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REVIEW

Opuntia Fiber and Its Potential to Obtain Sustainable Materials in the Composites Field: A Review

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ABSTRACT

Opuntia spp. is a plant widely distributed in the world that has traditionally been used in the food sector. Alternatively to the conventional uses of this plant, this work gives an overview of current knowledge about *Opuntia* fiber, focusing on several papers which have reinforced polymer matrices with this species. *Opuntia* cladodes are formed by a network of fibers with a hexagonal reticular hierarchical structure, which is believed to be responsible for their mechanical properties. *Opuntia* fiber has a cellulose content about 50% and a density (1.54 g/cm^3) similar to conventional fibers such as abaca (1.5 g/cm^3), jute (1.3 g/cm^3) and sisal (1.5 g/cm^3). Matrices such as polylactic acid (PLA) and polypropylene (PP) have been reinforced with *Opuntia* fibers and with ground cladodes, mainly by compression molding, increasing the tensile elastic modulus up to 135%. *Opuntia* fibers also offer good properties against energy absorption, being adequate for the design of lightweight materials with these characteristics. Further studies should be undertaken in order to establish the appropriate parameters to optimize fiber extraction, improve fiber-matrix compatibility and determine a general trend despite the plant own variability.

摘要

仙人掌是一种广泛分布于世界各地的植物, 传统上用于食品部门. 除了这种植物的常规用途之外, 这项工作概述了目前关于仙人掌纤维的知识, 重点介绍了几篇用仙人掌纤维增强聚合物基体的论文. 仙人掌枝状体由具有六角形网状层次结构的纤维网络构成, 这被认为是其机械性能的原因. 仙人掌纤维的纤维素含量约为50%, 密度 (1.54 g/cm3) 类似于传统纤维, 如阿巴卡 (1.5 g/cm3)、黄麻 (1.3 g/cm3) 和剑麻 (1.5 g/cm3). 聚乳酸 (PLA) 和聚丙烯 (PP) 等基质主要通过模压成型, 使用仙人掌纤维和研磨枝状物进行增强, 拉伸弹性模量提高到135%. 仙人掌纤维还具有良好的抗能量吸收性能, 适合设计具有这些特性的轻质材料. 应进行进一步研究, 以确定适当的参数, 优化纤维提取, 改善纤维基质相容性, 并确定总体趋势, 尽管植物自身存在变异.

KEYWORDS
Opuntia spp.; vegetal fibers; polymer; composites; materials

关键词
仙人掌; 植物纤维; 聚合物; 复合材料; 材料

Introduction

Composites with vegetal fibers have received a lot of attention due to the need to develop materials with new properties and more respectful with the environment at the same time. During the last years, vegetal fiber demand has increased in the industrial sector (Thyavihalli et al. 2019). Its use is a trend thanks to its low density (Pickering, Aruan Efendy, and Le 2016), low cost (Mohammed et al. 2015), low-energy consumption and biodegradability (Bourmaud and Baley 2009) among other factors compared to synthetic fibers. However, new vegetal fibers with lower cost and greater availability than the commonly studied and used ones need to be evaluated (Sarasini and Fiore 2018).

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Accordingly, *Opuntia* is presented as a candidate to be considered (Figure 1). It is a species belonging to the *Cactaceae* family that has historically been used for its fruit (Vigueras and Portillo 2001). It is native to the American continent, but it can be currently found in different countries such as Spain, Italy, Morocco and Tunisia (Sáenz, Sepúlveda, and Matsuhiro 2004). Its main body is formed by articulated stems called cladodes. These cladodes have spines, characteristic structures of *Opuntia* that have a defensive function and whose presence varies according to the species. Mucilage is another characteristic element of *Opuntia*; it is a complex carbohydrate that has a great capacity to absorb water (Sáenz, Sepúlveda, and Matsuhiro 2004). *Opuntia* genus has an asynchronous reproduction and Crassulacean Acid Metabolism (CAM), a photosynthetic adaptation to environmental stress that allows it to grow with a high level of efficiency under limited water conditions, adapting easily to arid areas and adverse environments.

In recent years, interest in *Opuntia* species has grown, a fact that is reflected in the considerable increase in the number of published articles. Cladodes have been investigated as nutritional supplements, showing functional properties like antidiabetic, antihyperglycemic and hypoglycemic effects (Nuñez-López, Paredes-López, and Reynoso-Camacho 2013; Ventura-Aguilar et al. 2017). Cladodes have also been used to improve dough toughness, adhesion, adherence and hardness (Ayadi et al. 2009) of different foods such as bread (Msaddak et al. 2017) and cookies (Msaddak et al. 2016). Moreover, cladodes have been evaluated as bio-coagulants to treat water turbidity (Rubini, Balamurugan, and Shunmugapriya 2019) and as raw materials for bioethanol production (Yang et al. 2015). Mucilage has also been examined for water treatment (Adjeroud et al. 2018; Ibarra-Rodríguez et al. 2017), although it is mainly used

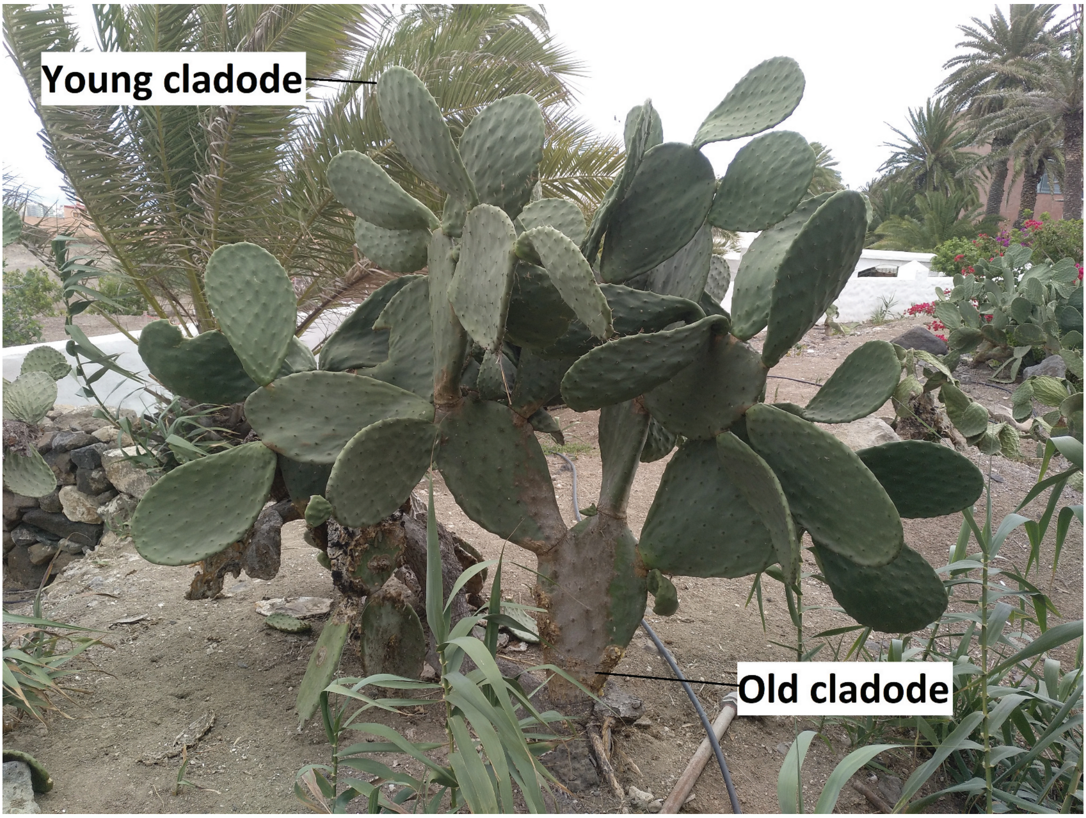

Figure 1. Opuntia plant.

in food, pharmacy and cosmetic industries (Sepúlveda et al. 2007). *Opuntia* fruits have been used for the betalains extraction (Aruwa, Amoo, and Kudanga 2018), which have shown anticancer properties (Abou-Elella, Farouk, and Ali 2014).

Despite all these uses, this plant is considered to be an invasive species in different parts of the world, so frequent pruning is required to contain its rapid growth and expansion. Additionally, during fruit processing a large amount of by-products are generated (Salamanca 2016; Sottile et al. 2019). Consequently, it obtained a lot of waste that can be used and evaluated as reinforcement of composites.

This work provides an overview of current knowledge about *Opuntia* fiber. First, *Opuntia* fiber extraction methods and its characteristics are described. Then, the preparation of different matrices reinforced with *Opuntia* fiber and their mechanical properties are elucidated and compared.

Opuntia fiber extraction methods

There are different methods traditionally used to obtain fibers from plants: dew retting, water retting, mechanical extraction, burial processes and chemical treatments are the most common ones. Using the appropriate method is essential for the following correct use of the fibers as reinforcement (Sanjay et al. 2019).

Inside the *Opuntia* cladodes, there is a woody skeleton formed by several layers with a structure similar to the veins of the human body and with the same of the cladode that it supports. Different processes have been evaluated to extract this skeleton (Table 1). The water retting process allows obtaining fibers with a better elastic modulus but it requires a long processing time. Chemical methods reduce this time, but they do not allow obtaining the fiber network: studies that have used chemical treatments work with ground cladodes and not with the cladode skeleton. For this reason, fiber mechanical properties have not been reported. According to these studies, acidic medium facilitates the fiber separation, obtaining a uniform structure and removing part of the lignin which covers the fiber outer surface (Cheikh et al. 2018). Scalding with hot water makes it difficult to press the fibers later, and scalding with 1% KOH at 50°C achieves fibers with less structural damage than scalding at

Table 1. Fiber extraction methods used for *Opuntia* fiber.

Extraction methods	Conditions	Yield	Fiber properties		Reference
			Tensile	Flexural	
Water retting	Cladodes 2 h in boiling water and 15–20 days in a closed container with water	30%	E: 2.93 GPa σ: 14.3 MPa : 5.04%	E: 2.36 GPa σ: 9.7 MPa : 6.18%	Mannai et al. 2018
	Ground cladodes were stirred with water at 100°C, 1/30 w/v for 1 h	48.74%	-	-	Cheikh et al. 2018
Chemical treatment	Steam extraction with lemon juice (ground cladodes, 220°C, 2 bars, 1/30 w/v, pH = 2, 1 h)	47.25%	-	-	
	Ethanol (ground cladodes were stirred with 80% ethanol (1/10 w/v) for 1 h	49.8%	-	-	
	1 and 2% KOH (scalding of cladodes for 15 min at 50 and 70°C)	1.5%	-	-	Victoria et al. 2012
	1 and 2% NaOH (scalding of cladodes for 15 min at 50 and 70°C)	1.5%	-	-	
Burial process	Cladodes were buried under 30 cm of soil without sand for 15 days	-	E: 1.10 GPa σ: 27 MPa : 2.60%	-	Bouakba et al. 2013
	An old cladode was buried under 30 cm of soil without sand for 45 days	-	E: 279 MPa σ: 1 MPa : 4.73%	-	Lahouaria et al. 2018
Manually ("dead" cladodes)	Fiber skeleton was directly extracted from the plant and treats with boiling water for 2 h	-	E: 157 MPa σ: 6.3 MPa : 1.4%	E: 354 MPa σ: 4.65 MPa : 0.03%	Greco et al. 2013

(a) Ground cladode (b) Extracted fiber

(c) “Dead” cladodes

Figure 2. *Opuntia* samples that can be used as reinforcement.

70°C, 2% KOH or with NaOH (Victoria et al. 2012). Burying methods also require long periods of time but avoid the excessive use of water and chemical compounds (Bouakba et al. 2013). It has been found that the fiber extraction yield depends on how developed the cladode lignocellulosic network is (Victoria et al. 2012): yields for young cladodes (1.6%) are lower than for old cladodes (30%) (Mannai et al. 2018).

Apart from the methods exposed above, there are studies that have directly used the dried fibers obtained manually from “dead” cladodes (Greco and Maffezzoli 2015; Scaffaro et al. 2019). Cladodes tend to dry out and lose part of their greenish elements when they finish their life cycle, leaving only the *Opuntia* fiber (Figure 2), which can be directly exploited (Alberto et al. 2017).

Among all these methods, no studies have been found that justify the choice of one or the other. For this reason, it is important to evaluate the method and conditions that allow optimizing the resources and the time required, as well as the fiber properties.

Fiber characterization

Cladodes and cladodes fiber composition

The chemical composition of *Opuntia* cladodes has already been detailed by different research groups in previous articles, but there are not much data about the chemical composition of *Opuntia* fiber. Taking into account that some studies directly use the ground cladodes as reinforcement elements, Table 2 shows the results distinguishing the part of the plant analyzed. There are

Table 2. *Opuntia* composition (% in dry weight).

<table>
<tr><th rowspan="2">Characteristics</th><th colspan="3">Structural components</th><th rowspan="2">Ash</th><th rowspan="2">Fat and waxes</th><th rowspan="2">Protein</th><th rowspan="2">References</th></tr>
<tr><th>Lignin</th><th>Cellulose</th><th>Hemicellulose</th></tr>
<tr><td><i>Opuntia ficus-indica</i> cladodes from Canary Islands (Spain)</td><td>1.0</td><td>6.7</td><td>24.0</td><td>33.0</td><td>-</td><td>4.2</td><td>Gil et al. 2016</td></tr>
<tr><td><i>Opuntia ficus-indica</i> cladodes from Canary Islands (Spain)</td><td colspan="3">36.7</td><td>18.0</td><td>-</td><td>5.0</td><td>Méndez et al. 2015</td></tr>
<tr><td><i>Opuntia ficus-indica</i> cladodes from Canary Islands (Spain)</td><td colspan="3">37.9</td><td>15.4</td><td>-</td><td>3.6</td><td></td></tr>
<tr><td><i>Opuntia ficus-indica</i> young ground cladodes (12 days) from Mexico</td><td colspan="3">29.8</td><td>15.5</td><td>3</td><td>18.5</td><td>Nuñez-López, Paredes-López, and Reynoso-Camacho 2013</td></tr>
<tr><td><i>Opuntia ficus-indica</i> ground cladodes from Mexico</td><td colspan="3">7.7</td><td>14.8</td><td>1.5</td><td>9.4</td><td>Guevara-Figueroa et al. 2010</td></tr>
<tr><td><i>Opuntia ficus-indica</i> cladodes without spines from Tunisia</td><td colspan="3">30.36</td><td>23.3</td><td>4.69</td><td>8.88</td><td>Ayadi et al. 2009</td></tr>
<tr><td><i>Opuntia ficus-indica</i> amylacea cladodes from Tunisia</td><td colspan="3">34.58</td><td>25.65</td><td>3.95</td><td>8.74</td><td></td></tr>
<tr><td><i>Opuntia ficus-indica</i> amylacea cladodes from Morocco</td><td>3.6</td><td>21.6</td><td>-</td><td>19.6</td><td>7.2</td><td></td><td>Malainine et al. 2003</td></tr>
<tr><td><i>Opuntia ficus-indica</i> mature cladodes from Tunisia</td><td>2.5</td><td>26.7</td><td>15.3</td><td>23.3</td><td>4.2</td><td></td><td>Cheikh et al. 2018</td></tr>
<tr><td><i>Opuntia</i> ficus-indica spines from Morocco</td><td>1.2</td><td>47.9</td><td>-</td><td>1.3</td><td>1.2</td><td></td><td>Malainine et al. 2003</td></tr>
<tr><td><i>Opuntia</i> ficus-indica seed pericarp</td><td>20</td><td>35</td><td>27</td><td>2.5</td><td>8</td><td></td><td>Habibi et al. 2008</td></tr>
<tr><td><i>Opuntia</i> ficus-indica fiber from Tunisia</td><td>4.8</td><td>53.6</td><td>10.9</td><td>5.5</td><td>–</td><td></td><td>Mannai et al. 2016</td></tr>
<tr><td><i>Opuntia ficus-indica ground cladodes</i> (300 µm) from United States</td><td>12.3</td><td>13.1</td><td>18.5</td><td>23.7</td><td>-</td><td>7.4</td><td>Yang et al. 2015</td></tr>
</table>

differences in the composition due to abiotic factors, characterization methods used, post-harvest handling, vegetative state or plant age (Aruwa, Amoo, and Kudanga 2018; Pettersen 1984; Sluiter et al. 2010; Ventura-Aguilar et al. 2017). Despite the variations, most studies agree that *Opuntia* has a low lignin content in its cladodes, while it can reach up to 20% in the pericarp of the seeds (Habibi et al. 2008). In the case of cellulose and hemicellulose, compositions vary between 6–27% and 15–27%, respectively. A high ash content is presented in the cladodes (15–33%): mainly calcium, potassium and magnesium (Ayadi et al. 2009; Mannai et al. 2016; Méndez et al. 2015; Yang et al. 2015).

It can be seen that only one study has evaluated the *Opuntia* fiber composition: it reported the highest cellulose ratio. It is logical considering that some non-structural components have been previously removed by the extraction process. This cellulose content of *Opuntia* fiber (53%) is greater than bamboo (26–43%) and coir (32–43%) fibers, while it is closer to those of kenaf (31–72%) and abaca (56–63%) fibers (Faruk et al. 2012). Normally, fibers with a higher cellulose content have better mechanical properties (Bourmaud et al. 2018)

Regarding the protein content (3–18%), there is a great variation: it increases in young pads, where the metabolic activity is higher, and it decreases in mature pads possibly as a result of nitrogen transport from old cladodes to young ones (Nuñez-López, Paredes-López, and Reynoso-Camacho 2013).

Fiber morphology

The hexagonal reticular hierarchical structure is considered as the main characteristic of *Opuntia* fiber (Bouakba et al. 2013). It is similar to a honeycomb (Greco and Maffezzoli 2015) and it is believed that it is responsible for its specific mechanical properties (Chen and Pugno 2012). Cell walls with a hierarchical structure are formed by *meatus* (defined as the void between cells) and large vessels

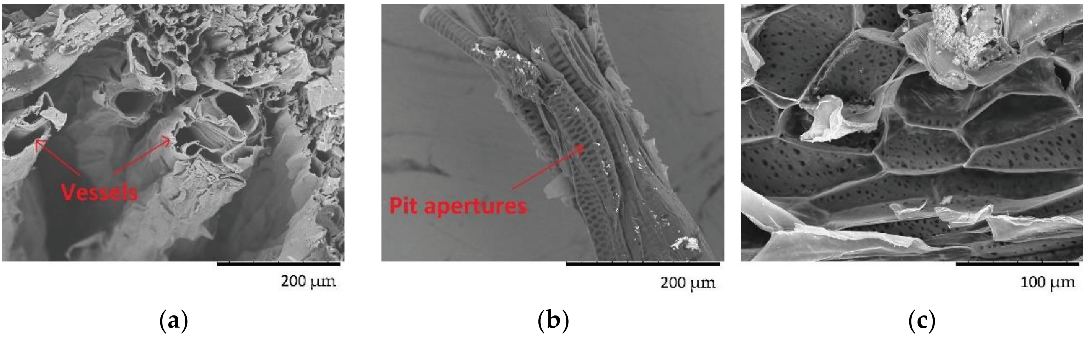

Figure 3. SEM images of *Opuntia* fiber bundles: (a) vessels, (b) tracheid with pit apertures, (c) periderm cell (Castellano et al. 2021).

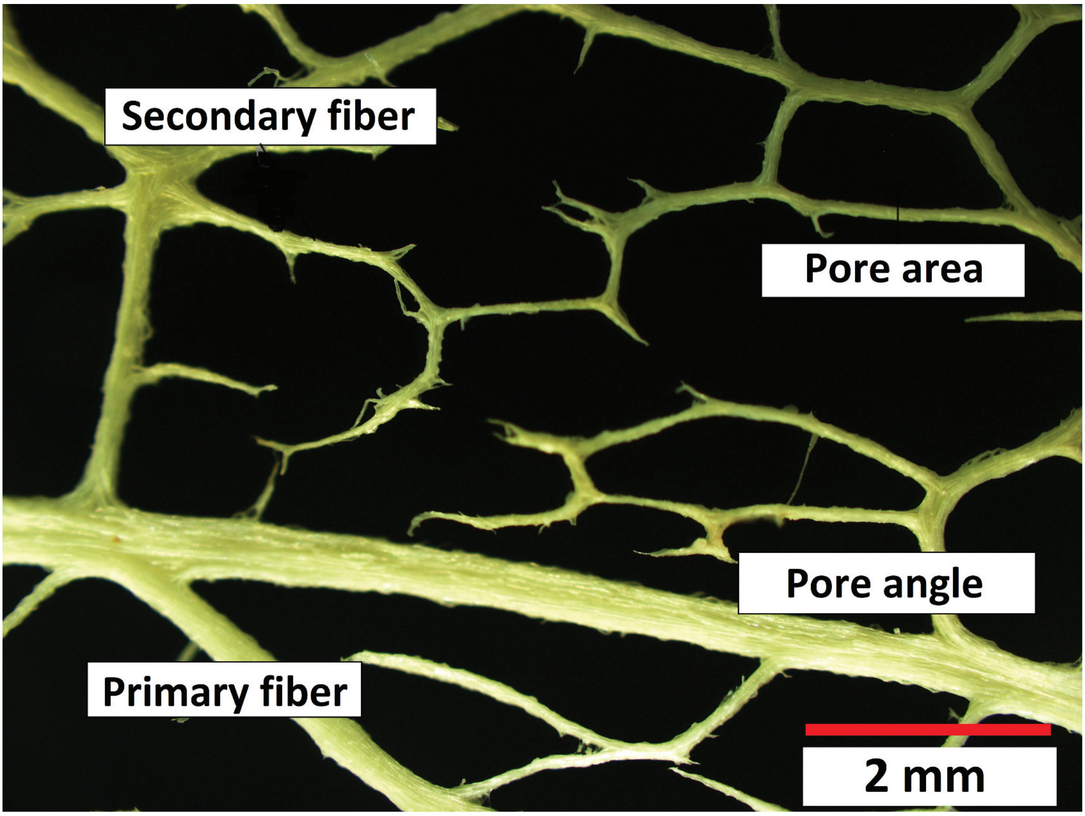

Figure 4. *Opuntia* skeleton: primary and secondary fibers.

with thick walls that provide great rigidity to the plant (Figure 3) (Mannai et al. 2018). Moreover, these fibers have a rough surface, which is believed to be able to promote bonding with polymeric matrices without the need for chemical treatments (Mannai et al. 2020).

Zampetakis et al. (2018) used 3D printing to study the architecture of *Opuntia* fibers finding that they show a fractal geometry with unique characteristics. At macroscopic level, *Opuntia* skeleton is formed by fibers with a random orientation that create a network where two types of fibers can be distinguished: primary axial fibers reticulated by secondary fibers (Figure 4). At microscopic level, fibers are heterogeneous and show an irregular porous structure (Mannai et al.

Table 3. Geometric characteristics of *Opuntia* fibers.

	Thickness (mm)			Pore areas (mm^2)			Pore angles (°)			
Fiber type	C	M	E	C	M	E	C	M	E	Reference
P	1.0	1.7	0.9	11.3	5.3	4.8	57.5	84.6	48.4	Bouakba et al. 2013
S	0.4	0.5	0.4	1.1	0.8	0.5	37.1	34.5	33.5	
P	1.0	1.3	1.7	18.58	5.74	2.87	90.7	80.3	54.8	Mannai et al. 2018
S	0.41	0.55	0.64	0.52	0.94	1.33	41.7	41.1	25.0	

P: primary fibers, S: secondary fibers, C: central zone fibers, M: middle zone fibers, E: external zone fibers.

2018). According to Malainine et al. (2003), cellulose is presented as parenchyma cell cellulose in cladodes and as fiber in spines. Individual cellulose microfibrils are approximately 5 nm in width and a longer length, presenting an almost infinite aspect ratio (Malainine, Mahrouz, and Dufresne 2005).

Considering each cladode, different topologies or architectures can be distinguished in the fibers depending on the part of the cladode from which they have been extracted (interior, middle or exterior zone), showing different geometric parameters (Table 3). According to Bouakba et al. (2013), external fibers presented the best mechanical properties (higher Young's modulus, tensile strength and deformation at break) possibly due to a higher fiber density and a smaller area of the mesh pores. These characteristics are consistent with those reported by Mannai et al. (2018) who also found that the pore areas are smaller in primary fibers of the external zone and can be observed in Table 3. With the pore angles (angle between the solid corners of the ends of the pore area) it occurs the same: they are smaller in the fibers located in the external part of cladodes. Fiber thickness increases from the central zone (1.0 mm for primary fibers and 0.4 mm for secondary fibers) to the external zone (1.7 mm for primary fibers and 0.64 mm for secondary fibers) according to Mannai et al. (2018). In contrast, Bouakba et al. (2013) observed that the thickest fibers are found in the middle zone (1.7 mm for primary and 0.5 mm for secondary). These discrepancies reveal the variability of vegetable fiber characteristics.

Fiber density

Opuntia fiber density is about 1.54 g/cm^3 (Mannai et al. 2018; Scaffaro et al. 2019). This value is similar to commercial vegetal fibers such as abaca (1.5 g/cm^3), jute (1.3 g/cm^3) and sisal (1.5 g/cm^3) (Faruk et al. 2012). Therefore, *Opuntia* fibers can be good candidates for lightweight composites.

Fiber crystallinity

Opuntia cladodes and *Opuntia* fibers showed the same crystalline peak at $2\Theta = 22.2^{\circ}$, due to crystalline cellulose (Greco and Maffezzoli 2015), while *Opuntia* spines have possibly a higher content of crystalline cellulose (Malainine et al. 2003).

Fiber applications

Opuntia fibers have been used to obtain art sculptures (Fabritz and Flagstaff), manufacture headdresses and hats (Falcón 2016), luminaries (Alberto et al. 2017) and manufacture furniture among other things. Sikalindi® uses *Opuntia* skeleton as a veneer to cover furniture and obtain unique and exclusive designs. Its use for concrete reinforcement has also been evaluated. Kammoun and Trabelsi (2019) included *Opuntia* fiber meshes (previously treated with hot water) of different dimensions (2 × 2, 3 × 3 and 5 × 5 cm) in different proportions (5, 10 and 15 kg/m^3) in a sand, gravel, Portland cement and water mixture. A 170% flexural strength improvement was achieved, while weight and thermal conductivity were reduced up to 25% and 42%, respectively. Elasticity modulus and compressive strength were also reduced (although it remained at acceptable values for a fiber content of 15 kg per m^3 of concrete) without achieving the recommended limit of the shrinkage values for wood concretes.

Opuntia as a reinforcement of composites

Different studies have used *Opuntia* fibers or *Opuntia* ground cladodes as reinforcement of different polymer matrices using different manufacturing processes. These studies are described, analyzed, compared and summarized below.

Matrices and process

Polylactic acid (PLA)

The choice of the most suitable polymer to be used as matrix depends on the final function and application of the composite (Vieyra et al. 2015) and it is limited by the temperature at which vegetable fiber degrades (Pickering, Aruan Efendy, and Le 2016). In recent years, interest in completely biodegradable materials has grown. In this context, PLA has achieved high relevance (Siakeng et al. 2019), being the most widely used biopolymer due to its good mechanical properties, which have been preserved for a long period of life even in wet conditions (Greco et al. 2013). Three studies evaluating the use of *Opuntia* as a reinforcement of PLA matrices have been found in the literature.

In 2013, Greco et al. published a paper in which they described the use of cladodes for obtaining wood flour-*Opuntia*-PLA composites and sandwich panels. PLA with wood flour (30 wt%) was blended with *Opuntia* fibers (20 wt%) to obtain sheets of 3 mm thickness by compression: the material was preheated in a forced convection oven to 170°C and pressed with a force of 20 tons reaching 180°C. Mechanical properties were lower than those obtained for a wheat flour-flax-PLA composite prepared under the same conditions. However, *Opuntia* composite showed a modulus similar to the matrix and a higher toughness due to higher resistance values (70.3 MPa vs. 48.5 MPa) and deformation (0.027% vs. 0.012%) as observed in Table 3. Sandwich panels obtained by adhesion of PLA and PLA-*Opuntia* sheets onto the *Opuntia* core were characterized by excellent adhesion, showing a high value of the interlaminar shear strength.

In 2015, Greco and Maffezzoli compared *Opuntia*-PLA composites obtained by rotational molding and compression. They used a PLA matrix and 15% polyethylene glycol (PEG) as a plasticizer to reduce the PLA viscosity and achieve good impregnation of the fibers. PLA and PEG were mixed in a twin screw extruder at 10 rpm using a temperature profile comprised between 453 and 417 K. A 148 mm side and 4 mm thick cube-shaped mold was used to obtain the composite material by rotational molding. A fully integrated fiber mesh was introduced into a mold wall (2.3 wt%) and 600 g of PLA: the mold was kept rotating for 20 min at 300°C. The temperature reached inside the mold under static conditions after the specified processing time was 210°C. Reinforced PLA sheets made by compression molding (in one and two stages) were obtained by applying a force of 20 tons at 200°C. Crystallinity degree of the composite obtained by rotational molding was higher than the composite obtained by double-stage compression and lower than the composite molded by single-stage compression. These differences could be attributed to the longer cooling time in single-stage molding.

Four years later, Scaffaro et al. (2019) added *Opuntia* ground fiber to a PLA matrix through a casting process using a batch mixer and two load levels (10% and 20%). Specifically, flours with sizes between 75–150 μm and 150–300 μm were used with a density equal to 1.54 ± 0.002 g/cm^3. Both, the matrix and the reinforcement, were vacuum-dried overnight at 90°C and then melted in a mixer at 190°C and 64 rpm for 4 min. The mixture obtained was cut into pellets and subjected to a compression molding process (using a Carver laboratory press) at 190°C and 180 bar for 2 min. By adding the *Opuntia* fiber powder, the PLA matrix rigidity (Young's modulus) was increased to 135%. However, the reinforced matrix showed a lower stretch capacity, decreasing tensile strength and elongation at break. Considering fiber size, it was obtained that the larger the fiber size, the greater the stiffness and fragility.

PP

Polypropylene (PP) is another matrix that has been evaluated. Malainine, Mahrouz, and Dufresne (2004) studied the effects of *Opuntia* cladodes as reinforcement of PP matrices by compression molding. They characterized the composites morphologically, thermally and mechanically, obtaining a weak but significant reinforcement only if a compatibilizer agent was used to improve matrix-reinforcement adherence. In detail, ground cladodes (with a size of less than 100 μm), PP pellets with a melting temperature of 176°C and a density of 0.905 g/cm^3 and a commercial compatibilizing agent MAPP with 1 wt% of maleic anhydride and physical properties similar to PP (melting temperature 175°C) were used. Ground cladodes were treated with MAPP at a rate of 0.3 wt% at 190°C for 10 min at a speed of 30 rpm. Treated and untreated fibers were mixed with the polymer matrix at 200°C for 10 min at a speed of 90 rpm. Mixtures with different fiber proportions (0–75 wt%) were obtained to manufacture 1 mm thick composites by compression molding at 14 MPa, 190°C and 15 min. Years later, Zampetakis et al. (2018) investigated discs (40 mm diameter and 10 mm thick) of PP (with anhydrous maleic grafts) reinforced with 0.4 wt% of *Opuntia* fiber powder. These discs were obtained by manual mixing and compression at 190°C, showing an increase in the matrix modulus compression by 33%.

Other matrices

Apart from PLA and PP, other matrices have been evaluated. Bouakba et al. (2013) obtained composites by molding at low pressure and room temperature using a polyester resin and 25 wt% of *Opuntia* as reinforcement. Specifically, the fiber (unmilled) and the resin were placed in a mold (350 x 220 × 2 mm dimensions) and subjected to a maximum pressure of 30 kPa for 24 h. Arévalo et al. (2010) reinforced a high-density polyethylene (HDPE) matrix with *Opuntia* fibers by injection, improving the matrix tensile modulus of elasticity by 36% (adding 15 wt% *Opuntia*). Scognamiglio et al. (2019) evaluated the use of *Opuntia* as reinforcement of a starch and glycerol thermoplastic film. The film was obtained by mixing 10 g of potato starch, 4 mL of glycerol and 400 mL of distilled water, stirring for 10 min. The solution was placed in a Teflon-coated steel mold for 1 h at 70°C and overnight at 45°C. In the same way, films were obtained by adding 8 and 16 wt% of *Opuntia*, varying the stirring time. The films with *Opuntia* mechanical properties decreased compared to pure thermoplastic film: it might be related to poor reinforcement distribution and the use of too large and variable fiber size (less than 1 mm and with different aspect ratios). However, *Opuntia* fibers improved the melting temperature of the thermoplastic by increasing its thickness (Scognamiglio et al. 2019). Nanocomposites obtained by casting at 37°C a mixture of cellulose microfibrils (0–10 wt%) from *Opuntia* and a matrix composed of an aqueous suspension of a copolymer of styrene and butyl acrylate have also been examined. The tensile modulus and the tensile strength of the nanocomposite filled with 7% of *Opuntia* cellulose are 30 times and 10 times higher, respectively, than the values reported for the unfilled matrix (Malainine, Mahrouz, and Dufresne 2005). Lahouaria et al. (2018) used *Opuntia* fibers mixed with an epoxy resin to obtain canoe paddles, increasing the tensile behavior of the matrix. Recently, Mannai et al. (2020) reinforced polyvinyl alcohol and styrene-butadiene rubber matrices with *Opuntia* fibers (3,6 and 9 wt%) by a simple hand lay-up method. They obtained promising thermal and thermomechanical properties and good results about the composite biodegradability thanks to a correct interfacial interaction fiber-polymer.

Comparative analysis

Table 4 summarizes some of the main characteristics of the composites obtained in the studies previously described. It is observed that mechanical properties vary depending on the matrix used, fiber percentage and even on manufacturing process. In the flexural tests of the PLA matrix and wood flour, there was a decrease in the elastic modulus and an increase in the flexural strength (Greco et al. 2013), while, adding *Opuntia* fiber to the PLA matrix with 15% of PEG, no improvement was produced in mechanical properties. However, better results for composites obtained by compression than by rotational molding were indicated (Greco and Maffezzoli 2015). All the reported tensile test

Table 4. Main characteristics of the reviewed *Opuntia* reinforced composites.

Opuntia	Matrix	Fiber extraction	Process	Mechanical properties			References
20 wt% *Opuntia* fiber	PLA and Wood-flour(30%)	Fibers extracted from cladodes (2 h in boiling water and 3 months drying)	Compression	**Matrix (flexural)** E: 4.8 GPa σ: 48.5 MPa : 0.012%	**Fiber (flexural)** E: 354 MPa σ: 4.65 MPa : 0.031%	**Composite (flexural)** E: 4.6 GPa σ: 70.3 MPa : 0.027%	Greco et al. 2013
2.3 wt% *Opuntia* fiber	PLA (15% PEG)	Fibers extracted from cladodes(2 h in boiling wáter and 3 months drying)	Rotational molding	**Matrix (flexural)** E: 3.7 GPa σ: 108 MPa : -	**Fiber (flexural)** E: 354 MPa σ: 4.65 MPa : 0.031%	**Composite (flexural)** E: 1.7 GPa σ: 32 MPa : 2.1%	Greco and Maffezzoli 2015
			Compression	**Matrix (flexural)** E: 3.7 GPa σ: 108 MPa : –	**Fiber (flexural)** E: 354 MPa σ: 4.65 MPa : 0.031%	**Composite (flexural)** E: 2.9 GPa σ: 67 MPa : 2.6%	
10 wt% *Opuntia* fiber (75–150 µm)	PLA	Washed, cut, and ground commercial fibers	Compression	**Matrix (tensile)** E: 3.5 GPa σ: 53 MPa : 6%		**Composite (tensile)** E: 4 GPa σ: 40 MPa : 2.6%	Scaffaro et al. 2019
0–75 wt% *Opuntia* cladodes	PP (MAPP)	Cut, dried and ground (100 µm) cladodes	Compression	**Matrix (tensile)** E: 200 MPa σ: 18 MPa : 40%		**Composite (tensile)** E: 250 MPa σ: 11 MPa : 5%	Malainine, Mahrouz, and Dufresne 2004
25 wt% *Opuntia* fiber	Polyester	Fibers extracted from a stem buried for 15 days	Molding technique at low pressure	**Matrix (tensile)** E: 800 MPa σ: 16 MPa : 2.1%	**Fiber (tensile)** E: 1.10 GPa σ: 27 MPa : 2.6%	**Composite (tensile)** E: 1.48 GPa σ: 15.8 MPa : 1.29%	Bouakba et al. 2013
15 wt% *Opuntia* cladodes	HDPE	Cut, dried, ground and sieved cladodes	Injection	**Matrix (tensile)** E: 956.1 MPa σ: 22.26 MPa : 0.1075		**Composite (tensile)** E: 1302 MPa σ: 19.72 MPa : 0.0966	Arévalo et al. 2010
Opuntia old stem fiber	Epoxy	Fibers extracted from a stem buried for 45 days	-	**Matrix (tensile)** E: 211 MPa σ: 12.8 MPa : 34.14%	**Fiber (tensile)** E: 279 MPa σ: 1.0 MPa : 4.73%	**Composite (tensile)** E: 369.5 MPa σ: 15.5 MPa : 4.45%	Lahouaria et al. 2018

E: elastic modulus, σ: strength, Ɛ: deformation at break.

results show an increase in the elastic modulus in the composites, evidencing a good reinforcement. Regarding elongation, a decrease occurs in general because the fibers are more rigid and, therefore, less deformed (Arévalo et al. 2010).

There are differences on whether *Opuntia* fibers perform better in flexion or traction. Bouakba et al. (2013) studied the polyester and *Opuntia* composites behavior to flexural loads, obtaining that the modulus (7.95 GPa) is 5.3 times greater than the measured from the tensile load (1.48 GPa), and the flexural strength (66.5 MPa) is 4.2 times greater than tensile strength (15.8 MPa). These results were attributed to the *Opuntia* fiber structure (Bouakba et al. 2013) and are in agreement with Greco and Maffezzoli (2015), who obtained that *Opuntia* fiber has a greater elastic modulus in flexion (354 MPa) than in tension (157 MPa). However, Mannai et al. (2018) found that the tensile behavior of *Opuntia* fibers (elastic modulus of 2.93 GPa) was better than flexural behavior (elastic modulus of 2.36 GPa), being much higher these values than those obtained by Greco and Maffezzoli (2015). These discrepancies may be due to the own fiber variability; Mannai et al. (2018) used fibers extracted from a mature cladode, while Greco and Maffezzoli (2015) used fibers from a still green cladode.

Opuntia fibers have shown interesting properties in terms of energy dissipation under cyclic applications of flexural loads: according to Bouakba et al. (2013), dissipated energy tends to decrease as the number of cycles increases for high load ratios, while it remains almost constant until breakage for load ratios equal to 0.70. In this context, they are considered adequate for the design of efficient lightweight materials against energy absorption (Chen and Pugno 2012), highlighting their properties for the dissipation and mitigation of impact effects (Zampetakis et al. 2018).

A priori, mechanical properties of *Opuntia* fibers are lower than those of vegetable fibers commercially used, whose modulus of elasticity is between 12 and 70 GPa and the tensile strength between 140 and 930 MPa (Faruk et al. 2012). However, the hierarchical structure of these fibers, the dimensions of the cell unit (large and thick-walled parenchyma cells, long fiber bundles and the densely distributed periderm with thick edges), the crystallinity degree and their chemical composition, which are considered to influence the toughness and elongation of the fibers, point out that the *Opuntia* fiber can provide good mechanical properties (Mannai et al. 2018). Furthermore, fibers heterogeneous structure suggests that the mechanical characteristics in the longitudinal direction are better than in the transverse direction. Moreover, the longer the fiber, the better the flexural resistance and thermal conductivity but the lower the compression resistance (Kammoun and Trabelsi 2019).

Finally, it is important to highlight the mechanical properties of *Opuntia* spines. They have showed mean values of the elasticity modulus around 33.5 GPa and 779 MPa of flexural strength, possibly due to the high orientation and crystallinity of the cellulose (Gindl-Altmutter and Keckes 2012). However, despite having better properties than the fiber from cladodes, its obtaining and handling are more complicated. For this reason, there are few studies that have evaluated its exploitation as reinforcement.

Treatments

It is well known that a good matrix–reinforcement interface bond is required to achieve an optimal reinforcement (Pickering, Aruan Efendy, and Le 2016). To cope with this, physical (stretching, calendering, thermal, corona, plasma) and chemical (coupling agents, alkaline treatment, silane treatment) fiber treatments are used (Henrique et al. 2015).

In the reviewed studies, no treatment of *Opuntia* fiber has been investigated to improve adhesion with the matrix, possibly due to the fact that some studies suggest that the surface roughness of *Opuntia* fibers favors this bond. However, there are references to the fact that water treatment allows removing part of the calcium oxalate crystals and other minerals from fibers, improving their mechanical and thermal properties (Mannai et al. 2018). It is important because the presence of minerals or impurities in the fibers can cause degradation of the polymers (Scaffaro et al. 2019). Reviewed papers suggest that alkaline treatment could be a good alternative: sodium hydroxide has been used to obtain pure cellulose from *Opuntia* (Malainine, Mahrouz, and Dufresne 2005) and to increase cellulose content from 21.6% to 63.7% (Malainine et al. 2003). In this way, it can be expected that alkaline treatment allows hemicelluloses and other impurities removal from *Opuntia* fibers and improves fiber-matrix compatibility.

On the other hand, it is necessary to consider the use of coupling agents as an alternative to fiber treatment. Polyethylene glycol was added to a polylactic acid (PLA) matrix prior to *Opuntia* addition. PLA viscosity was reduced from 620 Pa·s to 170 Pa·s at 210°C, improving fiber impregnation and, therefore, the matrix-reinforcement adhesion. Furthermore, the plasticizer produced an increase in crystallization kinetics allowing to obtain a semi-crystalline structure after PLA processing instead of a completely amorphous structure (Greco and Maffezzoli 2015). Similarly, the use of maleic acid modified polypropylene (MAPP) provided protection against *Opuntia* fiber water, reducing the moisture content and water diffusion coefficient, and consequently improving the fiber-matrix compatibility (Malainine, Mahrouz, and Dufresne 2004).

Conclusions

Several studies have evaluated the use of *Opuntia* fruits and mucilage, highlighting its functional properties with multiple benefits in the food sector. However, far too little attention has been paid to the study of *Opuntia* fiber and its use as reinforcement of polymeric matrices. The peculiar structure of *Opuntia* fiber and its possible extraction from cladodes without the need for chemicals and laborious processes have made it a candidate to consider in the composites field. It has been found that only one study has reported the *Opuntia* fiber composition: 53% cellulose, 4.8% lignin and 10.9% hemicellulose, while several studies have analyzed the cladode composition (with a lower cellulose content).

The highest fiber content is achieved in the old cladodes peripheral area, according to the works reported in this review, showing these fibers the better mechanical properties. Matrices such as PLA, PP, HDPE and polyester have been reinforced with *Opuntia* mainly by compression molding, showing different mechanical properties that evidence the own fiber variability. Most articles agree that *Opuntia* fiber offers good properties against energy absorption and allows increasing the tensile elastic modulus up to 135%.

Further studies, which focus on *Opuntia* fiber extraction, characterization, treatment and its composites should be undertaken in order to establish the appropriate parameters (time, resources . . .) to optimize fiber extraction, improve fiber-matrix compatibility and determine a general trend despite the plant own variability.

Highlights

1. *Opuntia* has good properties to be used as reinforcement of polymeric matrices alternatively to its use in the food sector.
2. Only one study has been found that reported the composition of *Opuntia* fiber, while several studies have analyzed the composition of *Opuntia* cladodes (with a lower cellulose content).
3. In the old cladodes peripheral area is achieved the highest fiber content, showing these fibers the better mechanical properties.
4. Different polymeric matrices have been combined with *Opuntia* fiber mainly by compression molding showing good results in energy absorption tests and increasing the tensile elastic modulus up to 135%.
5. It is needed to continue researching the *Opuntia* fiber due to the variability of the available data.

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