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FIBER LASER SURFACE MODIFICATION OF POLYLACTIC ACID FOR BIOMEDICAL APPLICATIONS

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ABSTRACT

Investigating the potential for fiber laser modification of polylactic acid (PLA) surfaces to enhance its suitability for biomedical applications is the aim of this study. In order to achieve controlled fiber laser texturing of PLA samples created using fused deposition modeling (FDM), different geometrical patterns and processing parameters were utilized. The resulting surfaces were evaluated through Water contact angle measurements, surface morphology analysis using a scanning electron microscope (SEM), chemical characterization using Fourier transform infrared spectroscopy (FTIR), and energy-dispersive X-ray spectroscopy (EDX). Laser treatment dramatically affected the chemical and morphological properties, resulting in improved surface wettability and oxidation with no impact on bulk integrity. Overall, the findings confirm that fiber laser processing is an effective method for tailoring PLA surfaces to improve biocompatibility and potential for tissue engineering applications.

Keywords: SEM, EDX, FTIR, water contact angle, polylactic acid, fiber laser, and surface modification.

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INTRODUCTION

Biomedical engineers are increasingly interested in polymeric materials due to their adaptability, biodegradability, and processability. Polylactic acid (PLA) is distinguished from these materials by its biocompatibility, clinical approval, and additive manufacturing adaptability. In general, surface modification techniques that maintain bulk qualities are required because the inherent hydrophobicity and bio-inertness of PLA surfaces impede cell adherence and tissue integration.

A precise and contact-free way to modify the surface of polymers is with laser-based surface treatment. Fiber lasers stand out due to their reliable operation, good beam quality, and compatibility with scalable processing. Studies have demonstrated that the addition of micro- and nano-structures to PLA through laser processing enhances its surface roughness, wettability, and biological responsiveness. Our goal in this research was to find out how different fiber laser engraving patterns and processing parameters affected the wettability, elemental composition, surface morphology, and chemistry of PLA, a material that could have biological uses.

MATERIALS AND METHODS

A. Materials

Commercial polylactic acid (PLA) filament (Creality) with 1.75 mm diameter and ~98–99% purity was used. The filament was vacuum-sealed to minimize moisture absorption and ensure consistent extrusion during 3D printing.

B. Sample Preparation

Using the following constant parameters: nozzle temperature 200 °C, bed temperature 60 °C, PLA samples were manufactured using fused deposition modeling (FDM) 3D printing and 100% infill. Samples were printed in square geometries suitable for laser processing and characterization. Before laser treatment, one surface of each sample was gently polished with fine-grit abrasive paper.

C. Laser Surface Treatment

At this stage, the PLA surface is treated using a fiber laser, and the treatment will take place in two steps: The first step involves designing Surface Patterns. Patterns being engraved on the PLA surface are designed using Autodesk AutoCAD Three patterns were chosen with varying dimensions. Choosing the patterns to be engraved is one of the most important steps in this project, as the shapes chosen may help increase absorbability, adsorbability, wettability, and other factors. The second step includes Laser engraving. In this step, a fiber laser device (OPT-F50) is used. The sample is placed on the device as shown in Figure-1, so that the laser beam is directed to the center of the sample at a wavelength of 1064nm, frequency of 20kHz, 50W and speed is 500mm/s. The designs that were made using AutoCAD, as shown in the previous steps, are engraved on the PLA surface.

The surface treatment was carried out using a fiber laser system with various pattern geometries, including oblique crossing lines, regular grid lines, and concentric circles. Post-treatment inspections were conducted to evaluate the morphological changes, chemical modifications, and elemental composition of the modified surfaces. This section introduces the observed

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outcomes and provides an overview of how these findings relate to the objectives of the study.

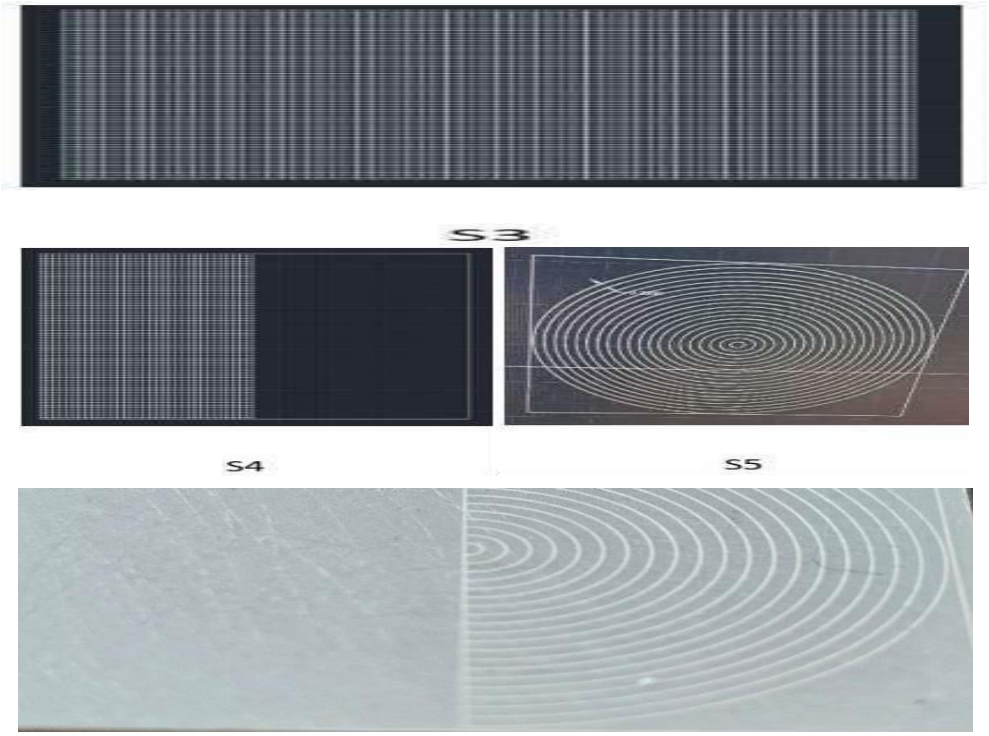


Figure-1. Samples after laser engraving.

D. Characterization Techniques

We used scanning electron microscopy (SEM) to look at the surface morphology. Fourier-transform infrared spectroscopy (FTIR, 4000-400 cm^{-1}) was used to review the chemical composition. The chemical composition was evaluated utilizing energy-dispersive X-ray spectroscopy (EDX) alongside scanning electron microscopy (SEM). We evaluated wettability by measuring the static water contact angle.

RESULTS AND DISCUSSIONS

a) Surface Morphology (SEM)

Scanning electron microscopy (SEM) was used to look at the changes in shape that the fiber laser treatment made to the PLA surface. In the scanning electron micrographs, you can see that laser irradiation created unique micro-scale designs, like grid structures, crossing lines, and concentric circles. The given shapes are matched by these patterns. The fused deposition modeling method left behind small layer lines on untreated PLA surfaces, but the surface was mostly smooth.

When the laser's power was increased, localized thermal effects were seen. These caused material to be ejected, partially melt, and be re-deposited along the engraved routes. Picosecond fiber lasers, which cause these effects, are different from femtosecond lasers because they deal with matter mostly through thermally driven ablation. Consequently, the planned microstructures were somewhat distorted due to the redistribution of molten PLA pieces within and around the laser-engraved regions.

The etched patterns were much more accurate once the laser power was reduced from 50 W to moderate levels of 25- 35 W. Nevertheless, microcracks were encouraged to form, and engraved grooves were partially clogged due to localized heat accumulation brought about by the repetitive overlapping of the laser beam during scanning. Mechanical sanding before laser processing reduced 3D printing surface imperfections, but it did not affect the pattern distortion that was detected. In order to obtain consistent and repeatable surface texturing that is appropriate for biomedical applications, SEM research shows that laser parameters, especially power, scanning speed, and overlap ratio, must be precisely controlled.

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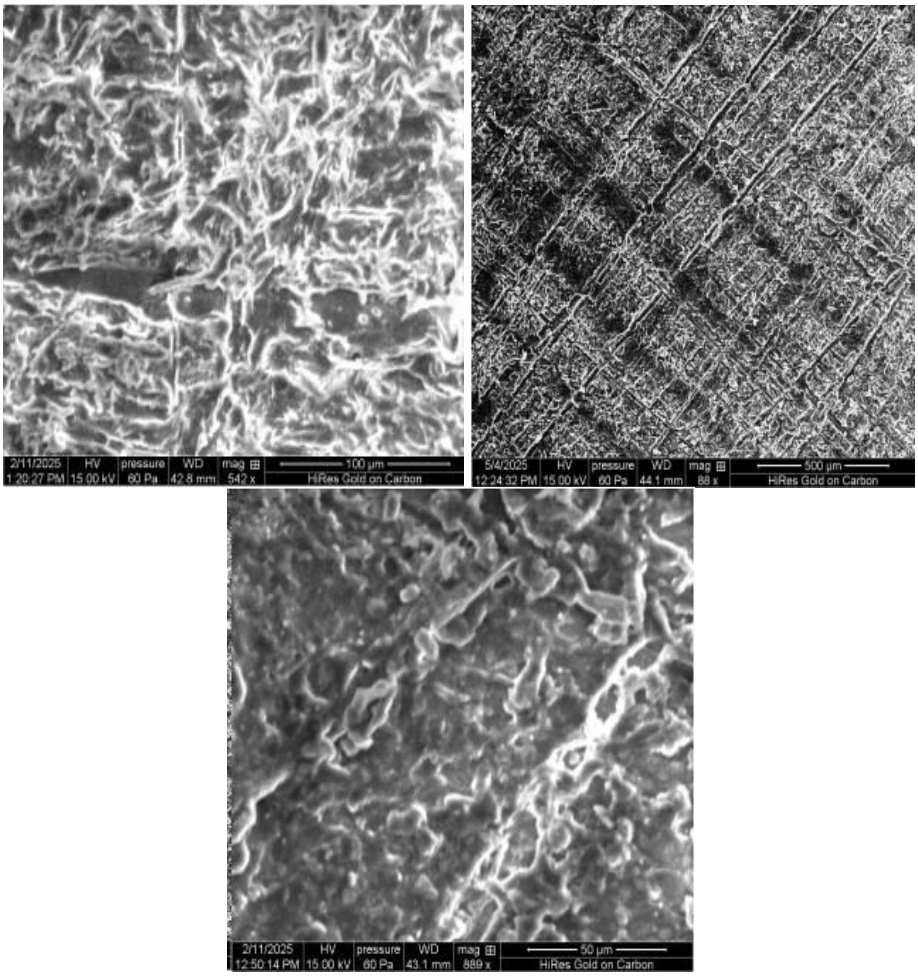


Figure-2. SEM images of the laser-treated PLA samples.

b) Chemical Structure Analysis (FTIR)

FTIR was employed to investigate any chemical modifications induced by the laser treatment on the molecular structure of PLA. The spectrum of the untreated sample was recorded in the range of 4000-400 cm^{-1}, as shown in Figure-3 Following treatment with the picosecond fiber laser; slight variations in the intensity of the characteristic peaks were observed in the (FTIR) spectra of polylactic acid. Although all the fundamental chemical groups associated with PLA were still identifiable, changes in peak intensities indicated minor surface-level chemical modifications induced by the laser process, as shown in Figure-3.3. The FTIR spectrum of the untreated PLA sample, Reference Sample (A3), shows typical PLA absorption peaks:

- Broad peak around 3500-3200cm-¹, attributed to-OH stretching (possibly from terminal groups or residual moisture). Peaks in the 1750- 1740 cm ¹ range indicate C=O stretching of ester groups, characteristic of PLA.
- Peaks around 1180-1080 cm^{-1} corresponding to C-O-C stretching vibrations

These peaks confirm the presence of the characteristic functional groups in PLA and provide a reference for detecting structural changes due to laser treatment.

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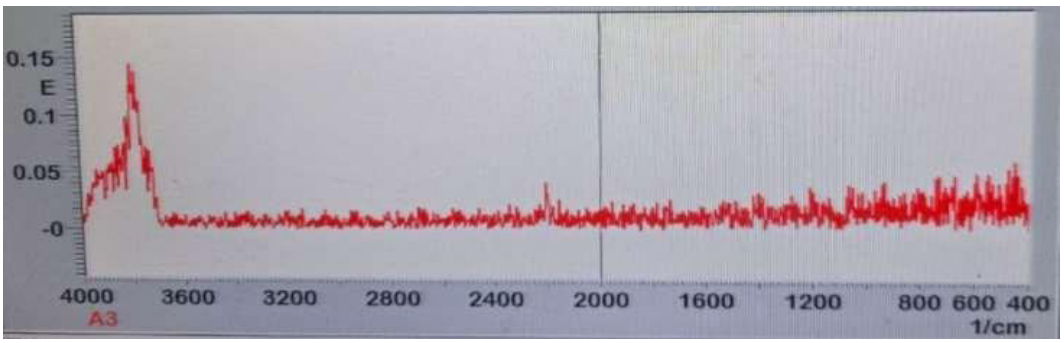


Figure-3. FTIR spectrum obtained from the untreated PLA sample (reference).

Two samples were analyzed with (A3) as a reference

Sample (a1): Laser-treated with a crossed lines grid (35W, 0.6 mm/s, 0.3 mm spacing)

And (c1) Laser-treated with concentric circles (50W, 0.6 mm/s, 0.5 mm spacing)

Sample (a1) Crossed Grid Laser Pattern: Thea1spectrum exhibits:

- Significant modulation and higher intensity across the entire range, particularly around 1700-1200 cm^{-1}, which indicates changes in the ester bonds and potential formation of new carbonaceous species
- A visible change in the fingerprint region (below 1500 cm^{-1}), suggesting microstructural modification or degradation
- A reduction in the clarity of the -OH stretching region, possibly due to localized heating and moisture evaporation. These results suggest that the grid pattern with moderate power (35W) and slower speed leads to partial decomposition or cross-linking of the PLA surface, modifying its chemical structure.
- Sample (c1) Concentric Circles Laser Pattern :Thec1spectrum presents:
- A strong, sharp peak near 1750 cm^{1}, which is more intense than in the first sample and the reference(A3), indicating enhanced formation of carbonyl groups, possibly from oxidation or fragmentation.
- Numerous sharp peaks across 3000- 1000 cm^{1}, possibly due to the formation of new functional groups or by-products, especially from more aggressive treatment (50W power). Overall noise and sharper peaks suggest higher structural modification, consistent with the higher power and energy density. This pattern implies that higher laser power combined with the concentric geometry results in greater thermal decomposition, possibly.

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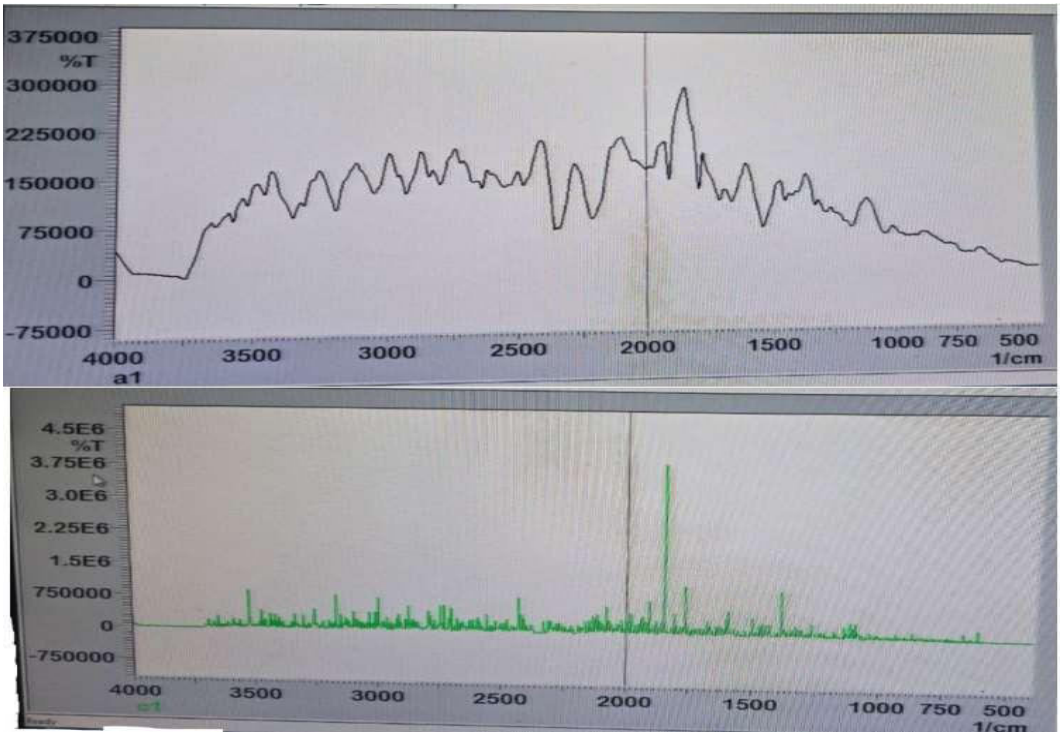


Figure-4. FTIR spectra of laser-treated samples (a1) being (S3) the crossed-lines grid pattern and (c1) being (S5) the concentric circles pattern.

c) Elemental Composition (EDX)

Energy-dispersive X-ray spectroscopy (EDX) was performed alongside scanning electron microscopy (SEM) to evaluate the elemental composition of PLA surfaces before and during laser treatment. The untreated PLA samples exhibited dominant carbon (C) and oxygen (O) peaks, consistent with the chemical structure of polylactic acid. It was determined that there were some trace elements or pollutants present,, as shown in Figure-5, which is evidence that the initial material was not of high quality and contained additives (dopants or fillers).

A rise in the relative oxygen content was found after laser irradiation, particularly for samples that were processed at higher laser power settings, so the laser parameters such as fluence: Energy/unit area and scanning speed. This was notably the case for samples that were processed. As a result of the contact between the laser beam and the oxygen in the atmosphere during the processing, surface oxidation has occurred, which is responsible for this increase. It is possible that oxygen-containing functional groups, such as carbonyl -COOH and hydroxyl -OH species, have formed as a result of the increased oxygen concentration. These functional groups are known to improve surface energy and interfacial interactions.

Importantly, there was no evidence of any foreign elements, such as titanium or calcium, which suggests that the environment in which the laser processing was performed stayed clean and that there was no introduction of any external contamination throughout the treatment process. The findings of the EDX analysis support the findings of the FTIR analysis and provide further evidence that laser surface texturing causes a regulated chemical activation of the PLA surface without affecting the bulk composition of the PLA.

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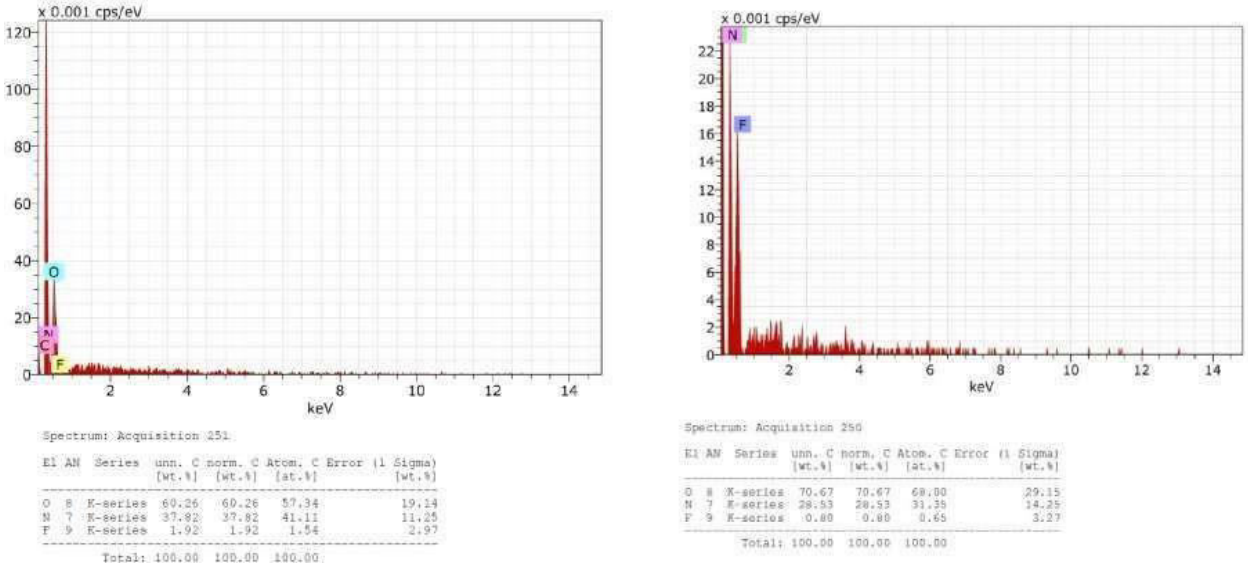


Figure-5. EDX (a) Results of reference sample (b) results of treated sample.

d) An Examination of the Water Contact Angle (WCA):

A drop of distilled water with a volume of one microliter was placed on the control and laser-modified surfaces of the PLA samples for a period of time ranging from five to seven seconds. Figure-6 shows the measurements that were taken in air. The measurements were carried out in accordance with the contact angle method, and the droplet was deposited by a micropipette that was fixed above the sample. The drops ranged from 0.1 to 10 microliters. A high-resolution camera, namely a Huawei P40 Pro camera purchased in China, was used to record the process. ImageJ software, which was equipped with a contact angle measuring plug-in, was used to perform the analysis on the collected images in order to perform the WCA evaluation.

Measurements of the water contact angle indicated that untreated PLA surfaces exhibited hydrophobic behavior with contact angles exceeding 100°. Laser-treated surfaces showed a slight reduction in contact angle values, suggesting moderate enhancement in surface wettability. Although the observed changes were within the experimental uncertainty, the results indicate that laser-induced microstructuring and oxidation contribute to modified wetting behavior. To establish statistically significant conclusions, future investigations should include repeated measurements with automated drop-shape analysis and controlled imaging geometry. Nonetheless, the current results.

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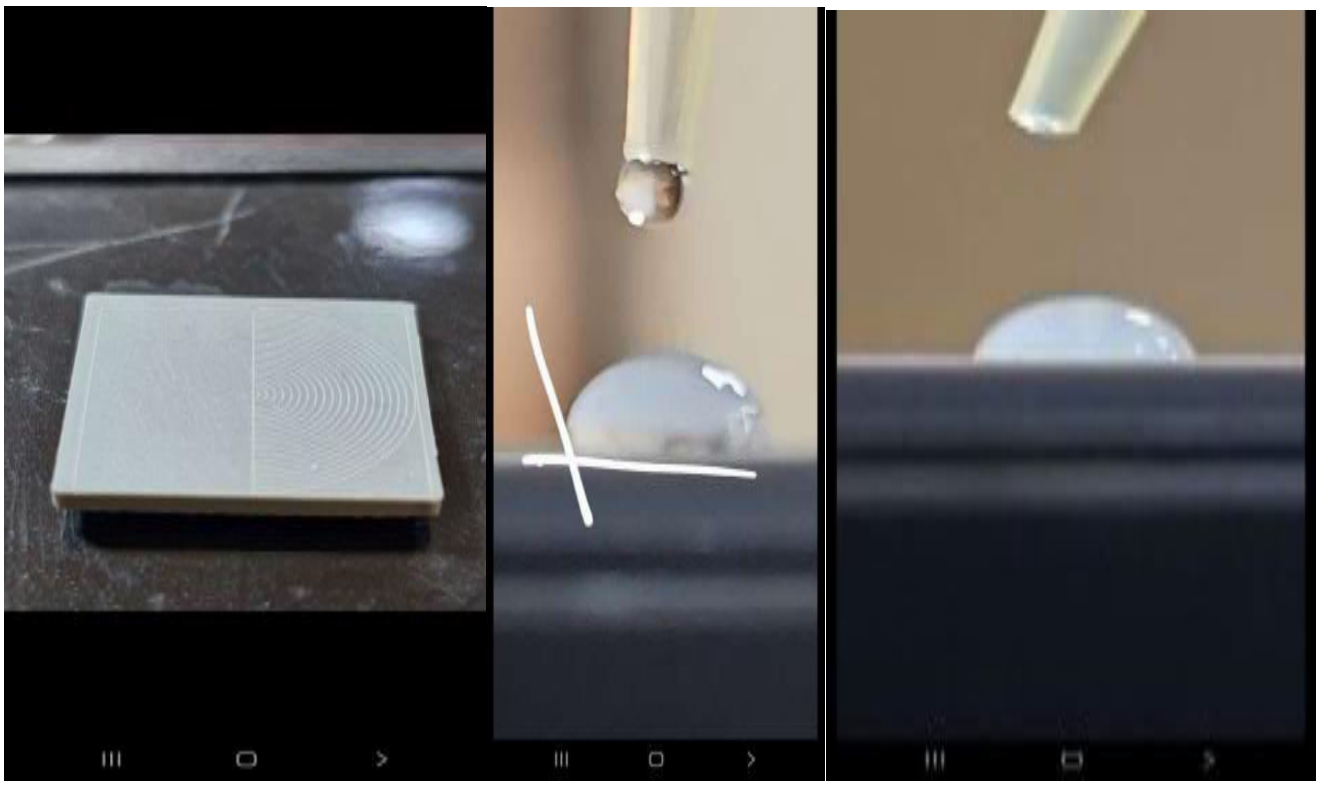


Figure-6. The Water Contact Angle (WCA) evaluation.

CONCLUSIONS

Polylactic acid's surface characteristics were altered through the effective use of fiber laser surface treatment. Analysis by scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), and energy-dispersive X-ray diffraction (EDX) verified that the method produced regulated micro- scale patterns and caused minor chemical oxidation. The water contact angle testing showed that the wettability has improved. Fiber laser texturing is a scalable and flexible way to customize PLA surfaces for biomedical uses.

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