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From Cactus to Composite: Thermo-Mechanical Analysis of Opuntia Fibers and Insights for Potential Composite Material Applications

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ABSTRACT

In this work, Opuntia (commonly called prickly pear cactus) was investigated as a source for reinforcing plant fibers, as it represents a low-cost and widely available alternative to other commonly used natural fibers, such as kenaf, hemp, sisal, or flax. A fiber network that reflects the shape of the leaf structure can be found in the cladodes of Opuntia. Water retting was identified as the most promising method to extract the fiber network from the plant. Tensile tests and thermogravimetric analysis were performed on the extracted fibers to evaluate the quality of the extraction process. Different parameters such as time, surface exposure, and temperature were investigated to optimize the water retting process. The results indicate that an increase in surface exposure and higher water temperature leads to a reduction in time needed for fiber extraction. The extracted fibers were then embedded in a PLA matrix by compression molding to fabricate a fiber-reinforced composite. The mechanical performance of the Opuntia fiber-reinforced plastic was investigated. Analysis (particularly mechanical, optical and fiber volume content) indicates that the impregnating quality was insufficient, leading to a weak performance of the material.

1 | Introduction

The need for a more sustainable resource utilization has raised interest in renewable materials. Modern composite materials usually involve non-renewable, often petrol-based, raw material sources, posing a challenge to the environment. So-called green composites, consisting of natural fibers and/or bio-based polymers, are a promising solution to reduce environmental impacts [1–5]. The production of a natural fiber reinforced polymer (NFRP) requires relatively low energy (9.55 MJ/kg) compared to conventional composites such as glass fiber reinforced polymers (54.7 MJ/kg), resulting in a lower environmental footprint, as well as reduced dependence on non-renewable energy and material resources [6]. An additional benefit is the potential biodegradability of the material.

One suitable plant choice for natural fibers is the prickly pear cactus (Figure 1), as it is an invasive plant in the Mediterranean that frequently requires management to prevent overgrowth. Additionally, the main agricultural focus of this plant is the fruit (known as the prickly pear or Indian fig). Consequently, large amounts of plant material, leftover as residues from the fig production, could therefore be utilized for technical applications [7]. The prickly pear cactus or Opuntia ficus-indica can reach a height of 5–7 m and forms a trunk, stem-like structure at the bottom, consisting of a network of cladodes (large green pads), which can grow up to 600 mm. These cladodes are flat and rounded and can grow spines of up to 25 mm [8]. The outer part of the cladodes is called epidermis and acts as a protective barrier against the environment, followed by the cortex and the inner cellular tissue. The fiber network is located between the

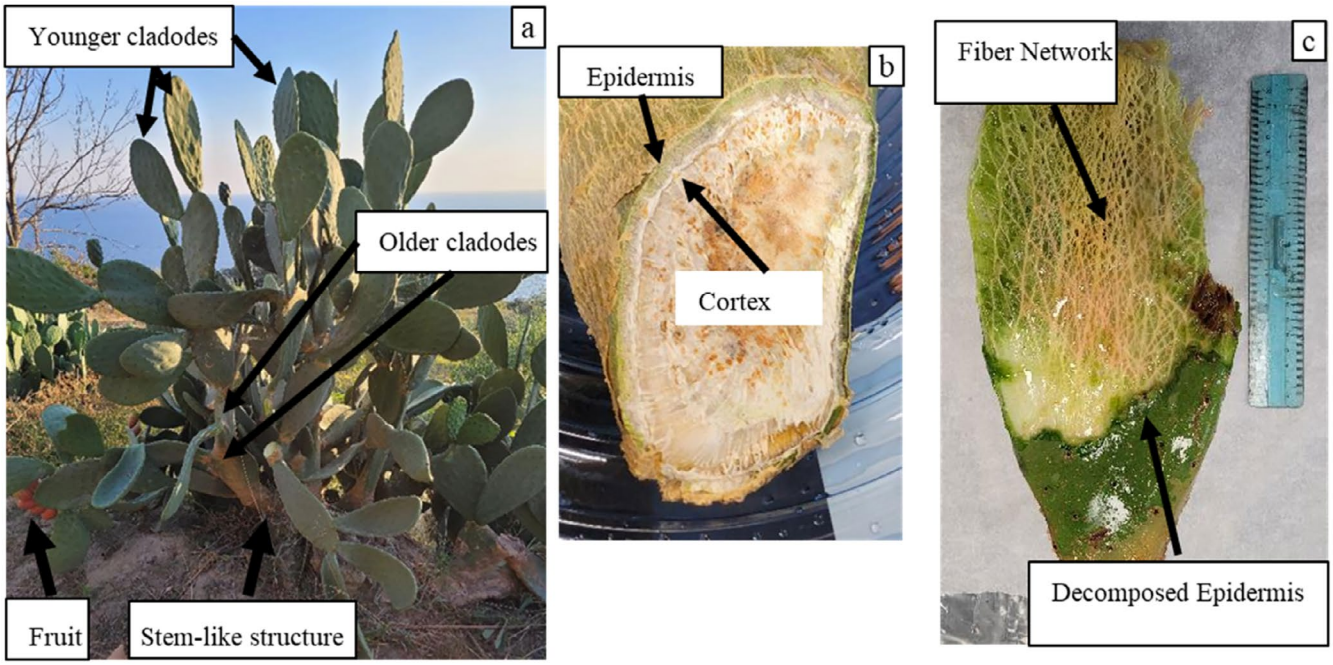

FIGURE 1 | Opuntia ficus india (a), picture of a cut cladode (b), and a cladode after water retting (c).

epidermis and the cortex (compare Figure 1). The geographical location strongly affects the plant's composition. The plant material for this work was collected in Pozzuoli, located in the Phlegrean Fields (Campi Flegrei), where the soil composition is heavily influenced by the active volcanic area, which contains high amounts of volcanic ash and tuff as well as nutrients like potassium, calcium, magnesium, and phosphorus with a sand to silty texture. Sulfur compounds may be present due to the geothermal activity [9].

Different procedures exist to extract plant fibers, such as water retting, chemical treatment, or burial in soil. Water retting is a widely applied process, where material is immersed in water to dissolve cellular tissue and gummy substance. The water penetrates the central stalk portion, causing swelling of the inner cells. This leads to a bursting of the outermost layer and an increased absorption of moisture, as well as decay-producing bacteria [10]. The timing of water retting is critical; insufficient duration does not allow fiber extraction, while prolonged exposure compromises fiber strength. The optimal duration of water retting lies between 15 and 40 days [11–16]. Instead of using water, fibers can also be extracted using chemicals such as ethanol, KOH, or NaOH to dissolve the cellular tissue of the plant. This can drastically reduce the extraction time to a few hours. Ultimately, through burying the plant material in soil, the cellular tissue can be dissolved by calcium oxalate fermentation. The time for burial extraction varies between 15 and 45 days [11].

The extracted opuntia fibers can directly be used as a reinforcement for polymer materials. Alternatively, the fibers can be milled to powder and compounded with polymers [15, 17, 18] or used as longer fibers in a molding process [19, 20]. For long fibers, fiber weight contents of 20%–25% can be reached [19, 21] with compression molding processes. Previous studies claim the mechanical properties summarized in Table 1.

TABLE 1 | Mechanical properties of green polymer composites with opuntia fibers reinforcement.

Process	Flexural modulus (GPa)	Flexural strength (MPa)	Deformation at break (%)
Compression molding fast cooling [20]	2.9 ± 0.85	67 ± 11.4	2.6 ± 0.2
Compression molding slow cooling [20]	3.1 ± 0.20	30 ± 7.0	1.0 ± 0.1
Rotational molding [20]	1.7 ± 0.5	32 ± 10.6	2.1 ± 0.3
Compression Molding [21]	4.6 ± 0.83	70.3 ± 9.52	2.7 ± 0.4
Compounding and extrusion (data taken from graph) [15]	3.4	~28	~1.1

While there are some findings regarding the use of ground fibers [15] or rotational molding [20] in composite production, there is missing knowledge on the correlation of the fiber extraction method and the mechanical properties, which is essential in understanding the behavior of opuntia fiber composites. Additionally, there are several papers [11, 15, 16, 22], which have investigated the water retting process, but none focused on decreasing process time to reduce process costs. This work therefore aims at a deeper understanding of the effect of different extraction parameters on the final behavior of the fibers. Specifically, the focus lies on the water extraction method,

where parameters such as immersion time, temperature and plant surface were systematically investigated. The aim was to find an optimized procedure for minimum time and energy consumption with a maximum fiber output.

So far, research work on manufacturing NFRPs with opuntia fibers [15, 17, 19–21] has neglected the use of the whole fiber network in the production of a composite as well as the influence of fiber content in the composite. Therefore, the extracted fibers from the water retting process are utilized to produce a composite material with a polylactic acid (PLA) matrix by compression molding using the largest fiber network extractable in three fiber-polymer combinations.

2 | Materials and Methods

2.1 | Materials

Two different types of cladodes were collected from one opuntia plant close to Puzzuoli in Campania, Italy. Younger cladodes from the top of the plant were used as well as older cladodes from the lower part of the same plant, as indicated in Figure 1. PLA was chosen as the matrix material and supplied in the form of pellets by Total Corbion (Gorinchem, Netherlands) under the trade name Luminy LX175.

FIGURE 2 | The halved cladodes for trial 4 and 5 to increase surface exposure to water.

2.2 | Methods

2.2.1 | Water Retting

The harvested cladodes were immersed in an open plastic container made out of Polycarbonate filled with tap water for different time intervals between 13 and 40 days. The intervals were selected based on literature data and optimized for lowest fiber extraction time. Further, two different water temperatures—room temperature (RT, 23°C) and 70°C—were considered. In the latter case, the cladodes were heated in a water-filled metal container, with a heating element set to 70°C for 2 h and then placed in the open plastic container with fresh tap water at RT. In order to reduce the immersion time, the surface area of the cladodes exposed to water was increased by cutting the cladodes in halves longitudinally, as shown in Figure 2. A detailed overview of the test conditions is presented in Table 2. For each trial, at least three cladodes were used.

2.2.2 | Tensile Testing of Single Fibers

Tensile tests were performed on Opuntia fibers extracted under various conditions (see Table 2), using an Instron 5564 universal testing machine (Instron Corporation, Canton, MA, USA), equipped with a 1 kN load cell at a crosshead speed of 2 mm/min, according to the ASTM D3822. Due to the novelty and the fiber structure of the Opuntia fibers, a relevant test standard does not exist at this point. The fiber diameter was measured at three points (top, center, and bottom) of each specimen using a caliper. A single fiber from the plant material was identified as the smallest indivisible component.

An overview of the mechanically tested fibers from the water retting process can be taken from Table 3. Tests were performed on young cladodes after 20 and after 30 days of water retting, as well as fibers from old cladodes after 28 days. Fibers with an initial exposure to 70°C hot water for 2 h with subsequent immersion at room temperature for 16 days were also selected for testing. The extraction times of the fibers through water retting differ between old and young cladodes, since the goal was to test the fibers as soon as they could be extracted from the cladodes to reduce exposure time to water. After determining the optimum retting parameters in terms of mechanical performance, these parameters were used for the composite production in Section 2.2.4.

TABLE 2 | Experimental overview of cladode immersion trials.

Trial number	Cladode type	Water temperature	Number of days	Exposure
1	Young	Room temperature	30	Full
2	Old	Room temperature	40	Full
3	Old	2 h at 70°C + room temperature	16	Full
4	Old	Room temperature	14	Halved
5	Old	2 h at 70°C + room temperature	13	Halved

2.2.3 | Thermal Characterization

A thermogravimetric analysis was performed using a Perkin Elmer Pyris Diamond (PerkinElmer, Shelton, CT, USA) in the temperature range from 25°C to 800°C at a heating rate equal to 3°K/min to determine the thermal stability to select polymer material and processing parameter. As detailed in Table 4, fibers were extracted for thermal characterization after 20, 28, and 30 days of water retting as well as fibers with an initial heat treatment at 70°C water and 10 days of water retting at RT water.

2.2.4 | Composite Manufacturing

Three different composite panels (roughly 25 × 15 cm in size) were manufactured by stacking layers of polylactic acid (PLA) films and Opuntia fiber network (see Table 5) and further hot compression molded. The PLA and the extracted Opuntia fiber networks were first dried in a vacuum oven (Binder GmbH, Tuttlingen, Germany) at 60°C for 4 h. The PLA films, with a thickness of 70 μm and the fibers were alternately stacked and further compacted at 180°C using a Collin P400E laboratory press (COLLIN Lab & Pilot Solutions GmbH, Maitenbeth, Germany) without a mold. Compaction was carried out using the following pressure cycle: 2 min at 0 bar, 1 min at 5 bar, 1 min at 10 bar, and 1 min at 20 bar. Finally, the material was cooled down to RT under the maximum compaction pressure. The process parameters, chosen essentially in light of previous experience [23, 24], are summarized in Table 5. For trial C3, the number of layers was increased, which required an extension of the pressing time, especially at low pressures to guarantee adequate impregnation of the material. So, trial C3 was manufactured with different time parameters (3–2–2). The number of PLA layers was increased along with the number of fiber layers to maintain a constant theoretical fiber volume content across different thicknesses of the material. To produce the reference material (PLA without fiber reinforcement) the aimed thickness was 2 mm.

TABLE 3 | Fibers selected for mechanical analysis.

Trial	Treatment
1.1 Young cladode	20 days RT water
1.2 Young cladode	30 days RT water
2 Old cladode	28 days RT water
3 Old cladode	70°C 2 h + 16 days RT water

TABLE 4 | Fibers selected for thermal characterization.

Trial	Treatment	Atmosphere
1.1 Young cladode	20 days RT water	Nitrogen
1.2 Young cladode	30 days RT water	Nitrogen
2 Old cladode	28 days RT water	Nitrogen
3 Old cladode	70°C 2 h + 16 days RT water	Nitrogen

2.2.5 | Mechanical Testing

Tensile and three-point bending were carried out on composite samples using an Instron 4505 universal testing machine (Instron Corporation, Canton, MA, USA), equipped with a 1 kN load cell at a crosshead speed of 2 mm/min. The support span for three-point bending tests was fixed at 50 mm, as required by the ASTM D790 standard method [25], and the gauge length for tensile tests was set at 50 mm according to ASTM D638 standard method [26]. Table 6 presents the dimensions of the samples tested.

2.2.6 | Optical Analysis

To support the discussions of the results, the cross sections of the composite samples were investigated by an optical microscope Leica M205 FCA (Leica Camera AG, Wetzlar, Germany).

TABLE 5 | Overview of the manufacturing parameters for composite production.

Trial number	Number of opuntia fiber layer	Number of PLA layer	Manufacturing temperature [°C]	Manufacturing pressure [Bar]	Manufacturing time [min]
C1	2	3	180	5–10–20	2–2–2
C2	4	5	180	5–10–20	2–2–2
C3	6	7	180	5–10–20	3–2–2

TABLE 6 | Dimension of the samples for mechanical testing.

	C1 (2 plies)	C2 (4 plies)	C3 (6 plies)
Tensile sample	1.5 × 9.7 × 80 mm	2.7 × 8.5 × 80 mm	9.5 × 3.2 × 80 mm
Flexural sample	1.5 × 12 × 80 mm	2.7 × 12.2 × 80 mm	0.8 × 13.2 × 80 mm

2.2.7 | Determination of Fiber Volume Content

The fiber volume content was determined following a modified solvent-dissolution approach: samples were immersed in acetone at room temperature for 24 h, washed, dried, and weighed to calculate actual fiber content. This approach is conceptually analogous to the well-established acid-digestion method (according to DIN EN 2564/ASTM D 3171) [27]. In more detail, three samples of 40×40 mm were cut from each composite variant. The samples were weighed with an accuracy of ±0.0001 g and then immersed in 50 mL of pure acetone at room temperature without stirring. After 24 h, the remaining solids were collected, washed with 50 mL of flowing acetone, and weighed to assess the actual content of fibers.

3 | Results and Discussion

3.1 | Fiber Extraction

For the first two trials, full cladodes (young and old) were immersed in water at room temperature. For trial 1, the fibers of the young cladode could be extracted after 28 days, while it took 40 days for the old cladode. However, in the case of the young cladodes, the fiber content within the cladode is very low. In Figure 3, clearly the epidermis at the bottom started to dissolve to about half of the cladode. A rotting process also started at the right side of the exposed fibers, where the material was exposed to air due to the floating behavior of the cladode. This indicates the variability and difficulty of fiber extraction of cladodes from Opuntia. Figure 4a,b, on the other hand, show the successful degradation of the cellular tissue and the complete extraction of an intact fiber network after 40 days of immersion in water at room temperature. The remaining plant material was washed off afterwards, and the fibers were dried at room temperature before being used as reinforcement of composite panels.

FIGURE 3 | Old cladode after 40 days (a) and 40 days (b) of water immersion from trial 2.

In order to optimize the fiber extraction process and reduce the number of days for fiber extraction, two approaches were pursued: an increase in temperature and an increase in the exposed surface area of the cladodes. In the first case (Trial 3), the cladodes were preliminarily immersed in water at 70°C for 2 h and subsequently placed in water at room temperature, as per Table 2. In the second approach (Trial 4), the exposed surface of the cladodes to water was extended by cutting them in half before immersion. In trial 5, a combination of the above-mentioned approaches was applied by placing halved cladodes in 70°C warm water for 2 h and subsequently in RT water. The results show that the immersion time could be significantly reduced down to 16 days when exposing the material to 70°C warm water at the beginning of the retting process. This procedure promotes a softening of the plant material, allowing greater impregnation of the cellular tissue. By halving the cladodes, the time could be decreased to 14 days. By combining the two approaches, the fibers could be extracted after 13 days, reducing the initial 40 days by a factor of more than 3. This is an additional time reduction to the already existing water retting times published [12, 15, 16, 19]. Generally, it is important to note that the fiber extraction process shows great variability in terms of time, quality, and repeatability. For the industrialization of this process, special attention should be paid to cladode age/fiber content and floatability during water immersion and closed containers, since odor development can be strong during the retting process.

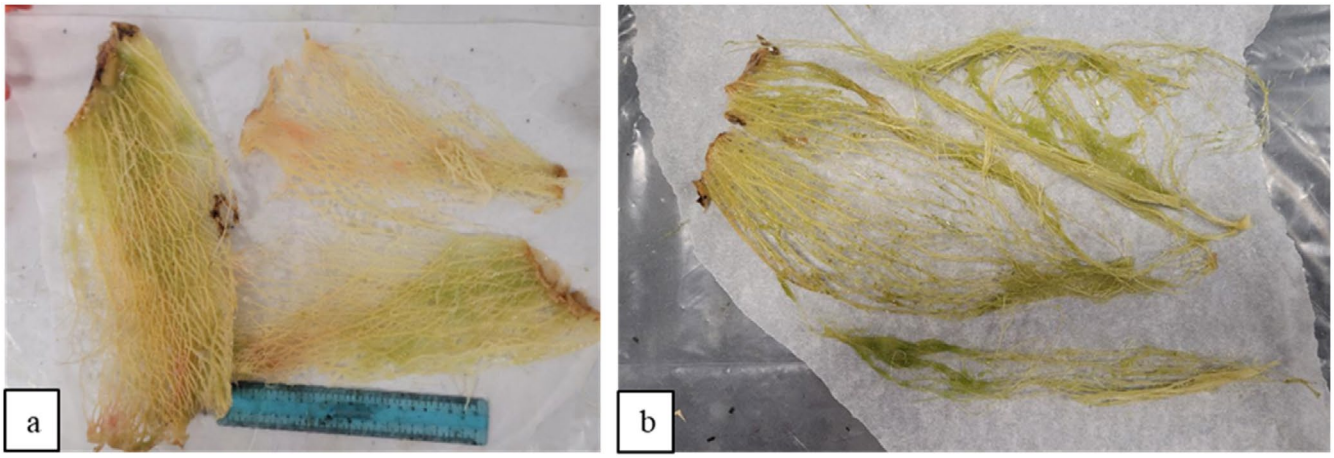

FIGURE 4 | Extracted fiber network from trial number 2 of old cladodes from trial 2 (a) and from trial 3 (b) at an initial exposure to 70°C warm water.

TABLE 7 | Main characteristics of different fiber types from thermal analysis of the opuntia fibers.

Trial	Treatment	First peak [°C]	Onset main [°C]	Main peak [°C]	Residue [%]
1.1 Young cladode	20 days RT water	60	236	316	20
1.2 Young cladode	30 days RT water	57	247	349	13
2 Old cladode	28 days RT water	64	242	334	4
3 Old cladode	70°C 2 h + 16 days RT water	60	252	355	< 1%

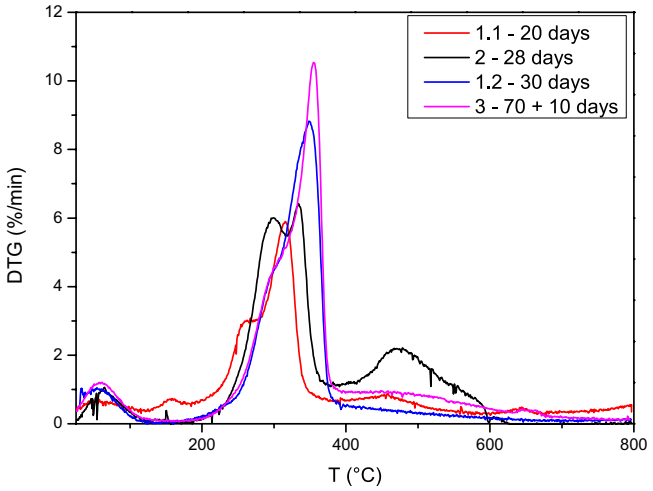

FIGURE 5 | Derivative of the thermogravimetric (DTG) curve of the opuntia fiber, obtained with different retting process parameters, obtained by thermogravimetric analysis.

3.2 | Thermal Characterization

Figure 5 shows the first derivative of the thermogravimetric (DTG) curve for the opuntia fibers, obtained from different water retting procedures. The results of thermal analysis are also reported in Table 7. The small deflection at temperatures below 100°C is clearly attributable to the dehydration of the samples analyzed. The main peak corresponds to the cellulose degradation, which takes place between 300°C and 400°C; the hemicellulose starts to thermally degrade between 210°C and 250°C, leaving a negligible amount of ash [28]. The lignin decomposes over the entire test duration, without evidencing any significant deterioration peaks [29]. The local extremum at approximately 250°C for samples 1.1 and 2 could be related to the presence of high hemicellulose content. The fibers from younger cladodes tend to leave behind a higher residue than fibers from older cladodes, which may indicate that the younger cladodes contain greater amounts of inorganic particles (e.g., sand or soil). This significant decrease in TGA residues of old cladodes could also be related to a different cellulose content in the old cladodes compared to young cladodes. This may be due to changes in the plant composition during their life cycle, which alter the composition of lignin, hemicellulose, and cellulose in the plant [30]. For sample 1.2, the main DTG signal relates to thermal degradation of cellulose, and the absence of curve peaks in the temperature range typical of hemicellulose (210°C to 250°C) degradation speaks for a high cellulose and low hemicellulose content, which is supported by the good mechanical properties of the fiber as per Table 8. Similar thermal behavior is also shown by sample 3, implying a high cellulose content. The degradation behavior of the

TABLE 8 | Content of cactus fibers for the different variants manufactured.

Sample	Fiber content [%]
PLA	0
2 Fiber plies	72.9
4 Fiber plies	43.3
6 Fiber plies	37.1

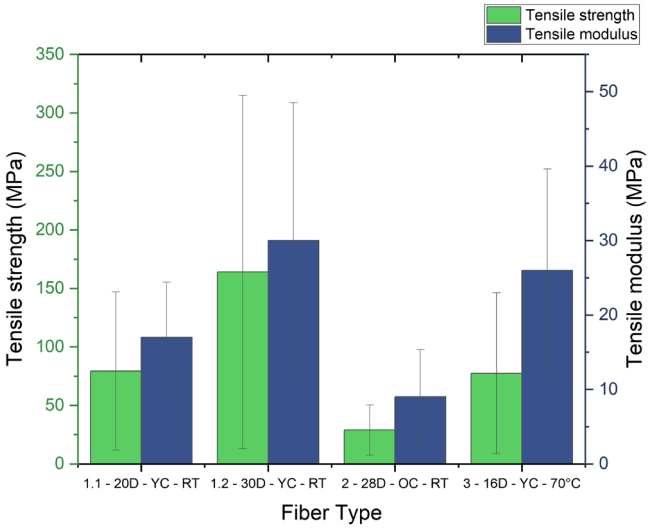

FIGURE 6 | Results from the single fiber tensile test for the different immersion trials with 20 days immersion of young cladode at RT water (20D-YC-RT), 30 days immersion of young cladode at RT water (20D-YC-RT), 28 days immersion of old cladode at RT water (28D).

Opuntia fiber strongly influences both manufacturing processing parameters and suitable polymer material selection for composite production. The onset point close to 200°C excludes many thermoplastics that need to be processed at higher temperatures in order to avoid fiber degradation.

3.3 | Mechanical Characterization of the Single Fibers

The results from the single fiber tensile test are presented in Figure 6. The results show a large variation in the mechanical response of the fibers. This is common for many natural fibers and can be attributed to their inherent dimensional and compositional variability [22–24]. Notably, all of the tensile test results

show a variability of results and a significantly high standard deviation. To present lower scattering, the tested specimen was increased to 10 for trial 2 leading to no visible improvement.

Fibers from trial 1.2 (30 days of water retting) show the trend of the highest tensile properties compared to the other tested fibers. The results indicate that an increased exposure to water can reduce the plant residues attached to the fiber, which could lead to increased fiber strength. Fibers from the same cladode with 20 days of water exposure (Trial 1.1) indicate a reduced tensile strength of about 50%. Fibers from old cladodes and 28 days of water retting (Trial 2) show the trend of very weak properties compared to the younger cladodes. This effect could be justified by assuming that fiber maturity reduces strength due to increased fatigue during plant life in combination with the long retting time. Additionally, the changes in the plant composition (e.g., a decreased cellulose content) during the life cycle, as also suggested in the thermal characterization, could result in lower mechanical performance. Fibers from the water retting at 70°C (Trial 3) present good tensile stiffness but a rather poor strength, which could correspond to the initial treatment at 70°C that decreases maximum strength but keeps stiffness of the fiber.

3.4 | Mechanical Characterization of the Manufactured Composite

Figure 7 compares the tensile and three-point flexural test results of the PLA matrix composite reinforced with 2, 4, and 6 layers of opuntia fiber with those of PLA without reinforcement.

With the awareness that mechanical performance is strongly influenced by the fiber content, this parameter was obtained for each composite sample and indicated in the same Table. From the analysis of the data, unexpectedly, it seems that, at least for what concerns the type of mechanical stresses applied, the inclusion of fibers leads to a deterioration in mechanical properties compared to conventional PLA. The composite containing 2 fiber plies with a fiber volume fraction of 72.9%, results in average flexural strength and flexural modulus of 28.3 and 2352.5 MPa, respectively. In contrast PLA samples have a flexural strength and stiffness of 149.8 and 4364.5 MPa, respectively. The 4 and 6 fiber-ply variants (43.3% and 37.1% fiber volume content) provide an increase in flexural strength and modulus (Modulus: 39.8 and 46.7 MPa; Strength: 2471.1 and 2856.8 MPa) compared to the 2-fiber-ply variant but still show the tendency of lower flexural properties than PLA without reinforcement. Tensile properties provide similar insights; only the 4-fiber ply variant has a tensile modulus close to PLA (34.5 MPa compared to 38.5 MPa) and the highest tensile strength (3665.8 MPa). These lower properties of the reinforced PLA arise due to poor surface bonding of the FRP, which leads to a weak load transfer between the fibers and the matrix. The poor surface bonding is probably linked to the uneven fiber surface and variations in fiber diameter. Optimum extraction of the fibers from the cladode as well as surface treatment could result in better bonding quality. Additionally, the fiber thickness often fluctuates along its length, which makes it challenging to optimize the manufacturing process to ensure consistent impregnation of the reinforcement. The mechanical performance of the tested material is comparable to other opuntia fiber composite data [19, 20, 31, 32] or jute fiber composites [33], which makes them suitable for automotive interior [34] or sports equipment applications [35], but lower than NFRPs with a higher performance like flax fiber composites by a factor 6 [36]. The selected process parameters need to be optimized to provide a better impregnation of the opuntia fibers and consequently adequate mechanical performance of the green composite material.

3.5 | Determination of Fiber Volume Content

The actual fibers content of each composite sample was investigated by comparing the volume and the weight of the samples before and after chemical dissolution of the PLA in acetone. The results are reported in Table 8 and are complemented by Figure 8. The 2 fiber-plies variant shows significant voids and a low quantity of polymer content (Figure 8a). The variants with 4 and 6 plies show better polymer impregnation of the fibers with a significantly lower number of voids, providing insights in the

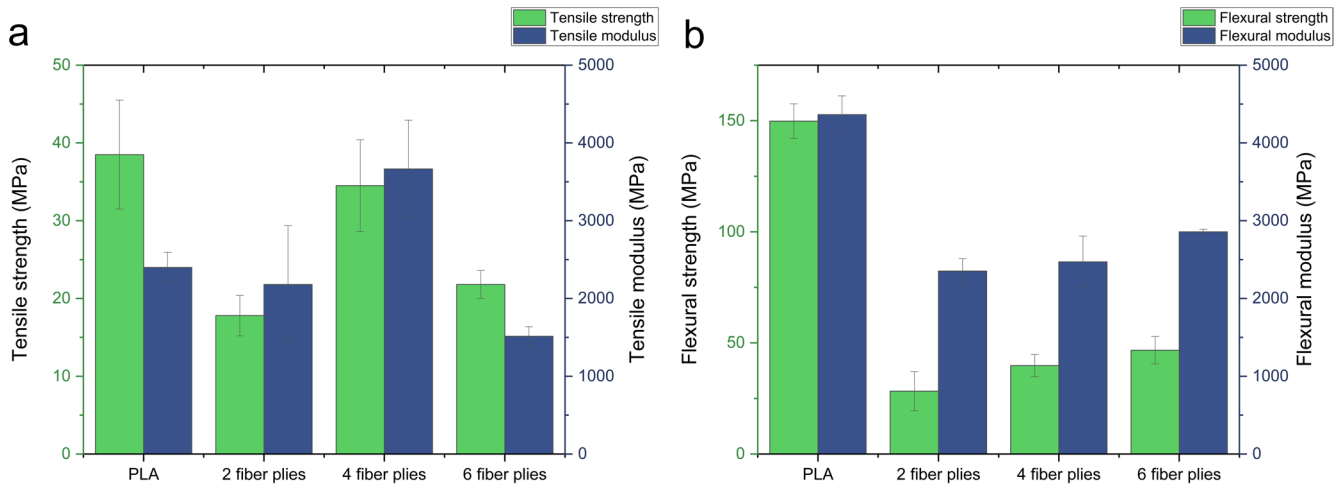

FIGURE 7 | Results from the mechanical test analysis of the composite samples based on PLA and opuntia fiber reinforcement with (a) Tensile and (b) three-point bending results.

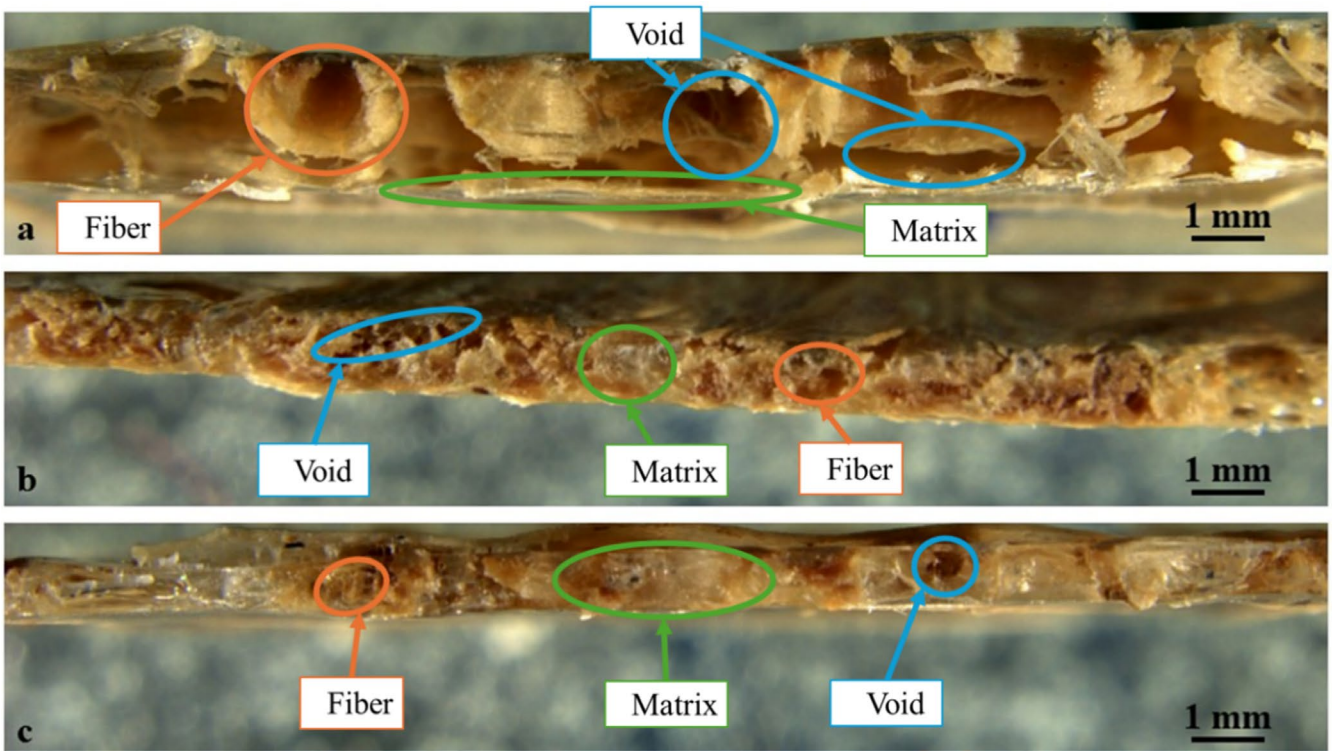

FIGURE 8 | Cross section of the composite samples, (a) two fiber-ply variant, (b) four fiber-ply variant, (c) six fiber-ply variant.

different mechanical properties. Moreover, Figure 8b,c give the indication that integration between fibers and polymer is better in the 6-ply variant and the 4-ply variant (Figure 8b,c) showing less voids and a compacter structure than the 2-ply variant.

The inclusion of geometrically and compositionally irregular opuntia fibers in a polymer can have a negative effect on the cohesion of the material. Additionally, the polar opuntia fibers tend to have weak adhesion properties to the non-polar PLA matrix, creating a weak load transfer resulting in poor mechanical properties compared to unreinforced PLA, as shown in Figure 7.

However, increasing the fiber content in the 4-ply variant has a positive effect on both the overall compaction of the sample and its distribution. Due to the increased number of layers, there is more polymer in between each layer, resulting in better load transfer and therefore an increase in mechanical properties. The irregularities in the fibers become more evenly distributed under the application of intense compaction force, forming a network-like structure that enhances the mechanical properties, including maximum strength and stiffness.

4 | Conclusions

The growing need to develop new sustainable materials has motivated this research toward exploiting the potential of wild plant materials such as Opuntia fibers. In this study, the fiber extraction process from Opuntia cladodes by varying the immersion time and the water temperature was investigated and optimized. The obtained fibers were used to produce a composite material by compression molding with PLA. This polymer was selected because of its biobased origin as well as the processing temperature compatible with the thermal sensitivity of the fibers.

The results show the successful dissolution of the cellular tissue and the extraction of an intact fiber network after 40 days of immersion in water at room temperature. The immersion time could be significantly reduced by more than a factor 3 to only 13 days when exposing the material to 70°C warm water for 2 h and increasing the surface exposed to water, e.g., by halving the cladodes longitudinally. However, through testing of thermal and mechanical properties, the best conditions were reached when the lignin content was low and there was a good balance between cellulose and hemicellulose. This was the case for fibers extracted from young cladodes, which have been immersed in water for 30 days at room temperature.

With the extracted fiber, three different variants with various amounts of fiber layers (2, 4, and 6) were manufactured through compression molding with PLA as a matrix. PLA without fiber reinforcement was produced with the same process as a reference material. The mechanical tests of these composites show mostly a lower performance of the opuntia fiber reinforced polymer compared to PLA without reinforcement. FVC and cross section analysis provide insight into the insufficient impregnation quality of the composite material leading to a weak load transfer and consequently, an early failure of the material. Additionally, a low fiber-matrix adhesion could be expected between opuntia fiber and PLA, as described in other research work, amplifying the weak load transfer and consequently the mechanical performance [20, 21, 31]. Future work is therefore necessary to enhance the manufacturing process to optimize impregnation quality and reduce void content of the composite material. Potential applications of the material could be lightweight furniture or agricultural products due to its biodegradability. If the impregnation quality and the mechanical properties are enhanced in future work, the material could be used in non-structural automotive components.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. R. A. Kurien, M. M. Anil, S. L. S. Mohan, and J. A. Thomas, "Natural Fiber Composites as Sustainable Resources for Emerging Applications: A Review," *Materials Today: Proceedings* (2023), https://ouci.dntb.gov.ua/en/works/9GkPxv39/.

2. L. Vijayaraghavan, K. H. Reddy, and S. M. J. Basha, *Emerging Trends in Mechanical Engineering* (Springer Singapore, 2020).

3. G. S. Kumar, A. Rathan, D. Bandhu, et al., "Mechanical and Thermal Characterization of Coir/Hemp/Polyester Hybrid Composite for Lightweight Applications," *Journal of Materials Research and Technology* 26 (2023): 8242–8253.

4. B. M. Reddy, B. C. M. Reddy, A. k. Kumar, G. S. Kumar, R. M. Reddy, and G. Sankaraiah, "Mechanical and Water Absorption Characterization of Jute/Flax/Polyester Hybrid Composite for Indoor and Outdoor Applications," *Journal of Polymer Research* 31, no. 12 (2024): 351.

5. B. M. Reddy, R. M. Reddy, P. V. Reddy, N. N. A. Prashanth, and D. Bandhu, "Effect of Alkali Treatment on Mechanical Properties and Morphology of the *Balanites Aegyptiaca* Composite," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 238, no. 11 (2024): 5077–5086.

6. S. Joshi, L. Drzal, A. Mohanty, et al., "Are Natural Fiber Composites Environmentally Superior to Glass Fiber Reinforced Composites?," *Composites Part A, Applied Science and Manufacturing* 35, no. 3 (2004): 371–376.

7. M. D. Herrera, J. A. Zegbe, V. Melero-Meraz, and R. K. Cruz-Bravo, "Functional Properties of Prickly Pear Cactus Fruit Peels Undergoing Supplemental Irrigation and Fruit Storage Conditions," *Plant Foods for Human Nutrition* 76, no. 4 (2021): 427–433.

8. P. Bakewell-Stone, *Opuntia Ficus-Indica (Prickly Pear)* (CABI Compendium, 2022).

9. P. Adamo, A. Basile, E. Coppola, et al., "The Development of Soil Science in Campania," in *Soil Science in Italy: 1861 to 2024*, ed. C. Dazzi, A. Benedetti, G. Corti, and E. A. C. Costantini (Springer International Publishing; Imprint Springer, 2024), 225–243.

10. M. T. Paridah, A. B. Ahmed, S. O. A SaifulAzry, and Z. Ahmed, "Retting Process of Some Bast Plant Fibres and Its Effect on Fibre Quality: A Review," *BioResources* 6, no. 4 (2011): 5260–5281.

11. J. Castellano, M. D. Marrero, and Z. Ortega, "Opuntia Fiber and Its Potential to Obtain Sustainable Materials in the Composites Field: A Review," *Journal of Natural Fibers* 19, no. 15 (2022): 10053–10067.

12. J. Castellano, M. D. Marrero, Z. Ortega, F. Romero, A. N. Benitez, and M. R. Ventura, "Opuntia spp. Fibre Characterisation to Obtain Sustainable Materials in the Composites Field," *Polymers* 13, no. 13 (2021): 2085.

13. L. D. Soraisham, N. Gogoi, L. Mishra, and G. Basu, "Extraction and Evaluation of Properties of Indian Banana Fibre (Musa Domestica Var. Balbisiana, BB Group) and Its Processing With Ramie," *Journal of Natural Fibers* 19, no. 13 (2022): 5839–5850.

14. C. Ververis, K. Georghiou, N. Christodoulakis, P. Santas, and R. Santas, "Fiber Dimensions, Lignin and Cellulose Content of Various Plant Materials and Their Suitability for Paper Production," *Industrial Crops and Products* 19, no. 3 (2004): 245–254.

15. A. Alane, I. Zembouai, A. Benhamida, L. Zaidi, N. Touati, and M. Kaci, "Opuntia Ficus Indica Fibers as Reinforcement in PHBV Biocomposites," *Materials Today: Proceedings* 53 (2022): 218–222.

16. F. Mannai, H. Elhleli, M. Ammar, R. Passas, E. Elaloui, and Y. Moussaoui, "Green Process for Fibrous Networks Extraction From Opuntia (Cactaceae): Morphological Design, Thermal and Mechanical Studies," *Industrial Crops and Products* 126 (2018): 347–356.

17. C. Colin Chavez, H. Soto Valdez, A. Rodríguez Féliz, et al., "Papermaking as Potential Use of Fibers From Mexican *Opuntia ficus-indica* Waste," *Biotecnia* 23, no. 1 (2021): 141–150.

18. F. T. Escárcega Olivares, R. Olayo-Valles, R. García-Arrazola, et al., "Valorization of Cactus Cladode Wastes and Chitin Nanowhiskers in Biocomposite Designed for Sorption of New Methylene Blue," *International Journal of Environmental Science and Technology* 20, no. 12 (2023): 13655–13672.

19. M. Bouakba, A. Bezazi, K. Boba, F. Scarpa, and S. Bellamy, "Cactus Fibre/Polyester Biocomposites: Manufacturing, Quasi-Static Mechanical and Fatigue Characterisation," *Composites Science and Technology* 74 (2013): 150–159.

20. A. Greco and A. Maffezzoli, "Rotational Molding of Biodegradable Composites Obtained With PLA Reinforced by the Wooden Backbone of Opuntia Ficus Indica Cladodes," *Journal of Applied Polymer Science* 132, no. 48 (2015): app.42447.

21. A. Greco, R. Gennaro, A. Timo, F. Bonfantini, and A. Maffezzoli, "A Comparative Study Between Bio-Composites Obtained With Opuntia Ficus Indica Cladodes and Flax Fibers," *Journal of Polymers and the Environment* 21, no. 4 (2013): 910–916.

22. M. Cheikh Rouhou, S. Abdelmoumen, S. Thomas, H. Attia, and D. Ghorbel, "Use of Green Chemistry Methods in the Extraction of Dietary Fibers From Cactus Rackets (Opuntia Ficus Indica): Structural and Microstructural Studies," *International Journal of Biological Macromolecules* 116 (2018): 901–910.

23. L. Aliotta, B. Dal Pont, V. Gigante, P. Russo, J. Passaro, and A. Lazzeri, "Investigation of New Poly(Lactic Acid) (PLA)/poly(Butylene Succinate-Co-Adipate) (PBSA) Thermoplastic Composites Reinforced With Different Amount of Twill Hemp Fabrics," *Journal of Materials Science* 59, no. 3 (2024): 847–862.

24. I. Papa, A. Langella, F. Napolitano, and P. Russo, "Comparison of FDMed and Compression Molded Biocomposites in Polylactic Acid and Food Flour Waste," *Journal of Composite Materials* 57, no. 29 (2023): 4521–4533.

25. ASTM International, *Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials* (ASTM International, 2017), D790.

26. ASTM International, *Standard Test Method for Tensile Properties of Plastics* (ASTM International, 2014), D638.

27. D. Grund, M. Orlishausen, and I. Taha, "Determination of Fiber Volume Fraction of Carbon Fiber-Reinforced Polymer Using Thermogravimetric Methods," *Polymer Testing* 75 (2019): 358–366.

28. V. A. Alvarez and A. Vázquez, "Thermal Degradation of Cellulose Derivatives/Starch Blends and Sisal Fibre Biocomposites," *Polymer Degradation and Stability* 84, no. 1 (2004): 13–21.

29. H. Li, Y. Qu, and J. Xu, "Microwave-Assisted Conversion of Lignin," *Production of Biofuels and Chemicals With Microwave* 3 (2015): 61–82.

30. A. Gholampour and T. Ozbakkaloglu, "A Review of Natural Fiber Composites: Properties, Modification and Processing Techniques, Characterization, Applications," *Journal of Materials Science* 55, no. 3 (2020): 829–892.

31. R. Scaffaro, A. Maio, E. F. Gulino, and B. Megna, "Structure-Property Relationship of PLA-Opuntia Ficus Indica Biocomposites," *Composites Part B: Engineering* 167 (2019): 199–206.

32. O. A. Jiménez Arévalo, M. A. Cruz Marin, A. E. Martinez, and M. Trujillo, "Obtención de Fibras de Nopal Para su Utilización en Composites," *Proceedings of the XVI Congreso Internacional Anual de la Somim, Monterrey, Mexico* (2010).

33. B. A. Acha, N. E. Marcovich, and M. M. Reboredo, "Physical and Mechanical Characterization of Jute Fabric Composites," *Journal of Applied Polymer Science* 98, no. 2 (2005): 639–650.

34. R. Swayam, S. P. Sahoo, M. Nayak, A. Sahoo, and T. Khuntia, "Design and Analysis of Coir Fibre Reinforced Polypropylene Based Internal Car Door Panel," *International Conference on Recent Advances in Mechanical Engineering Research and Development* (Springer Nature Singapore, 2022).

35. S. Maiti, M. R. Islam, M. A. Uddin, S. Afroj, S. J. Eichhorn, and N. Karim, "Sustainable Fiber-Reinforced Composites: A Review," *Advanced Sustainable Systems* 6, no. 11 (2022): 2200258.

36. L. Yan, N. Chouw, and K. Jayaraman, "Flax Fibre and Its Composites: A Review," *Composites Part B: Engineering* 56 (2014): 296–317.