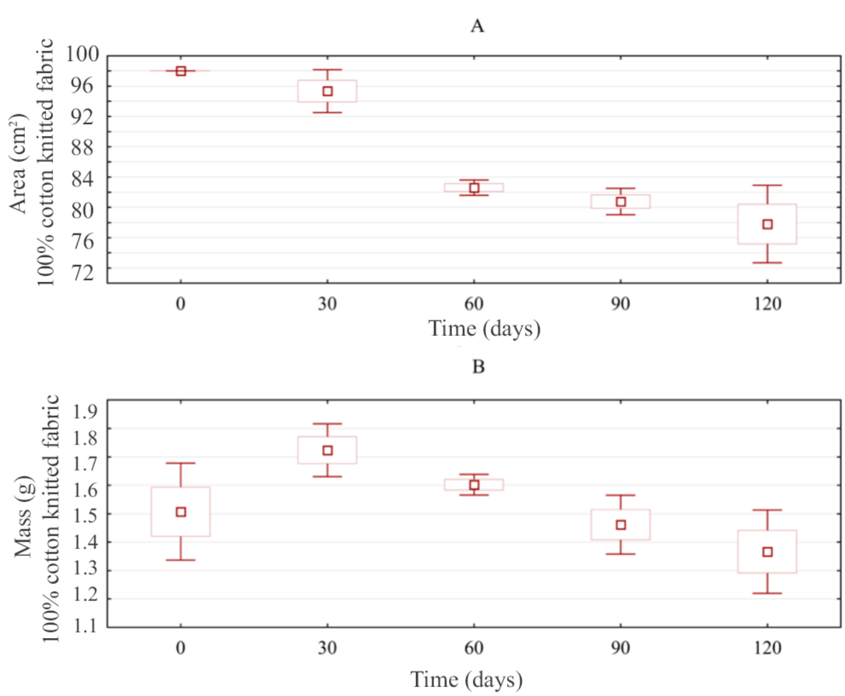

Figure 20 – Analysis of the (A) loss of mass (g) and (B) area (cm²) by degradation of natural textile fibers of 100% cotton (knitted fabric) buried for 0, 30, 60, 90, and 120 days.

Synthetic textile fibers: 100% polyester flat and knitted fabric

In the case of flat fabrics and 100% polyester knit, it was observed that over the period of 120 days, there was a small loss of mass and area. At 30 days, the flat fabric showed the same gain of mass, possibly due to the soil and water residue present in the sample during weighing. At the end of the experiment, there was a decrease in mass, equivalent to 3.84%; and a reduction of 3.96 cm^2 compared to the initial area (Figure 22).

Figure 23 illustrates the loss of area throughout the experiment, by the gradual reduction in height and width of the samples, especially sample 1. In the other samples, there was a reduction, but lower, as identified in sample 3. This is because only one side of the container was exposed to the sun, and by the positioning of the samples inside the container because whenever they were taken from the ground, they were buried in the same place of the container.

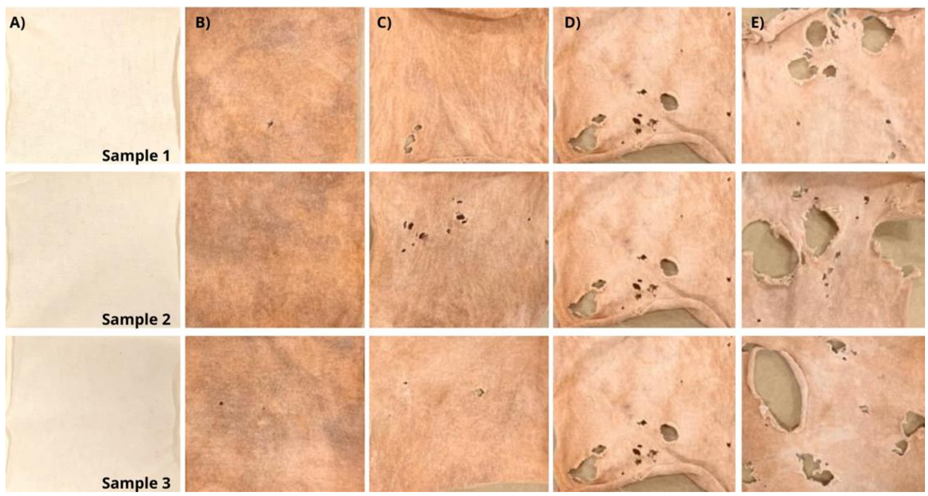

Figure 21 – Degradation process of 100% cotton (knit) natural fiber fabric samples buried for (A) 0, (B) 30, (C) 60, (D) 90, and (E) 120 days.

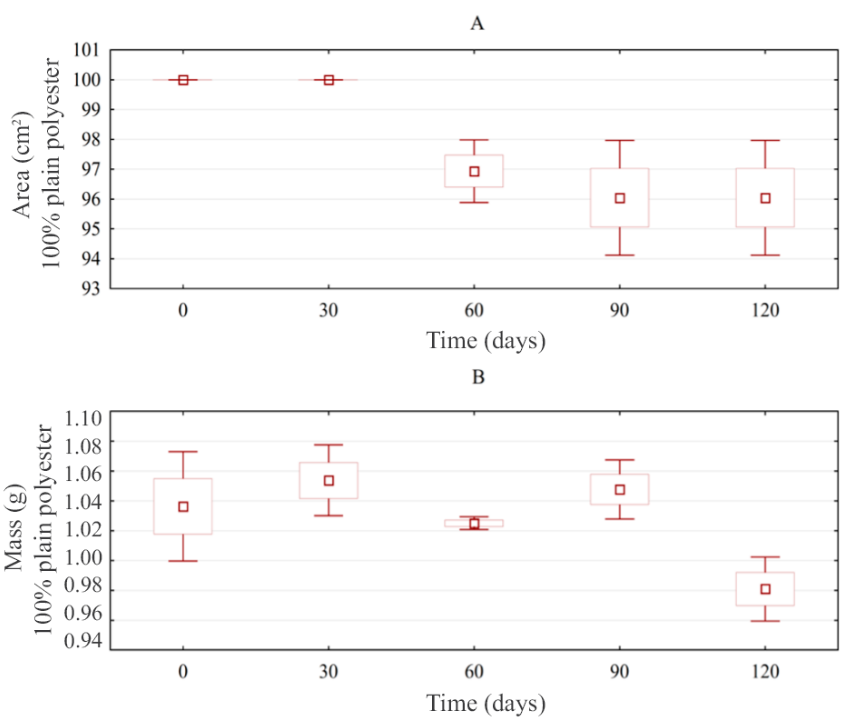

Figure 22 – Analysis of the (A) loss of mass (g) and (B) area (cm²) by degradation of synthetic textile fibers of 100% polyester (flat fabric) buried for 0, 30, 60, 90, and 120 days.

The results obtained in 100% polyester knitted fabrics during the period of 60 days, according to Konell et al. (2020), showed a smaller loss than the flat fabric (0.72%). Here, the increase in mass and reduction in area (3.07%) (Figure 24) can be justified by the soil residue or moisture present in the fabric (Figure 25), since there is a difference between the methodology used herein and that used by Konell et al. (2020).

When observing the results of degradation of 100% polyester flat fabrics and knitted fabrics proposed by Konell et al. (2020), in a period

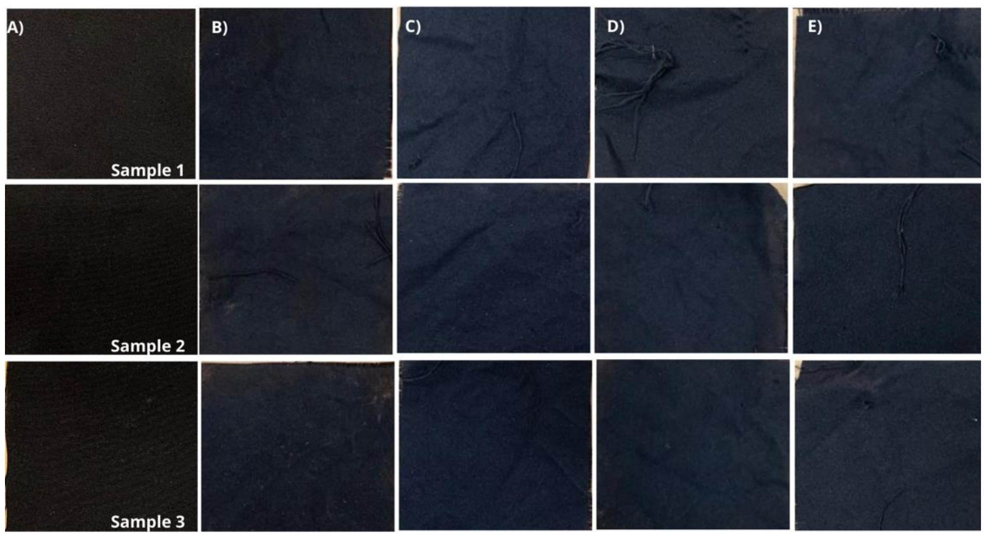

Figure 23 – Degradation process of 100% polyester (flat) synthetic fiber fabric samples buried for (A) 0, (B) 30, (C) 60, (D) 90, and (E) 120 days.

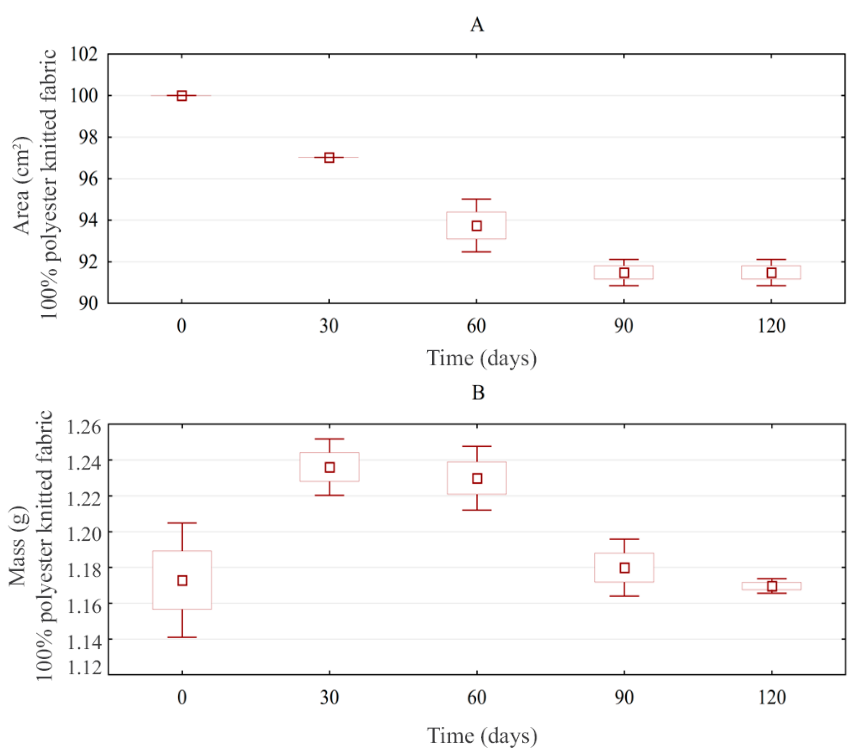

Figure 24 – Analysis of the (A) loss of mass (g) and (B) area (cm²) by degradation of synthetic textile fibers of 100% polyester (knitted fabric) buried for 0, 30, 60, 90, and 120 days.

of 60 days, there was a loss of 1.09% for 100% flat polyester; in the present study, there was a loss of mass of 0.1%, while for the area, there was a greater loss (3.07%). It was possible to notice that synthetic fibers, regardless of the methodology used, presented a lower loss, because of the synthetic origin of the fiber, making it resistant to chemical and biological attacks from the fiber degradation medium, maintaining its structure, as presented by Konell et al. (2020).

It can be observed that the greatest mass loss occurred in the 100% flat cotton fabric, equivalent to 60% initial mass, and the fabric with the largest degraded area was the 100% cotton knitted fabric, which showed a loss of 20.20 cm^2.

Since the production of flat fabric is made by interlacing the warp and weft yarns, it ends up becoming a more stable structure, consequently more difficult to defiber. Finally, the author Udale (2015), also states that the manufacture of the knitted fabric takes place from interlocking loops along the warp or weft, formed by horizontal lines known as “weft threads”, and the vertical “warp threads”. It can also be classified into weft knit — easily unravels —, and warp knit — which is like weaving, more complicated to unweave (Udale, 2015).

As these constructions are different, it can be observed that the knit fabrics are more unstable compared to the flat fabric, because their connections tend to break more easily compared to the weft of flat fabric. A different process is then observed concerning the degradation of flat and knitted fabrics, as shown in Figure 26.

Considering the result obtained in the degradation of cellulosic (100% cotton) and synthetic (100% polyester) fibers, the cellulosic part (cotton) is the one that degrades easily in a short period, either in its entirety or in the mixture with other fibers (Mazibuko et al., 2019).

When analyzing the records made over the period, the presence of soil in the samples was observed, and the rupture of the links that unite the geometry forming the non-woven. Therefore, it can be said that the soil weight, due to burying the samples and the degradation process, contributed to this.

Making a comparison with the type of fabric weft and geometry, the greatest loss in mass (%) was found for flat and geometry fabrics 3, in relation to the mean (Chart 3). However, the fact that there was a large variation around the mean, as seen in Figures 26 and 27, evidenced that all means did not present significant differences at the 5% significance level.

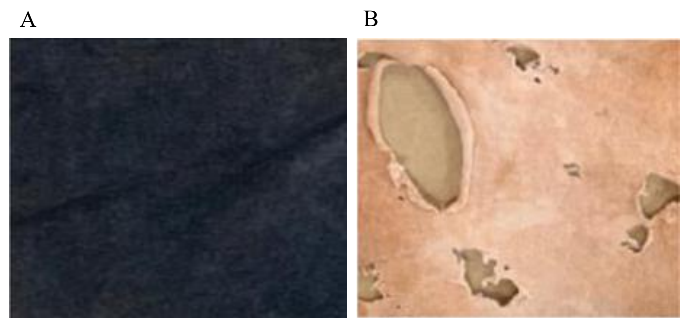

Figure 26 – (A) Fabric samples in the last stage of degradation, comparative of flat fabric; and (B) knitted fabric 100% cotton.

Chart 3 – Mean values and standard deviations of the loss of mass (%) concerning the weft of the fabric*.

Weft of the fabric	Loss of mass (%)
Flat	$4.79^a \pm 1.36$
Knit	$1.22^a \pm 1.34$
Geometry 1	$0.80^a \pm 2.81$
Geometry 2	$1.78^a \pm 1.80$
Geometry 3	$4.78^a \pm 2.13$

*Mean values, in the same column, followed by different lowercase letters are significantly different by Tukey’s test, at a 5% significance level.

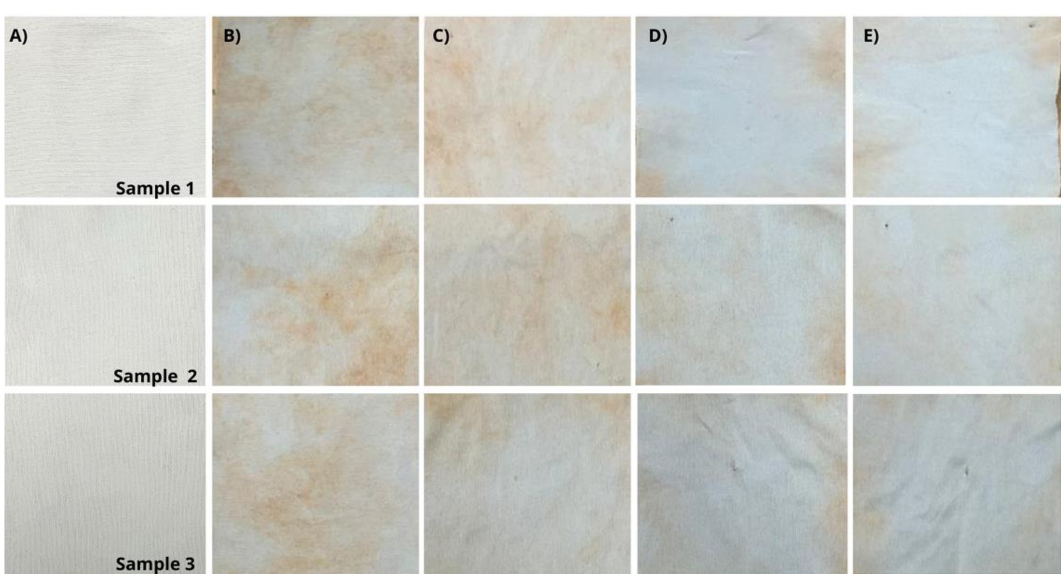

Figure 25 – Degradation process of 100% polyester (knit) synthetic fiber fabric samples buried for (A) 0, (B) 30, (C) 60, (D) 90, and (E) 120 days.

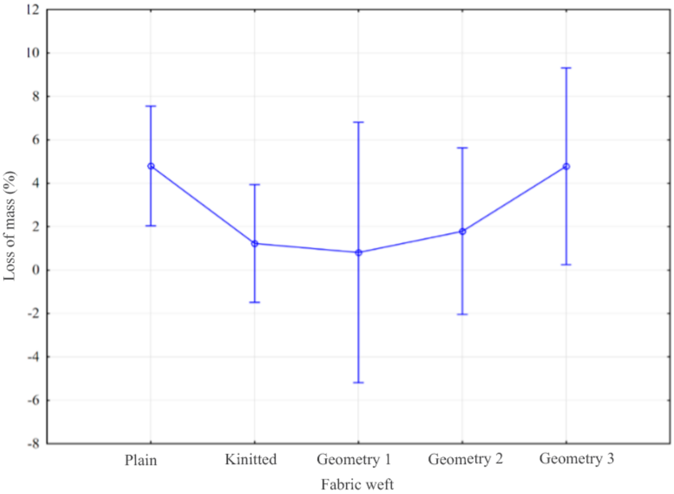

Figure 27 – Mean and standard deviation of the loss of mass concerning the weft of the fabric.

Given the results presented, for the 3D-printed PLA biopolymer, the sample with the greatest mass loss was geometry 2 in flexible PLA (13.4%). Regarding the area, the greatest reduction was geometry 1 in flexible PLA (46.5%), compared to its initial mass.

Considering the results obtained in the degradation of samples printed with flexible PLA, under the soil conditions proposed in the study, it presented better degradation in a short period, then it represents an alternative material that meets the process of degradation in soil.

Conclusion

With the demand for new yarns, fabrics, smart textiles, and products with technological innovations, the textile industry has invested in sustainable solutions that add value to the planet and society. In this sense, the use of raw materials, such as PLA biopolymer, emerges as a solution to the problem caused by the clothing industry, and allied to this, 3D printing is seen as a technology that can help in this sense and contribute to the sustainability of the sector.

In this study, each group of samples presented different results due to their composition. In particular, samples composed of natural fibers achieved more satisfactory results regarding the visual aspect of degradation compared to the polyester samples. This can be explained by the longer life span of plastics, in this case, polyester, which comes from a thermoplastic polymer formed by the reaction of terephthalic acid with mono-ethylene glycol, both from synthetic origin.

When comparing the degradation of natural and synthetic fiber textiles to the degradation of 3D-printed PLA biopolymer samples, it is clear that there was no significant degradation since only two of the geometries showed visible degradation.

In the biodegradation process, fibers are broken down into simpler substances by microorganisms, light, air, or water, in a process that must be non-toxic and occur over a relatively short period if controlled in a laboratory. Not all fibers are biodegradable. Synthetic fibers (polyester), made from a raw material derived from petroleum, are not considered biodegradable. They resist and accumulate in the environment because microorganisms lack the enzymes necessary to break them down. On the other hand, fibers derived from plants and animals soon decompose into simpler particles due to their composition (Fletcher and Grose, 2011, p. 18).

In this sense, although it has not degraded rapidly when exposed to the weather, the PLA biopolymer aims to reduce the environmental impact compared to plastic waste, since plastic waste causes serious environmental pollution, directly affecting the daily activities of various organisms, whether on land or in water. This ends up negatively affecting the environment as its degradation can take decades or even centuries.

Contribution of authors:

DO BEM, N. A.: Methodology; Research; Writing — First Draft. CARDOSO, F. A. R.: Statistical Tests. PACCOLA, E. A. S.: Methodology; Writing — First Draft. REZENDE, L. C. S. H.: Research; Methodology; Writing — First Draft; Supervision.

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