PROMOTING SUSTAINABILITY THROUGH A 3D PRINTING WASTE RECYCLING WORKSHOP

PROMOVENDO A SUSTENTABILIDADE POR MEIO DE UMA OFICINA DE RECICLAGEM DE RESÍDUOS DE IMPRESSÃO 3D

PROMOCIÓN DE LA SOSTENIBILIDAD A TRAVÉS DE UN TALLER DE RECICLAJE DE RESIDUOS DE IMPRESIÓN 3D

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ABSTRACT: In 3D printing process using fused deposition modeling (FDM), filaments are used, including polylactic acid (PLA), coming from sugar cane or corn, which is melted during printing to form parts in three-dimensional layers. However, with the growing demand for 3D printing in different sectors of society, the trend is towards irregular disposal and the accumulation of this material in the form of waste. Therefore, we aim to reuse 3D printing waste made from PLA through mechanical recycling conversion. To this end, we held a 3D printing waste recycling workshop with High School and Higher students from the Instituto Federal do Amazonas Campus Manaus Distrito Industrial (IFAM CMDI). During the workshop, we asked students about 3D printing and sustainability and taught a class on the basics of 3D printing and recycling their waste. Later, the students used the single-screw extruder to form the PLA filament that can be used again in a new print. The students learned how to develop filaments for 3D printers, combining Environmental Education and Professional and Technological Education, stimulating learning and making them makers, manufacturing their own material, being able, in the long term, to undertake and work in this area. Therefore, with this PLA recycling workshop, we promote the circular economy, so that products and materials are reused, increasing their useful life and reducing waste.

KEYWORDS: 3D printing. Circular Economy. Sustainability. Environmental Education. Waste Recycling.

RESUMO*: No processo de impressão 3D por modelagem de deposição fundida (FDM), filamentos são utilizados, entre eles o ácido poliláctico (PLA), advindo da cana de açúcar ou do milho, que é derretido durante a impressão para formar peças em camadas tridimensionais. Contudo, com a crescente demanda de impressões 3D em diversos setores da sociedade, a tendência é o descarte irregular e o acúmulo desse material na forma de resíduos. Por isso, temos como objetivo reaproveitar resíduos de impressões 3D feitos do PLA por meio da conversão mecânica de reciclagem. Para isso, realizamos uma oficina de reciclagem de resíduos de impressão 3D com alunos de Nível Médio e Superior do Instituto Federal do Amazonas Campus Manaus Distrito Industrial (IFAM CMDI). Durante a oficina, perguntamos aos alunos sobre a impressão 3D e a sustentabilidade e ministramos uma aula sobre princípios básicos de impressão 3D e reciclagem de seus resíduos. Posteriormente, os alunos utilizaram a extrusora de parafuso monorrosca para formar o filamento de PLA que pode ser usado novamente em uma nova impressão. Os alunos aprenderam a desenvolver filamentos para impressora 3D, aliando a Educação Ambiental e a Educação Profissional e Tecnológica, estimulando a aprendizagem e tornando-os makers, fabricando o próprio material, podendo, a longo prazo, empreender e trabalhar nessa área. Logo, com esta oficina de reciclagem de PLA, promovemos a economia circular, a fim de que os produtos e materiais sejam reaproveitados, aumentando a vida útil e reduzindo o desperdício de resíduos.*

PALAVRAS-CHAVE*: Impressão 3D. Economia Circular. Sustentabilidade. Educação Ambiental. Reciclagem de Resíduos.*

RESUMEN: *En el proceso de impresión 3D por modelado de deposición fundida (FDM), se utilizan filamentos, entre ellos el ácido poliláctico (PLA), procedente de la caña de azúcar o del maíz, que se funde durante la impresión para formar piezas en capas tridimensionales. Sin embargo, con la creciente demanda de impresión 3D en diferentes sectores de la sociedad, la tendencia es hacia la eliminación irregular y la acumulación de este material en forma de residuos. Por lo tanto, nuestro objetivo es reutilizar los residuos de impresión 3D fabricados a partir de PLA mediante conversión de reciclaje mecánico. Para ello, realizamos un taller de reciclaje de residuos de impresión 3D con estudiantes de Secundaria y Universitarios del Instituto Federal do Amazonas Campus Manaus Distrito Industrial (IFAM CMDI). Durante el taller, preguntamos a los estudiantes sobre la impresión 3D y la sostenibilidad y les impartimos una clase sobre los conceptos básicos de la impresión 3D y el reciclaje de residuos. Posteriormente, los estudiantes utilizaron el extrusor de un solo tornillo para formar el filamento PLA que podrá usarse nuevamente en una nueva impresión. Los alumnos aprendieron a desarrollar filamentos para impresoras 3D, combinando Educación Ambiental y Educación Profesional y Tecnológica, estimulando el aprendizaje y convirtiéndolos en makers, fabricando su propio material, pudiendo, a largo plazo, emprender y trabajar en este ámbito. Por eso, con este taller de reciclaje de PLA fomentamos la economía circular, para que productos y materiales se reutilicen, aumentando su vida útil y reduciendo los residuos.*

PALABRAS CLAVE: *Impresión 3D. Economía Circular. Sostenibilidad. Educación Ambiental. Reciclaje de Residuos.*

Introduction

3D printing, also called additive manufacturing, creates the object in three dimensions, depositing layer by layer (Pinheiro *et al.* 2018). There are several 3D printing techniques as an additive manufacturing process (Han *et al.*, 2023; Wong; Hernandez, 2012; Kumar; Prasad, 2021) such as: Stereolithography (*Stereo Lithography Apparatus* – SLA, Direct Metal Laser Sintering (DMLS), Direct metal deposition (DMD), Selective Laser Sintering (SLS), Laminar object manufacturing (Laminated Object Manufacturing - LOM) and Fused Deposition Modeling (FDM).

The FDM technique is currently the most used additive manufacturing technique for rapid prototyping of materials, in which the most common materials are polymer-based thermoplastic filaments coupled to the 3D printer, which are melted to form the object, these being the PLA biopolymer (polylactic acid) from sugar cane and corn and ABS polymers (acrylonitrile butadiene styrene) and PETG (polyethylene glycol terephthalate) derived from petroleum (Tao *et al.*, 2017).

3D printers are gaining more and more space in the domestic environment around the world, based on the modeling of the object to be manufactured in software and the choice of the 3D printer that suits the type of material to be printed, also disseminated in maker culture (do-it-yourself), in which people can produce their own object (Pinheiro *et al.* 2018; Littlemaker, 2019). 3D printing is also applied in the construction of concrete buildings, aerospace, biomedical, automotive, decorative objects, cooking, clothing.

With 3D printing technology, new questions have emerged aimed at reducing costs and improving techniques, which is vital for production lines and sustainability. For example, during some prints, it is necessary to use supports for the main part, which must be programmed according to the type of filament used, which will be waste when the print is finished. Also, parts with printing failures, incomplete or broken, resulting in wasted material and more waste.

In line with the debate on the use of plastics, companies, societies and governments have, over the years, sought alternatives to reduce, reuse and recycle waste. According to the United Nations (UN), the world's seven billion inhabitants produce 1.4 billion tons of urban solid waste (MSW), an average of 1.2 kg of garbage per day per capita (UN, 2023). Therefore, the problem is global, and it is essential that initiatives are encouraged to reduce the generation of waste and increase the useful life of each material.

To optimize the use of materials and avoid post-consumption waste, it is necessary to implement the circular economy, which is based on a *regenerative system of material and energy cycles* in a continuous process, as occurs in natural ecosystems *and "this can be achieved through lasting design, maintenance, repair, reuse, remanufacturing, refurbishment and recycling*." Thus, material that could previously be discarded returns to the production cycle (Geissdoerfer *et al.* 2017).

The production and inappropriate disposal of plastic materials in everyday life has become natural, as shown in the study carried out by the World Wide Fund for Nature (WWF) and released in 2019, in which Brazil produces 11 million tons of plastic waste per year and it is in 4th place as the largest producer of plastic waste in the world, and is also one of those that recycles the least: only 1.2% of this material is recycled (WWF, 2023; De Paoli; Spinacé; Romão, 2009).

In turn, by using Environmental Education to teach sustainable processes, we seek to create in the generations that are at school a new mentality of environmental preservation, as

> By implementing an education project that involves the environment and sustainability, we will be providing students with a fundamental

> understanding of the existing problems of human presence in the environment, their responsibility and their critical role as citizens, developing the skills and values that will lead to rethink and evaluate in a different way their daily attitudes and their consequences on the environment in which they live (Ross; Becker, 2012, our translation).

Regarding the use of 3D printing waste and studies on the environmental impact of 3D printing waste, we have a limited and scarce scenario and almost no data available on recycled 3D (Zhao *et al.*, 2018; Anderson, 2017). Ong *et al.* (2020) state that recycling is viable to form new filaments, despite reduced mechanical properties. Anderson (2017), in his study, reports that PLA waste has properties similar to natural PLA.

Liu, Li and Jiang (2016) explain that sustainable manufacturing is necessary, printing better and faster, having ideal parameter settings for commands on the 3D printer, as well as life cycle assessment (LCA) that can be used when modeling the environmental impacts of 3D printing. They analyzed that applying Life Cycle Costing (LCC) to study the economic benefit of 3D printing gave some promising results. However, the authors report that the research did not consider the environment and social aspects. The authors conclude that in 3D sustainability assessment modeling, printing needs to integrate the three pillars (environmental, economic and social) in a comprehensive way, including improvements in configuration parameters, filaments and more environmentally friendly filament types.

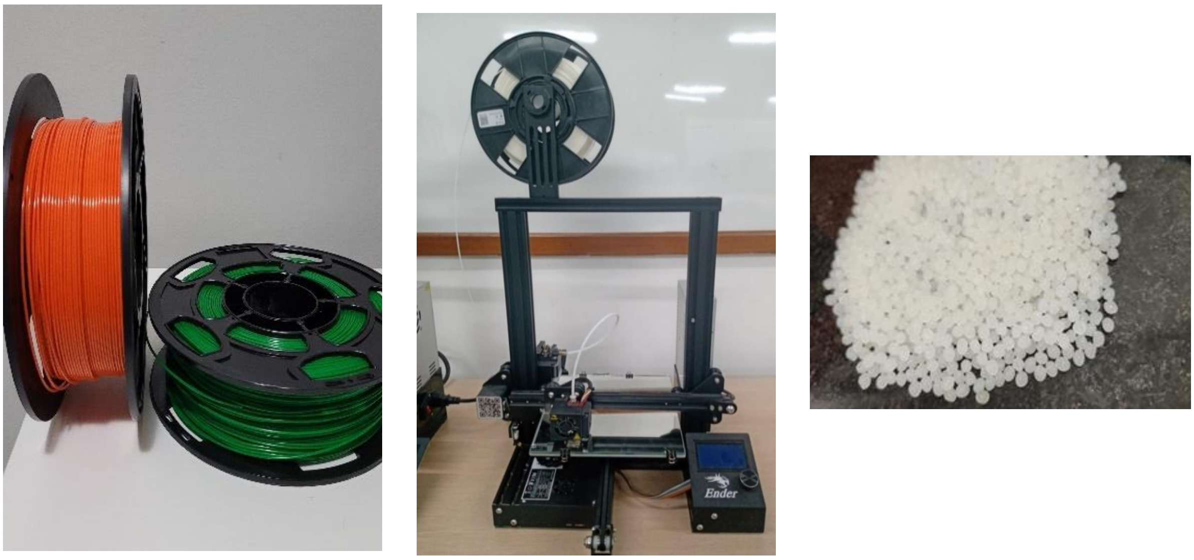
In this sense, this work seeks, through Environmental Education and Sustainability, and Professional and Technological Education, to act within the Sustainable Development Goals (ONU, 2023), which are a group of 17 global objectives, established by the General Assembly of Nations United. That said, we implemented a workshop to use waste from 3D printing, specifically PLA filaments, to manufacture new filaments and teach this technique to high school and higher education students at the Federal Institute of Amazonas, Campus Manaus, Distrito Industrial (IFAM CMDI).

Additive Manufacturing

3D printing, known as additive manufacturing, is a technique for producing three-dimensional objects from a three-dimensional model in digital media. One of the best-known forms of 3D printing is by melting filaments (Figure 1a) to produce the object, using the fused deposition modeling (FDM) process. The operation of the 3D printer (Figure 1b) consists of the deposition on the x, y and z axes of each new printed layer that moves in one plane (for example, horizontally) while the platform moves in another (for example, vertically). In the FDM process, deposition occurs in a continuous flow through a nozzle under constant pressure and the material is melted in the liquefaction chamber at 200ºC before entering the nozzle; the layer is then deposited sequentially until the object is completed.

In this process, one of the most used filaments is that made of polylactic acid (PLA), which is a thermoplastic biopolymer made up of lactic acid molecules of biological origin obtained from corn starch or sugar cane, which has the potential to replace plastics derived from petroleum, being biodegradable (Singh *et al.*, 2022; Tao *et al.*, 2017; Pinheiro *et al.*, 2018). PLA is considered a valuable substitute for synthetic polymers and has diverse uses such as 3D printing, packaging, healthcare and textiles, due to its strong mechanical qualities, high rigidity and biodegradability (Singh *et al.*, 2022). Figure 1c shows PLA in its granulated form.

Figure 1 – Materials for 3D printing. (a) PLA filament spools
(b) Creality brand 3D printer, Ender 3 model**.** (c) Granular form of PLA

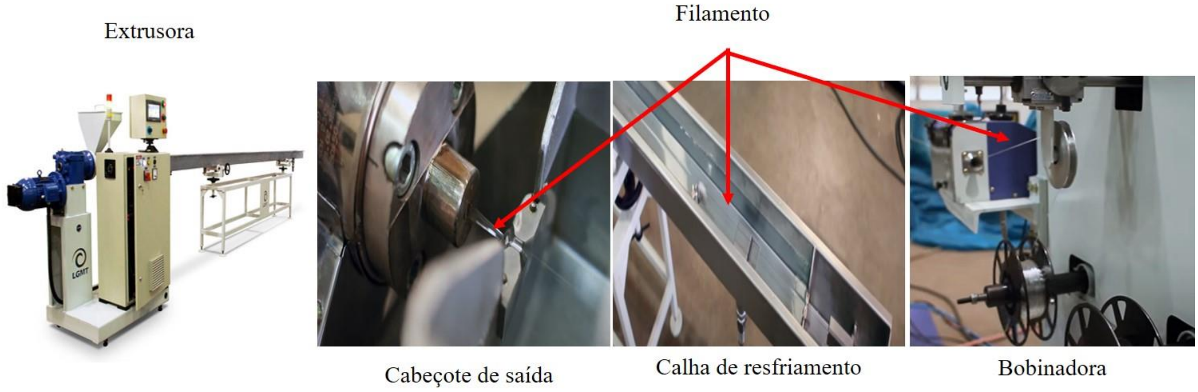


(a) (b) (c)

Source: Prepared by the authors.

The filaments that go to commerce are developed in industries specialized in manufacturing raw materials for 3D printing. The formation of the filament takes place using a twin-screw or single-screw extruder. In Figure 2, we have an example of producing filament in transparent color to be used in the 3D printer. The *fresh pellets* (granules) of a polymer are fed into the extruder, which in turn will melt the plastic due to heating and the material will exit through a nozzle with a diameter of approximately 1.75 mm, in which it will undergo a thermal shock in the cooling trough and will be pulled through a rewinder, which will wind the filament onto a spool.

Figure 2 – PLA filament industrial extrusion process



Source: Adapted from https://www.lgmt.com.br/linha-filamento-impressora-3d.

The techniques of obtaining polylactic acid by bacterial fermentation of starch and polymerization of PLA "made it a biodegradable renewable source polymer of greater competitiveness in the market, with affordable prices and large-scale production, reaching a global production capacity of 350 kt/year in 2014" (Dartora, 2018, our translation).

PLA is a material that has high surface hardness, having a harder structure than ABS. PLA is very resistant to abrasion, has high printing quality and excellent adhesion between layers, being considered an environmentally friendly polymer compared to petroleum plastic materials, such as ABS, polyethylene and polypropylene. In the current market, in Brazil, a kilo of a spool containing PLA costs an average of R$130.00.

The main mechanism of PLA degradation is hydrolysis, followed by bacterial biodegradation. The rate of degradation by hydrolysis can be catalyzed by acids or bases, causing PLA to degrade in weeks or months, in periods of less than two years. On the other hand, the high moisture content, pH and temperature, both in aerobic and anaerobic conditions are factors that contribute to biodegradation. However, under conditions favorable to use, PLA maintains its characteristics and properties for years (Dartora, 2018; Vaccioli, 2015).

Parallel to the issue of PLA biodegradation, with the advancement of technology and Industry 4.0 a new concept has emerged: Sustainability 4.0, which comes from the premise of new thinking about the use of natural resources and the use of technologies in favor of the environment. The evolution of thought and technology are driven by environmental challenges in relation to the use of natural resources and the integration of man in the reconnection to change thoughts, attitudes and values towards behavior that values the forest and changes degrading habits regarding the environment. Companies will need to review the conduct of their environmental practices and consumers are more attentive, demanding and willing to consume (read as pay for) sustainability (Maya, 2019).

As a result, with environmental concerns and pressure for more sustainable production changes in industries, the circular economy model emerged as an alternative to the current economic model and as one of the solutions for sustainable development, in a closed cycle of material flows in the economy (Santos; Shibao; Silva, 2019).

The traditional mode of production and consumption is carried out in a linear manner through the manufacture of products, marketing, consumption and subsequent disposal of the product in landfills. However, this model does not consider that natural resources are finite, which leads to waste and pressure for exploitation, which hinders the ability of an ecosystem to regenerate (Gonçalves; Barroso, 2019). The circular economic model is based on three principles: 1. Preserve and improve capital, through controlling the stock of finite natural resources and balancing the flow of use of renewable resources; 2. Optimize the yield of resources, promoting the use of waste and encouraging recycling through the 5 Rs (reduce, recycle, reuse, rethink and refuse) and 3. Stimulate the effectiveness of the system (Pontes; Ângelo, 2019).

During the circular economy cycle, reverse logistics is applied in the economic flow as it is an important tool for waste management, not only business but also domestic. The National Solid Waste Policy (PNRS), Law No. 12.3051 of 08/02/2010, in Article 3, item XII, defines reverse logistics as:

> Instrument of economic and social development characterized by a set of actions, procedures and means designed to enable the collection and return of solid waste to the business sector, for reuse, in its cycle or in other production cycles, or other environmentally appropriate final destination (Brasil, 2010, on-line, our translation).

Materials and methods

In our work, the recycled PLA filament was made from granules (cut pieces) of PLA waste from 3D printing, demonstrating the use of discarded prints using an extruder, which has technological properties that make it usable. Therefore, for the workshop to be carried out, we followed the steps listed below in this action research:

Workshop preparation

Before holding the workshop, we carried out a technical adaptation for the mechanical conversion of PLA waste (Hidalgo-Carvajal *et al.*, 2023; Spinacé; De Paolli, 2005). We collected waste from 3D prints (Figure 3a) made with PLA filaments from the manufacturer 3D LAB (3D Lab, 2023), from the Rivelino Lima Maker Space of the Federal Institute of Education, Science and Technology of Amazonas do Distrito Industrial (IFAM/CMDI). Then, at the Nanomaterials Synthesis and Characterization Laboratory (LSCN/IFAM), belonging to the IFAM Innovation Hub (INOVA), the waste was cut with the aid of cutting pliers into sizes of 2 to 4 cm in length and width (Figure 3b) and were crushed in a knife mill (Figures 3c and 3d). Then, the cut pieces were weighed (Figure 3e) and, at the end, they went through the drying process in an oven at 90ºC for 2 hours (Agaliotis *et al.* 2022) in order to remove moisture (Figure 3f).

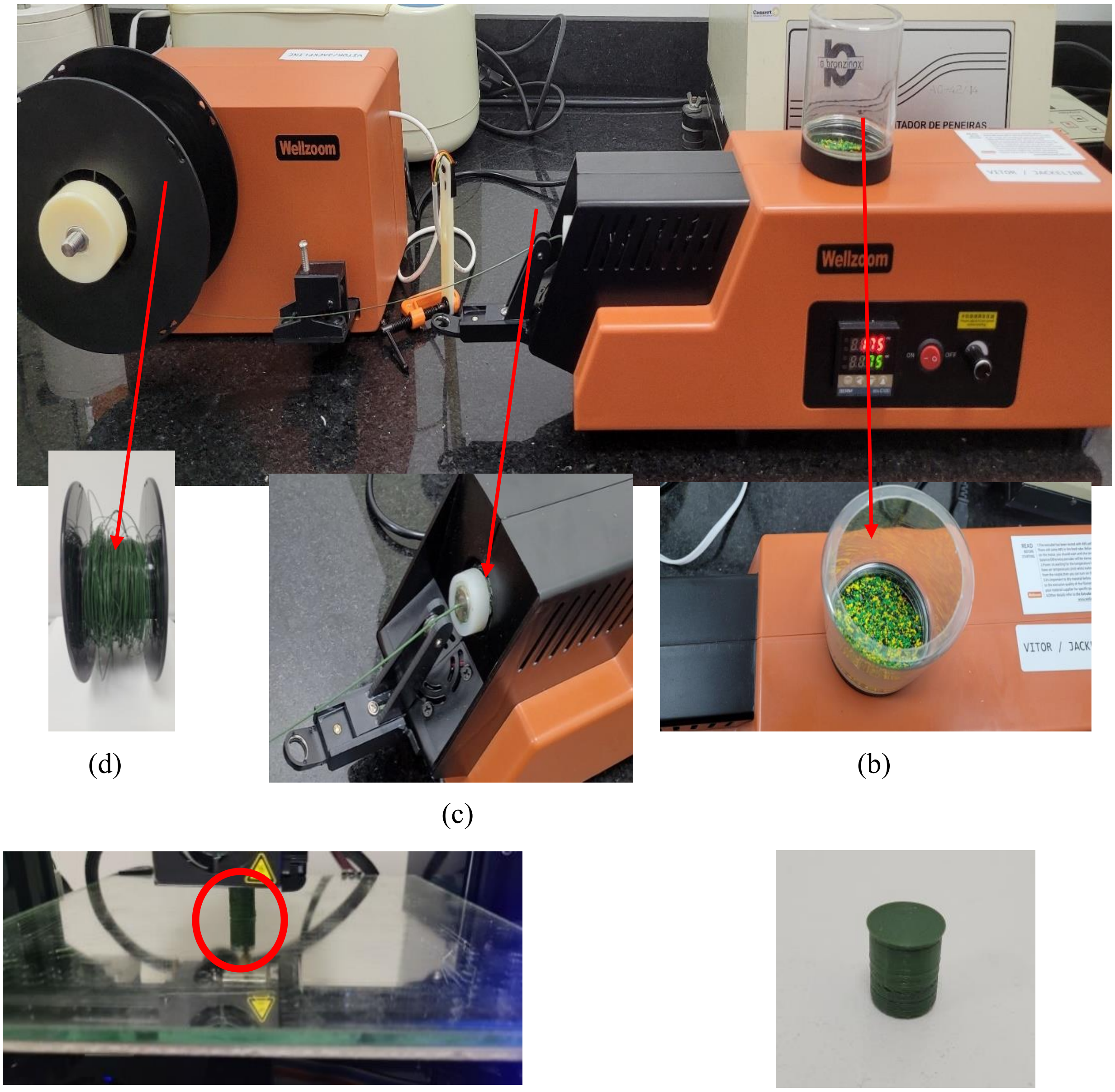
Figure 3 – Manufacturing process of recycled filament
(a) Waste. (b) Cutting waste. (c) Grinding in the mill. (d) Crushed waste. (e) Weighing the residue. (f) Oven drying

Source: Prepared by the authors.

Obtaining recycled filament

After drying in the oven, we obtained a filament made from PLA waste, initially in order to check whether the extruder met manufacturing expectations and to detect possible improvements in our extrusion process before starting the workshop. Figure 4a shows the single-screw extruder and rewinder used in this workshop, both from the Chinese brand *Wellzoom* (Wellzoom, 2023), together with the filament generated by the extrusion process. Figure 4b shows the waste inside the feeder and Figure 4c shows an extrusion being carried out successfully. The extrusion process consisted first of feeding the PLA residue into the extruder (Figure 4b), with a temperature of 175ºC using a rotating single-thread screw to melt the material, which resulted in the output of the filament with a diameter of approximately 1.75 mm (Figure 4c), which went to automatic winding on the rewinder (Figure 4d). After completion of the extrusion process, we print on the *Creality 3D printer* (CrealityStore, 2023) the *Ender* 3 model (already shown in Figure 1b) a cylindrical part (Figure 4e) to visualize the 3D printed object from recycled PLA, which can be seen in Figure 4f.

Figure 4 – Obtaining the recycled filament from the extruder and printing a part
(a) Extruder and rewinder. (b) Waste in feeder. (c) Recycled filament. (d) Spool with recycled filament. (e) Printing 3D part. (f) Ready piece



(d) (c) (b)

(e) (f)

Source: Prepared by the authors.

Carrying out the workshop with students

After the preparation process, the PLA filament recycling workshop took place in the training room of the IFAM Innovation Hub. 19 IFAM students participated in the workshop, including 2 from the Software Engineering Higher Education Course, 2 from the Control and Automation Engineering Higher Education Course, 1 from the Industrial Mechatronics Technology Higher Education Course, 5 from Integrated Technical High School in Electronics and 9 of Integrated Technical High School in Mechatronics. All students were already familiar with 3D printing. The workshop lasted around 2 hours and went through the following itinerary: first, a presentation was made on Materials Technology and LSCN, which is the laboratory where this project is being developed.

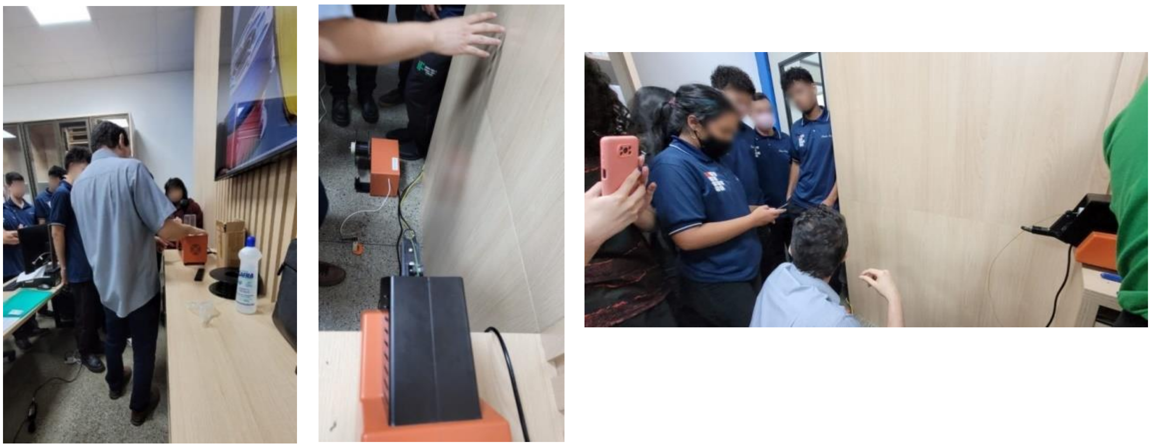
Next, we present the concepts of 3D printing, the types of filaments used, we emphasize the concept of polymers and the importance of using waste from 3D printing, as well as empty spools after the filament is finished. It was also taught how industrial and laboratory filament manufacturing is carried out, and finally, we explained the processes carried out in steps (1) and (2), so that students could understand more clearly the steps to be taken to recycle waste PLA filaments. Figure 5 shows the workshop, when the steps for recycling PLA shown in Figure 3 were being explained.

Figure 5 – PLA filament recycling workshop carried out at the IFAM Innovation Hub

Source: Prepared by the authors.

We then carried out the practical part of the workshop, in which all students learned how to manufacture recycled filament, as shown in Figure 6. In this stage, we used the already crushed and dried waste resulting from the preparation process in the laboratory before the workshop and explained to students in the theoretical class. In Figure 6a, we explain about the extruder; In Figure 6b, we present how it works for the students and in Figure 6c, the students recorded the moments of production of recycled PLA. During the workshop, we asked some students if they understood sustainability, 3D printing, the process of manufacturing filaments for 3D printing and what they found interesting about this workshop.

Figure 6 – Practice in the PLA filament recycling workshop
(a) Presentation of the extruder machine. (b) Extruder in operation in front of the students (c) Students recording the operation of the extruder



(a) (b) (c)

Source: Prepared by the authors.

Results and discussion

As a result of the questions asked to students, all students knew about 3D printing and 68.8% had already printed a 3D object. Regarding the process of manufacturing filaments for 3D printers, 56.3% already knew, however, they did not understand in depth all the stages of industrial manufacturing. Regarding sustainability, among the most frequent responses, some students agreed that sustainability represents the balance found in the exploration of natural resources and the preservation of the environment, being able to reuse materials, being a means of making life on the planet more lasting and with quality.

The students also found it interesting to be able to manufacture PLA filament from 3D printing waste and to be able to use what was previously considered waste in new 3D objects. Among some opinions, it was reported that the reuse of materials that are currently thrown away is essential to reduce the volume of waste in the environment. Furthermore, using 3D printing waste to make new filaments becomes relevant and sustainable, which in the future can generate income for people who are interested in 3D printing. This is because organizations seek to combine plastic recycling and 3D printing technology to create innovative, low-cost and sustainable solutions that can be adapted for production in micro-enterprises, individual micro-entrepreneurs (MEIs) and *startups* (Pires, 2022).

The students also mentioned that by reusing waste, it is possible to use almost all of the filament for printing, reducing waste and filament manufacturing costs. The students were interested in the area, showing their desire to manufacture their own filament and even, in the future, set up their own extruder, using not only PLA, but other extrusion materials. Studies show that other materials can be used in the extrusion process for 3D printing, such as PET polymers (polyethylene terephthalate), polyethylene and polypropylene (Ferreira, 2020; Pires, 2022).

Positive feedback from students shows that we managed to awaken environmental perception in them, stimulating interest in the reuse of materials that could previously be discarded inappropriately in the environment, as according to Ross and Becker (2012) environmental education seeks solutions and results in favor of of the environment and even preparing citizens as transformative agents.

Although the workshop duration with the students was 2 hours, it was enough to obtain positive results. This workload is also due to the fact that the availability of students has been limited, since many higher education students work and high school students work full time, reducing their free time. For work that was carried out for the first time within the scope of IFAM, integrating Environmental and Professional and Technological Education, these results were satisfactory, confirming the usefulness of the workshop held.

We noticed that in this workshop there was an environmental perception among students, which raised awareness in each student of the importance of sustainability and valuing the environment, even with industrial progress. In our approach, we integrate the technological area with environmental sciences, at the same time that we prepare students for the world of work in the Technological and Engineering areas, as well as seeking to raise awareness about sustainability. Thus, we add additive manufacturing technology to a sustainable economy, in addition to contributing to reducing the volume rejected from the reuse of 3D printing.

Final remarks

In this work, we present an experience report of a 3D printing waste recycling workshop, especially PLA filament, from obtaining waste, through preparing the workshop to its practical execution. This process contributes to sustainability since PLA, despite being biodegradable, is a polymer that can accumulate in nature if not properly reused.

It was possible, through the workshop, to apply in practice concepts of sustainability and technology in the use of waste from 3D printing to form recycled filaments that return to the consumption cycle in new prints, in addition to encouraging the teaching of this technique by combining the areas of students involved, which are Technologies and Engineering. We noticed that in this workshop there was an environmental perception of the students, in which the importance of sustainability and the appreciation of the environment, combined with industrial progress, was raised in each student's awareness.

As future work, we consider 3D printing workshops together with the recycling process with a larger target audience, covering other shifts and more courses, with a broad workload, possibly within a discipline involving the environment or as an extension course for students who are unfamiliar with 3D printing and recycling printing materials. We also envision using this technique in communities, within the scope of solidarity economy and entrepreneurship, using 3D waste from various sectors of society such as domestic, industrial, educational, and makerspaces.

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