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# A SUSTAINABLE APPROACH TO RECYCLING WASTE: EXAMPLES OF THE APPLICATION OF 3D PRINTING TO EXTEND THE LIFE CYCLE OF MATERIALS

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**ABSTRACT**
The environmental questions emerged in recent decades have caused a transition from a linear economy, which involves the extraction of raw materials, production, distribution, consumption and final disposal of a good, to a circular economy (CE). CE is based on the reuse of materials in subsequent production cycles by extending their useful life, with the aim of reducing and if possible, eliminating any waste. Fused Filament Fabrication (FFF), a 3D printing technique, has emerged in recent years as a promising methodology for green and sustainable purposes. The use of natural and biocompostable materials for the production of filaments for FFF, such as poly(lactic acid) (PLA), has made this 3D printing technique one of the most promising in several fields. Furthermore, scientific research is focusing on improving the sustainability of primary materials used in 3D printing, through the development of composite filaments from green or recycled materials. This paper presents some applications concerning the development of innovative and sustainable materials focused on reducing the environmental impact of conventional FFF materials, carried out in recent years in our laboratories. In particular, various composite filaments incorporating poly(lactic acid) (PLA) and different handicraft or agro-industrial waste materials, including olive wood waste (OW), cocoa bean shell waste (CBSW), ceramic waste (CW) and Lecce stone waste (LSW), have been produced by extrusion. A comprehensive analysis was conducted on the innovative biocomposites developed, including structural, morphological, thermal and mechanical evaluations, and the comparison of the results obtained with the different subproducts is presented in the paper. Finally, some simple real objects first reproduced manually, were later 3D printed using the developed biocomposite filaments, demonstrating the effectiveness of FFF in successfully recycling artisanal and agro-industrial waste within the same production company, reducing costs and supporting the CE.

## 1. INTRODUCTION

Excessive use of synthetic materials (such as metallic, ceramic, stone materials) and plastic, that are generally difficult to discard, has caused increasing environmental problems. Stringent European waste management legislation emphasizes the importance of creating new material recycling strategies, highlighting a necessity for a complete transition from a linear economy to a circular economy (CE) (Ghisellini et al., 2016; Kirchherr et al., 2017). Fused Filament Fabrication (FFF), an Additive Manufacturing (AM) technique, has recently emerged in several industries as a versatile, low-cost and sustainable methodology (Fico et al., 2022). FFF allows to reduce the disproportionate use of raw materials compared to traditional manufacturing processes, explore innovative methods of waste management and valorization, and at the same time extend the life cycle (Fico et al., 2022). Usually, the heating element of commercially available FFF machines achieves a maximum working temperature of about 300°C, so thermoplastic polymers have until now remained the most widely used materials in 3D printing, due to their processability, the multiplicity of types and colors available on the market, versatility and sufficient mechanical properties conferred to printed objects (Vyavahare et al., 2020). Among them,

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polylactic acid (PLA) is perhaps the most widely used thermoplastic polymer in FFF printing, since it is of natural origin, biodegradable and biocompatible (Mikula et al., 2021). However, despite its versatility and environmental benefits, PLA shows great sensitivity to high temperatures and moisture (Rizzo et al., 2023). In addition, the final properties of PLA-printed objects may not be suitable for structural applications (Algarni & Ghazali, 2021).

Over time, rapid advances in materials engineering have facilitated the development of innovative polymer-based composite for use in FFF printing. In particular, innovative filaments for FFF have been developed, using natural or recycled materials as fillers for the polymer matrix (Rajendran Royan et al., 2021; Rett et al., 2021); in the first case, green, natural, biodegradable and low-density composite filaments for FFF were obtained (Carichino et al., 2023; Kariz, Sernek, Obućina, et al., 2018); in the second case, scientific research has led to the development of composite filaments with better mechanical performance compared to pure polymer, with economic and ecological benefits (Corcione et al., 2017; Esposito Corcione, Scalera, et al., 2018; Fico et al., 2023).

For example, several scientific studies have developed and tested innovative filaments for FFF containing wood from different plant species as a filler added to the polymer matrix, either in the form of particles or fibers (Das et al., 2021; Fico et al., 2022; Vásquez-Garay et al., 2021; Xu et al., 2018). The FFF filaments that have been produced are non-toxic, completely biodegradable, have good elasticity but in some cases have a high stiffness and hygroscopicity compared to traditional polymer; this is the reason that scientific research continues to propose several studies with the aim of increasing the final properties of wood-based filaments. Even less used in the scientific research are cocoa bean shell waste (CBSW), whose production is growing due to the ever-increasing consumer demand for chocolate, currently disposed of as organic fertilizer, animal feed or fuel, even if with negative environmental effects. However, a few research conducted in recent years have also seen its use as a filler to the polymer matrix (poly(lactic acid) or polycaprolactone) in 3D printing (Fico et al., 2024; Puglia et al., 2016; Sanyang et al., 2017; Tran et al., 2017). The condition is different for non-biodegradable inorganic materials, such as ceramic or stone, whose growing use in the artistic, engineering, construction, biomedical, aerospace and automotive fields cause a considerable accumulation in the environment and greater difficulties and costs associated to their disposal. These requirements have given rise to many works in the scientific literature on the recycling of these materials for the production of composite filaments used in FFF, with excellent thermal and mechanical properties, and used specifically for biomedical or tissue engineering applications (Esposito Corcione et al., 2019; Esposito Corcione et al., 2018; Fico et al., 2022).

Our research group on "Additive Manufacturing" at the University of Salento (Lecce, Italy) has also been actively involved for years in the recycling of several types of organic and inorganic waste mainly supplied by local artisans and manufacturers, through FFF technology (Corcione et al., 2020; Ferrari et al., 2020, 2022; Lionetto & Esposito Corcione, 2021). The main goal of our research is not only to reduce the environmental impact, to promote the principles of the CE by giving new life to raw materials, but to produce new 3D objects starting from agro-industrial and artisanal waste, which as a novelty can help producers to reduce waste disposal practices and costs and at the same time obtain new objects that preserve the unique value of their creations.

This paper presents some of these applications regarding the development of innovative and sustainable materials for FFF printing. In particular, different composite filaments based on poly(lactic acid) (PLA) and several artisanal or agro-industrial waste materials have been produced by extrusion process. A complete structural-morphological, thermal and mechanical characterization was carried out and the results were compared with each other. Finally, some simple real objects were faithfully reproduced by hand and then three-dimensionally to be 3D printed, showing the adaptability of the FFF methodology as a low-cost, easy and sustainable solution to recycling materials in the same waste production company (Figure 1).

## 2. EXPERIMENTAL

### 2.1 Materials and methods

In this work, the applicability of artisanal and agro-industrial waste recycling of FFF printing and its possibility to extend the life cycle of materials were tested through the development of biocomposite filaments for FFF, from some scraps provided by local companies. Waste of organic and inorganic origin was added in powder form as filler to the polymer matrix selected for its green properties, the poly(lactic acid) (PLA), and extruded to form the biocomposite filaments later used for 3D printing.

Details of the materials and methodologies used are provided in the following paragraphs.

#### *2.1.1 Materials*

For the production of the new biofilaments potentially used for the 3D printing technology known as FFF, the following scraps were used: poly(lactic acid) (PLA), cocoa bean shell (CBSW), Olive wood (OW), Lecce stone (LSW) and ceramic waste (CW).

Ingeo 4043D poly(lactic acid) (PLA) was purchased in pellet form (diameter of 5 mm) from the company NatureWorks LLC (Blair, NE, USA). PLA is characterized by a melt flow index (MFI) of 6 g/10 min at a temperature of 210°C and a density of 1.24 g $cm^{-3}$. The pellet was stored in an oven at 60°C for 24 h, ground using the Retsch ZM 100 ultracentrifugal mill (Retsch GmbH, Haan, Germany), obtaining a particle diameter of about 0.75 mm.

The organic waste used in the production of new filaments are cocoa bean shell waste (CBSW) and Olive wood (OW). The CBSW derive from the chocolate processing residues of the company "Maglio Arte Dolciaria S.R.L." (Maglie, Lecce, Italy). CBSW was supplied in the form of a coarse powder, with a brown color and a chocolate-like odor. The Olive wood (OW) waste was instead supplied by "I Lumi del Faso di Sante Musa", member of the "Fatto in Bottega" association (Brindisi, Italy). CBSW and OW were oven dried at 60°C and subsequently ground to a diameter

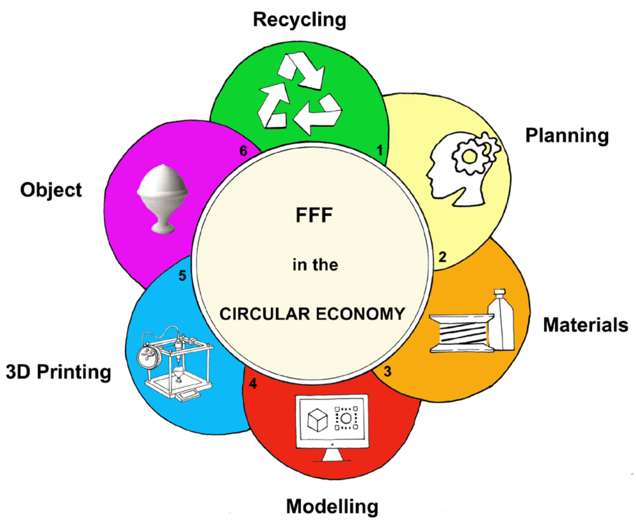


**FIGURE 1:** Applicability of FFF printing to Sustainability, Recycling and Circular Economy.

of about 0.25 mm, using a Retsch ZM 100 ultracentrifugal mill (Retsch GmbH, Haan, Germany).

The inorganic waste used in the production of new filaments are Lecce stone (LSW) and ceramic (CW). The Lecce stone (LSW), a local calcarenite, was supplied by the company Décor srl (Monteroni, Lecce, Italy), in the form of a monolithic block having a water content of 88% by weight. The stone was then first dried in an oven at 60°C (reducing the water content to 20% by weight) and then crushed with a mortar and sieved through a fine mesh sieve (0.25 mm diameter). Instead, the CW waste was supplied by the ceramic laboratory of the "Fatto in bottega" association (Brindisi, Italy). The waste was subjected to an initial washing under tap water, followed by drying in an oven at 100°C. Finally, the waste was reduced to powder with a diameter of approximately 0.02-0.03 mm using first manually the hammer and then the planetary ball mill of the Ceramic Instruments company (Sassuolo, Italy).

### *2.1.2 Experimental procedure*

The experimental activity carried out mainly consisted of following steps (Figure 2):

- Recycling of artisanal and agro-industrial waste materials through their use as an additive to the PLA polymer matrix and development of new biofilaments for FFF printing;
- 3D printing of simple prototypes (bars) starting from composite filaments used for printability evaluation tests;
- Identification of real models to be returned to the companies producing the waste and their manual reproduction;
- Three-dimensional reproduction and 3D printing.

The following composite filaments for FFF were developed starting from the waste materials indicated previously: the first consisting of 100 wt. % of PLA, the other filaments were developed starting from 90 wt. % of PLA and 10 wt. % of the several wastes CBSW, OW, LSW, CW. The denomination of the developed filaments is shown in Table 1. To obtain the new filaments, the PLA and waste powders were first mixed manually at room temperature and then inserted into the 3Devo Composer 450 Filament Maker single-screw extruder (Utrecht, The Netherlands), using the parameters reported in Table 2.

Simple prototypes (bars) were printed using the Creality CP-01 printer (Creality, London, United Kingdom) starting

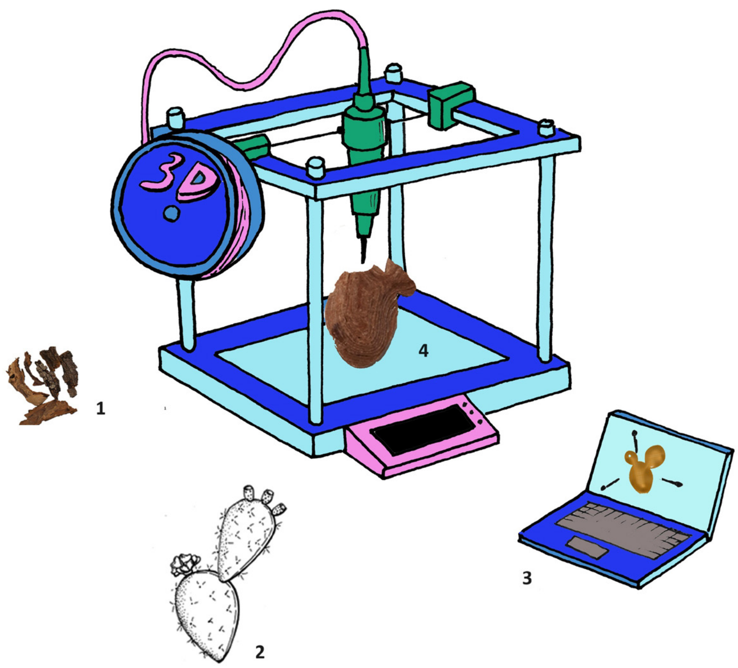


**FIGURE 2:** Chart of the experimental procedure: recycling of artisanal and agro-industrial waste materials (1), real object models and their manual reproduction (2), 2D and 3D reproduction (3), 3D printing (4).

**TABLE 1:** Biofilament and bars labels and weight composition (wt. %).

| Form | Label | Composition (wt. %) |
|---|---|---|
| Filament | 100PLA | 100 PLA Ingeo 4043D |
| Filament | 90PLA/10CBSW | 90 PLA Ingeo 4043D and 10 cocoa bean shell waste |
| Filament | 90PLA/10OW | 90 PLA Ingeo 4043D and 10 Olive wood powder waste |
| Filament | 90PLA/10LSW | 90 PLA Ingeo 4043D and 10 Lecce stone powder waste |
| Filament | 90PLA/10CW | 90 PLA Ingeo 4043D and 10 ceramic waste powder |
| Bar | 100PLA_3D | 100 PLA Ingeo 4043D |
| Bar | 90PLA/10CBSW_3D | 90 PLA Ingeo 4043D and 10 cocoa bean shell waste |
| Bar | 90PLA/10OW_3D | 90 PLA Ingeo 4043D and 10 Olive wood powder waste |
| Bar | 90PLA/10LSW_3D | 90 PLA Ingeo 4043D and 10 Lecce stone powder waste |
| Bar | 90PLA/10CW_3D | 90 PLA Ingeo 4043D and 10 ceramic waste powder |

**TABLE 2:** Extrusion process parameters for biofilaments.

| Extrusion Process Parameters | 100PLA | 100PLA/10CBSW | 100PLA/10OW | 100PLA/10CW | 100PLA/10LSW |
|---|---|---|---|---|---|
| Screw speed (rpm) | 3.5 | 4 | 4 | 3.5 | 3.5 |
| Fan cooling speed (%) | 0 | 30 | 0 | 0 | 0 |
| Feed zone temperature (°C) | 170 | 165 | 185 | 200 | 220 |
| Compression zone temperature (°C) | 185 | 180 | 190 | 190 | 210 |
| Metering zone temperature (°C) | 190 | 185 | 185 | 210 | 190 |
| Die temperature (°C) | 200 | 165 | 187 | 220 | 170 |

from the developed filaments, with the aim of carrying out evaluation tests of the final properties and in accordance with the European standard ISO178:2014 (Table 1). Fusion 360 software (Autodesk, San Rafael, CA, USA) was used to create the CAD model and Cura software (Ultimaker B.V., Utrecht, the Netherlands) was used to obtain the printer-readable G-Code file. The following printing parameters were used: extrusion temperature at 200°C, platen temperature at 50°C, print speed at 50 mm/s, infill at 100%, and cooling fan speed at 100%.

An evaluation of the final properties of the biofilaments developed in the work was carried out by observing the surfaces and sections under a scanning electron microscope (SEM), model Zeiss E Evo 40 (Oberkochen, Germany) and measuring the thermal features with the DSC instrument (Mettler Toledo DSC1 StareSystem), temperature range 25°C to 200°C, heating rate of 10°C/min. For each filament, 5 measurements were carried out. An evaluation of the final properties of the biocomposites was carried out by bending testing on bars using a Lloyd LR5K dynamometer (Lloyd Instruments Ltd., Bognor Regis, UK) at a test speed of 2 mm/min and a support spacing of the 64 mm specimen. For each sample 5 measurements were carried out. The printability of the new biofilaments was also evaluated with magnify images of bars sections after mechanical tests obtained with the Dino-Lite digital microscope (AnMo Electronics Corporation, New Taipei City, Taiwan).

Finally, some simple objects to be displayed in the companies that supplied the waste materials were identified as an application example of the total experiment. These were initially reproduced manually in two dimensions; the same two-dimensional models were transformed into CAD format using Fusion 360 software (Autodesk, San Rafael, CA, USA) or Rhinoceros software (Robert McNeel & Associates, USA) and converted to G-Code files using Cura software (Ultimaker B.V., Utrecht, The Netherlands). Specifically, 3D objects printed from CBSW and OW waste-based green filaments were made using the Creality CP-01 printer (Creality, London, UK), an extrusion temperature of 190°C, plate temperature of 50°C, printing speed of 60 mm/s and infill of 20%. Objects obtained from LSW and CW filaments were printed using 3DPRN LAB printer (3DPRN company, Castiglione M.R., Italy), extrusion temperature of 200°C, plate temperature of 50°C, printing speed of 40 mm /s and infill of 100%.

## 3. RESULTS AND DISCUSSION

New and sustainable composite filaments were produced by the extruder with a diameter of 1.75 mm. Following the extrusion of the new filaments from the waste materials, some initial evaluations under a scanning electron microscope (SEM) were made. While the 100PLA filament preserves the smooth surface (Figure 3-A), the addition of fillers based on waste materials causes a different surface property. Among the different additives used for the PLA polymer matrix, OW scraps show the greatest increase in surface roughness and aggregation of particles into larger lumps (Figure 3-B). Tao et al. 2017 in the paper regarding the incorporation of wood flour into the PLA matrix to produce 3D printing filaments, highlight an increase in roughness compared to neat polymer filament (Tao et al., 2017). In addition, their paper shows poor interfacial adhesion between the hydrophilic wood particles and hydrophobic polymer particles, caused by the difference in polarity at the interface of the two materials, which causes problems

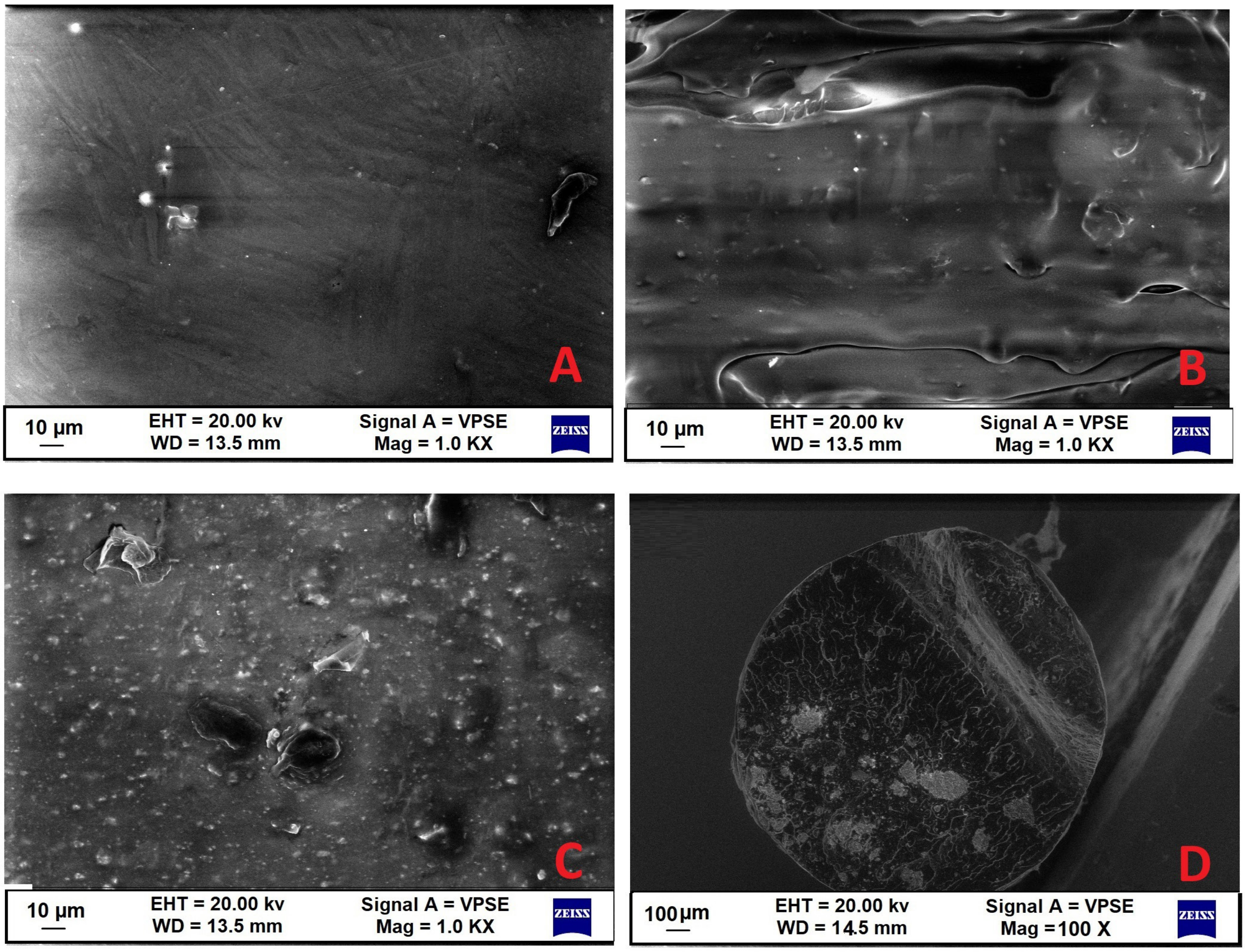


**FIGURE 3:** SEM images of filaments: 100PLA external filament surface (A), 90PLA/10OW external filament surface (B), 90PLA/10CW external filament surface (C) and 90PLA/10CW filament section (D).

of biocomposite inhomogeneity and preferential fracture planes. The inhomogeneity of the developed biocomposite may also be due to the different diameter of the particles in the blend used, and according to the scientific literature can sometimes be reduced through the use of compatibilizing agents. For example, Xie et al. 2017 studied the behavior of two plasticizers, glycerol and tributyl citrate, to improve the interaction between poplar wood flour and PLA, demonstrating better compatibility following the addition of 4% of tributyl citrate (Xie et al., 2017).

Otherwise, the new biofilaments containing CBSW or inorganic wastes (LSW and CW) fillers have a fairly homogeneous surface, although it is roughened in 90PLA/10LSW and 90PLA/10CW filaments (Figure 3-C). However, all biocomposites show particle aggregates in section, especially the 90PLA/10CW filament (Figure 3-D). Inhomogeneity may also be in these cases due to different particle diameters between the polymer matrix and the fillers.

The results of the DSC analysis of PLA-based filament and waste biofilaments are shown in Table 3, in which the glass transition temperatures $T_g$ were measured using the inflection point. The 100PLA filament has a $T_g$ equal to 59.19°C, values similar to those reported in the literature (Algarni & Ghazali, 2021; Fico et al., 2022). The addition of organic waste fillers to the polymer matrix causes a reduction of the glass transition temperatures compared to pure polymer in the 90PLA/10CBSW and 90PLA/10OW samples (Table 3). This indicates that the CBSW and OW particles interacted with the matrix PLA on a molecular scale, causing some changes in the mobility of the polymer chains. The similar thermal behavior of biocomposites based on organic waste is also observed in the crystallization and melting processes. The crystallization temperature $T_c$ of the 90PLA/10CBSW and of the 90PLA/10OW filaments decreases compared to the 100PLA at 106.99°C

**TABLE 3:** Thermal properties obtained from DSC analysis of polymeric neat materials: glass transition temperature ($T_g$), temperature of crystallization ($T_c$) and melting temperature ($T_m$, $T_{m1}$).

| Label | $T_g$ (°C) | $T_c$ (°C) | $T_m$ (°C) | $T_{m1}$ (°C) |
|---|---|---|---|---|
| 100PLA_3D | 59.19 | 124.39 | 154.68 | / |
| 90PLA/10CBSW_3D | 56.66 | 106.99 | 148.12 | 155.40 |
| 90PLA/10OW_3D | 53.43 | 105.67 | 148.67 | 154.50 |
| 90PLA/10LSW_3D | 61.30 | 125.43 | 156.54 | / |
| 90PLA/10CW_3D | 59.40 | 116.11 | 152.24 | / |

and 105.67°C, respectively. Moreover, the thermograms of both biofilaments manifest a double melt peak ($T_m$ and $T_{m1}$) unlike pure PLA and filaments containing inorganic fillers (LSW and CW). The presence of the double melt peak has also been observed by several authors in the literature and has been attributed to the presence of biocomposites to different behavior between the polymer and the organic filler, as well as to different degradation temperatures of cellulose and hemicellulose, the main constituents of CBSW and OW particles (Bryś et al., 2016; Leonard & Berrio, 2021; Tsujiyama & Miyamori, 2000).

The result of the DSC analysis of the 90PLA/10LSW sample show a negligible increase in the temperatures $T_g$, $T_c$ and $T_m$, compared to the 100PLA sample (Table 3). While the 90PLA/10CW sample retains thermal properties similar to PLA (Table 3). The double melting peak is absent in both thermograms.

After 3D printing of bars from the developed composite filaments, mechanical tests were performed and the overall results are shown in Table 4.

The Young's modulus (E) of 2.74±0.03 GPa, the flexural stress ($\sigma_R$) of 102.5±4.12 MPa and the flexural strain ($\varepsilon_R$) of 4.1±0.3% relative to the virgin PLA 3D bars, fall into the ranges reported in the literature (Fico et al., 2022). The flexural test results of the CBSW-based bars indicate a value of $\sigma_R$ (MPa) about half as low as that of the pure poly(lactic acid) bars. $\varepsilon_R$ (%) also decreases to about 3.7±0.2%. These values, in accordance with the scientific literature (Puglia et al., 2016; Tran et al., 2017), indicate an increase in fragility and decrease in ductility of CBSW-based composites compared to PLA bar. However, an increase in Young's modulus (E) of 3.14±0.08 GPa was measured for the CBSW-based biocomposite. As demonstrated in the literature (Rothon, 2003), CBSW particles create polymer phase modifications by interacting with PLA to form an adsorbed polymer interphase. The value of Young's modulus therefore depends on the thickness of the interphase formed and the CBSW-PLA bond, and thus on the shape, size, percentage amount of filler particles and surface area of interaction. The CBSW particles seem to have inhibited the mobility of the polymer chain of the PLA matrix, establishing a strong bond and thus increasing the stiffness of the 3D sample.

A deterioration of the mechanical properties is observed in wood-based biocomposites. Specifically, the flexural modulus decreases 2.1±0.05 GPa, but the most significant changes are observed for $\sigma_R$ (MPa) and $\varepsilon_R$ (%) (Table 4).

Das et al., 2021 in their review of the use of wood for 3D printing technology, report several studies showing a reduction in mechanical properties, at least for substantial percentages of wood added to the polymer matrix (Das et al., 2021). Le Guen et al. 2019, on the other hand while showing a decrease in flexural strength and deformation with the addition of wood powder, indicate an increase in flexural modulus (Le Guen et al., 2019). The phenomenon described in the paper is attributed to the poor interfacial bonding between polymer and wood particles, which does not promote encapsulation of the particles in the polymer binders, resulting in low bonding and the presence of voids in the biocomposites causing a decrease in mechanical strength. According to Kariz et al. 2018 the low affinity between the polymer and the wood particles also results in some difficulties in the melting process of the composite biofilament, resulting in nozzle clogging during the 3D printing process (Kariz et al. 2018; Kariz et al., 2018).

Overall, the results of bending tests obtained from the addition of LSW and CW waste powders are different from the OW-based composites. Specifically, while the σR (MPa) and εR (%) values decrease, the Young's modulus (E) of LSW- and CW-based composites increases, compared to those of virgin PLA (Table 4). As a result, the mechanical performance of the developed biocomposites is sufficient when the addition of fillers reaches 10 wt. %, even if successful mixing of the particles in the polymer matrix has not occurred.

The study of the printability of the biocomposite filaments developed with the waste materials was also accompanied by a Dino digital optical microscope observation of the breaking surfaces of the 3D bars, subjected to the bending tests (Figure 4).

As expected, the 100PLA_3D sample has perfect adhesion between layers (Figure 4-A, F). Good printing properties were obtained in the 90PLA/10CBSW_3D bar, whose magnified image shows good adhesion between layers (Figure 4-B, G) and the 90PLA/10CBSW filament manifests excellent printability. In addition, the organoleptic features of cocoa are preserved in the printed bars, despite the low percentage of filler relative to the polymer matrix and the high temperature melting processes subjected (extrusion and printing). Difficulties due to the printing process occur for the 90PLA/10OW and 90PLA/10LSW filaments, while the breaking surfaces of the composite bars (Figure 4-C, H and Figure 4-D, I, respectively) show poor adhesion between the layers; deformation and voids are also evident in some areas. in addition, the presence of increased porosity of the samples is observed, which probably inhibits the mechanical performance of the composite material, especial-

**TABLE 4:** Mechanical flexural properties: E flexural modulus of elasticity (GPa), $\sigma_R$ flexural stress (MPa), $\varepsilon_R$ flexural strain (%).

| Label | E (GPa) | | $\sigma_R$ (MPa) | | $\varepsilon_R$ (%) | |
|---|---|---|---|---|---|---|
| 100PLA_3D | 2.74 | 0.03 | 102.5 | 4.12 | 4.1 | 0.3 |
| 90PLA/10CBSW_3D | 3.14 | 0.08 | 56.39 | 1.53 | 3.7 | 0.2 |
| 90PLA/10OW_3D | 2.10 | 0.05 | 40.90 | 2.61 | 3.3 | 0.2 |
| 90PLA/10LSW_3D | 3.10 | 0.03 | 70.02 | 2.45 | 3.9 | 0.3 |
| 90PLA/10CW_3D | 3.16 | 0.02 | 76.07 | 5.42 | 3.7 | 0.2 |

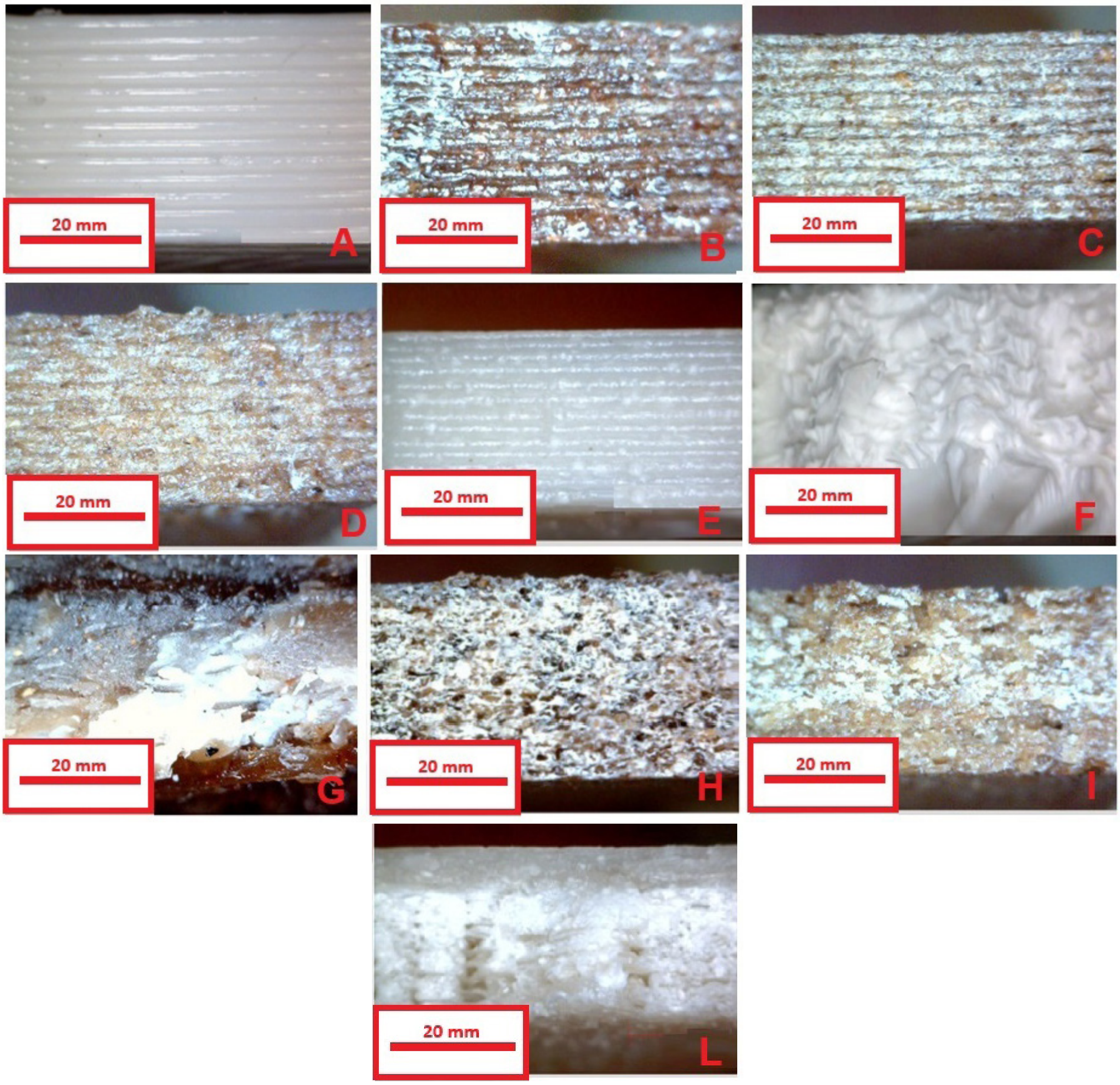


**FIGURE 4:** Magnified images (50x) of the 3D bars after bending test: printing surface of 100PLA (A), 90PLA/10CBSW (B), 90PLA/10OW (C), 90PLA/10LSW (D) and 90PLA/10CW (E); breaking surface after bending test of 100PLA (F), 90PLA/10CBSW (G), 90PLA/10OW (H), 90PLA/10LSW (I) and 90PLA/10CW (L).

ly in the wood sample. Finally, 90PLA/10CW_3D, although showing some air voids between the layers, shows good printability (Figure 4-E, L).

The study of the morphological and thermal features of the new biofilaments and the printability and mechanical properties of the bars printed using FFF were finally accompanied by some application examples that the authors want to show below to attest to the success of the overall experiment.

In collaboration with the companies producing the waste, the authors selected some real objects to reproduce starting from the recycling of raw materials. Specifically, in most cases these are objects widespread by hand or naturally in Puglia (Italy), such as the so-called pumo, the monument in Piazza Sant' Oronzo in Lecce or the Opuntia Ficus Indica plant, or objects that retain the shapes of the original raw materials, for example chocolates. The manual and faithful reproduction of the real objects (Figure 5) was followed by the simplified reproduction of the respective CAD models (Figure 6). The CAD files were converted into GCode and the prototypes were printed using FFF, both in the case of 90PLA/10CBSW, 90PLA/10CW biofilaments with good printability, and in the case of 90PLA/OW and 90PLA/10LSW with sufficient printability.

The experimental activity demonstrates the effectiveness of the FFF methodology in recycling artisanal and agro-industrial waste within the same production company, in favor of important issues such as the circular econo-

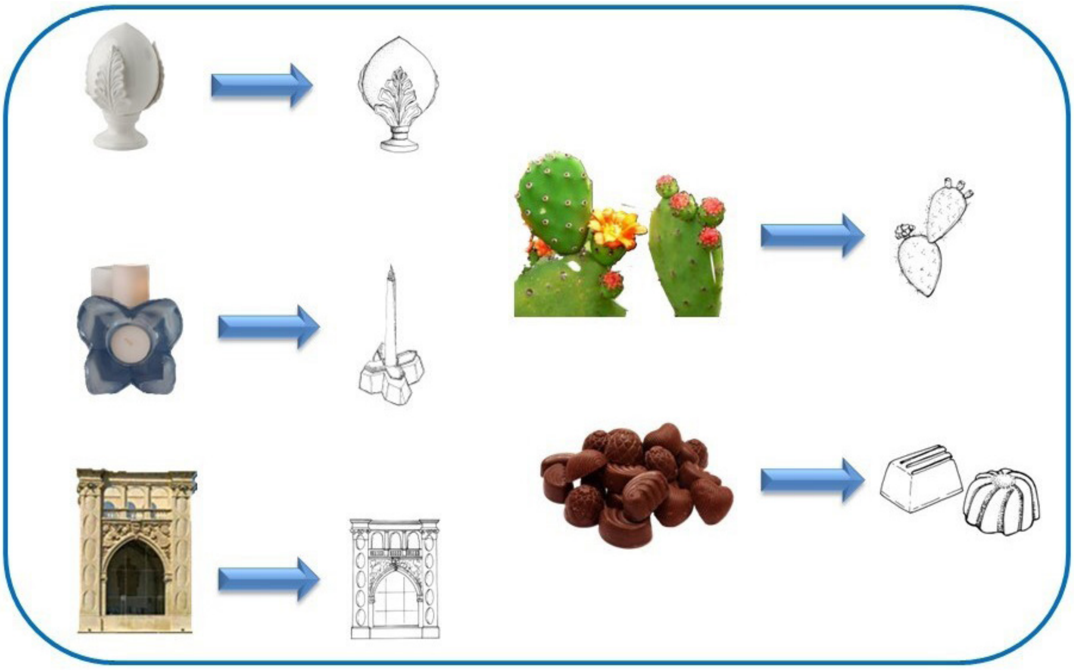

**FIGURE 5:** Real objects and manual and faithful reproduction.

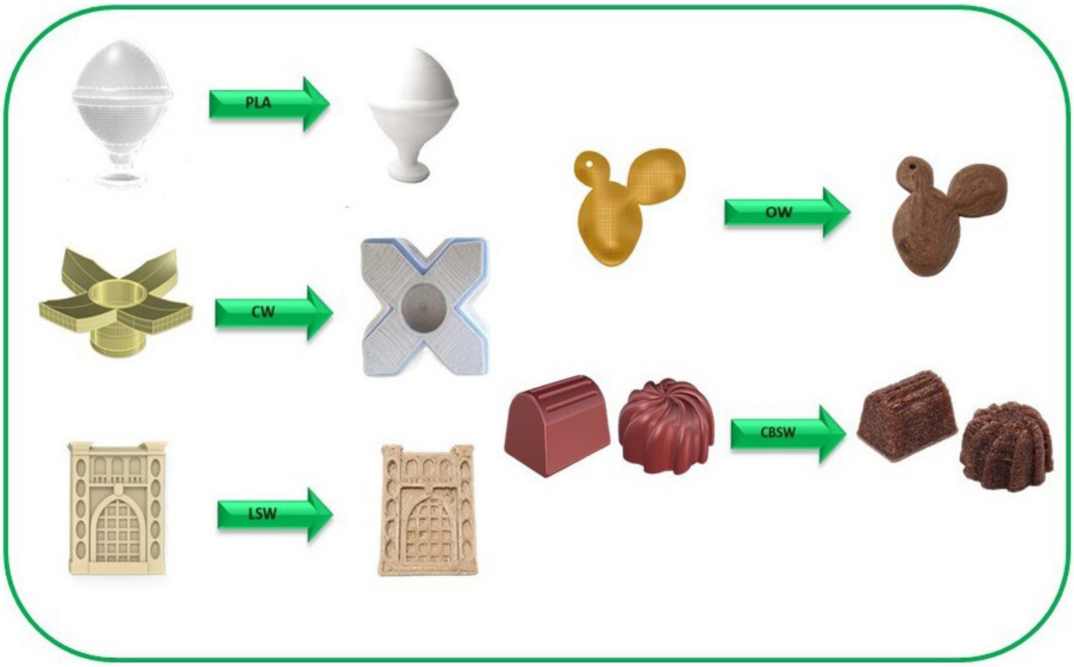


**FIGURE 6:** CAD models and related 3D printed objects.

my and sustainability. At the same time, with FFF printing, green objects with a unique design are produced in an easy and low-cost way.

## 4. CONCLUSIONS

In this paper, the authors demonstrated some examples of the application of Fused Filament Fabrication (FFF) printing to current and pressing issues of sustainability and circular economy. Specifically, the feasibility of producing green biocomposite filaments for FFF from waste derived from artisanal and agro-industrial processes and using polylactic acid (PLA) as the matrix of the biocomposite, due to its biodegradability and biocompostability properties, was studied. For this purpose, local inorganic or organic wastes, such as cocoa bean shell (CBSW), olive wood (OW), leccese stone (LSW), and ceramic (CW) were oven-dried, pulverized, and used in a mixture with PLA, at a concentration of 10 wt. %. Biocomposite filaments with a diameter of 1.75 mm and suitable for the use in FFF were obtained by extrusion and the properties of these and 3D printed bars were evaluated by microscopic-structural observations and bending tests. The results highlight the printability of all biocomposite filaments obtained from waste materials. Among them, CBSW and CW-based composites show similar or even better mechanical properties than neat PLA. The biocomposites OW and LSW-based show a lower adhesion at the interface between the filler and the polymer and the greater presence of particle aggregates in the filaments, which also leads to greater porosity of the 3D composites and a worsening of the flexural properties. Following the study of the printability of the developed filaments, real models were selected to be returned to the waste producing compagnie These models were reproduced manually and transformed into a digital format suitable for 3D printing. The 3D printed objects produced from the developed biofilaments conserve in some cases the material properties of the original waste, such as the roughness of Lecce stone or the organoleptic characteristics of chocolate. Furthermore, with FFF printing it is also possible to create objects with complex shapes and quickly, which are difficult for artisans to create by hand.

Overall, the study demonstrates the potential of FFF printing technology to recycle waste by extending the life cycle of materials, with numerous environmental, economic and ecological benefits.

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