Opuntia spp. Biomass: Composition, Green Extraction Technologies, and Applications in Bioproducts and Biomaterials

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In recent years, the increasing demand for sustainable and renewable materials has intensified interest in biomass resources capable of supporting green processing and circular bioeconomy strategies. Among these, *Opuntia* spp. (commonly known as nopal or prickly pear cactus) has emerged as a promising biomass resource due to its adaptability to arid environments and its rich and diverse chemical composition. This review aims to provide a comprehensive and integrated analysis of *Opuntia* spp. biomass, focusing on its chemical composition, extraction and processing technologies, and its potential for the development of bioproducts and biomaterials. One of the key aspects addressed is the comparison between conventional and environmentally friendly extraction approaches, considering their efficiency, limitations, and suitability for recovering important fractions such as mucilage, structural polysaccharides, and bioactive compounds. This review evaluates the utilization of these fractions in food systems, biodegradable materials, hydrogels, composite materials, and environmental remediation, with an emphasis on their functional attributes and technological potential. Sustainability is considered from a biorefinery perspective, focusing on the efficient use of biomass and the mitigation of environmental impacts. This work gives a critical analysis of recent progress and highlights mayor challenges concerning process standardization, scalability and material properties. The findings support the potential of *Opuntia* spp. as a versatile platform for sustainable materials and point to future research needed for industrial implementation.

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INTRODUCTION

Opuntia spp. (commonly known as nopal or prickly pear cactus) plants are widely distributed across arid and semi-arid regions, where their distinctive physiological traits enable sustained biomass production under conditions of limited water availability (Nefzaoui and El Mourid 2010; Inglese *et al.* 2017). Their ability to tolerate drought, high temperature fluctuations, and degraded soils has positioned these species as resilient biomass sources, especially in areas affected by land degradation and freshwater scarcity. In addition to their ecological robustness, *Opuntia* species produce substantial amounts of cladodes, fruits, and seeds, ensuring a continuous supply of renewable biomass suitable for a range of industrial and biotechnological applications (Sáenz *et al.* 2004; Koufan *et al*. 2024).

In addition to their ecological adaptability, *Opuntia spp.* are cultivated on a large scale in several regions worldwide, particularly in America, Africa, and the Mediterranean basin, where they represent a significant source of biomass for food, feed, and emerging industrial applications (Santos Díaz *et al*. 2017). *Opuntia ficus-indica* is cultivated in more than 30 countries and occupies hundreds of thousands of hectares worldwide, particularly in arid and semi-arid regions, underscoring its relevance as a biomass resource (Inglese *et al.* 2017). Its high productivity under low-input conditions and year-round biomass availability make it especially attractive as a sustainable feedstock for biorefinery processes. This is relevant in arid and semi-arid regions, where water availability limits conventional forage production (Pastorelli *et al*. 2022).

Sustainable exploitation of *Opuntia* spp. biomass needs to be managed carefully to avoid potential environmental impacts associated with uncontrolled harvesting from natural ecosystems. Unsustainable removal of vegetation cover in arid and semi-arid regions may contribute to deterioration of the soil and elevated risk of desertification. Biomass production should be primarily based on cultivated systems rather than wild collection, ensuring soil conservation, maintaining vegetation cover and supporting long-term ecosystem stability (Inglese *et al.* 2017; Nefzaoui and El Mourid 2010).

The growing interest in *Opuntia* biomass is largely associated with its diverse chemical composition, which includes biopolymers, mucilage, soluble fibers, and structurally relevant polysaccharides of interest for material design and process engineering (Cárdenas *et al.* 1997; Medina-Torres *et al.* 2003). *Opuntia* tissues contain a broad array of secondary metabolites such as phenolic compounds, flavonoids and betalains that contribute antioxidant activity, stabilization capacity, and natural coloration, leading to enhanced functional performance of bio-based materials (Andreu *et al.* 2018; Mazri 2021). While these compounds have been traditionally investigated in food-related applications, their physicochemical properties also support their integration into bioprocessing and green material systems within biomass valorization frameworks.

Growing pressure to develop sustainable industrial solutions has further stimulated research on *Opuntia* biomass as a feedstock for green extraction technologies, bio-based materials and circular bioeconomy strategies (Ali *et al.* 2024; Hernandez *et al.* 2024). Recent advances in environmentally responsible extraction, fractionation, and conversion methods have enabled the more efficient use of cladodes, peels, seeds, and fruit pulp, helping to reduce waste and improve resource efficiency across processing chains. With this framework, this review provides an integrated perspective of *Opuntia* spp., bringing together botanical, agronomic and chemical aspects to better understand its potential for biomass valorization.

This review aims to provide a comprehensive and critical analysis of *Opuntia* spp. biomass, focusing on its chemical composition, extraction, and processing technologies and its possible applications in bioproducts and biomaterials. Emphasis is placed on comparing conventional and green extraction methods and assessing their relevance within sustainable and circular bioeconomy frameworks. This approach offers a methodical framework for assessing current advances and identifying future research directions.

BOTANICAL AND AGRONOMIC FEATURES OF *OPUNTIA SPP*

Morphological Characteristics

Species belonging to the genus *Opuntia* are characterized by segmented, flattened stems known as cladodes, which serve as the main photosynthetic organs of the plant. These succulent structures are rich in water, mucilage, and structural polysaccharides; these attributes contribute to both efficient water storage capacity and mechanical stability under arid and semi-arid conditions (Sáenz *et al*. 2004; Mazri 2021). In addition, cladodes represent the primary source of harvestable biomass, contributing substantially to yield due to their rapid growth and high moisture content, which can exceed 80-90% depending on environmental conditions (Inglese *et al.* 2017; Pastorelli *et al.* 2022). The presence of hydrocolloids such as mucilage further supports their relevance for industrial applications, particularly in the development of biomaterials, thickeners, and biodegradable systems, as illustrated in Fig. 1.

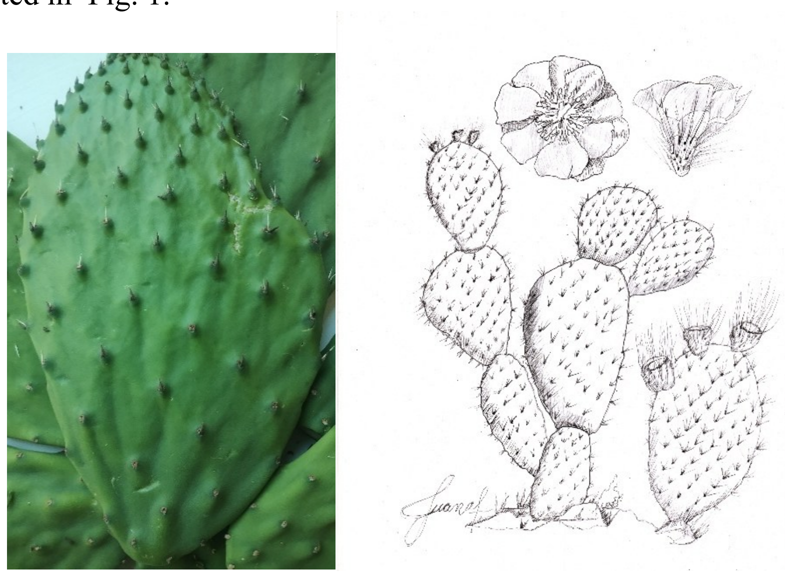

Fig. 1. Morphological characteristics of *Opuntia spp.* (A) Photograph of *Opuntia* cladodes showing external morphological, including, areoles and spines (author's own image). (B) Morphological illustration of *Opuntia spp.* highlighting cladodes, flowers and fruits (adapted and modified from Arreola-Nava *et al.* 2017).

The surface of the cladodes is covered with areoles, which are specialized meristematic regions from which spines, glochids, flowers, and new cladodes originate, supporting vegetative propagation and structural renewal, which contributes to sustained biomass production (Ahmed *et al*. 2021). This capacity for continuous regeneration supports sustainable biomass production and repeated harvesting cycles, which are potentially advantageous for large-scale biorefinery schemes.

The root system of *Opuntia* spp. is typically shallow but highly extensive, enabling rapid water absorption following sporadic rainfall events and contributing to enhanced survival rates and sustained biomass accumulation in marginal environments (Neupane *et al*. 2024). This trait is associated with improved resource-use efficiency and reduces irrigation requirements, supporting the potential economic and environmental feasibility

These species exhibit crassulacean acid metabolism (CAM), a photosynthetic adaptation that minimizes transpiration losses by shifting gas exchange to nighttime hours, resulting in improved water-use efficiency (Cushman 2001). This metabolic strategy allows continuous carbon assimilation under stress conditions, contributing to relatively stable biomass productivity in arid regions.

The integration of these morphological and physiological traits influences biomass yield, chemical composition and functional properties, thus contributing to the suitability of *Opuntia* spp. for applications in bioproducts, biomaterials and sustainable biorefinery processes.

Cultivation, Productivity, and Biomass Availability

Opuntia spp. are widely cultivated in arid and semi-arid regions of Latin America, Africa, and the Mediterranean basin, where they are traditionally used as sources of food and forage and, increasingly, as industrial raw materials. Among the cultivated species, *Opuntia ficus-indica* is the most extensively domesticated, owing to its high biomass productivity, large cladode size, and broad adaptability to diverse agroclimatic conditions (López-Palacios *et al*. 2019).

In recent years, the cultivation of *Opuntia* spp. has expanded in arid and semi-arid regions worldwide, driven by the growing demand for drought-resilient crops, climate change adaptation strategies, and sustainable agricultural systems. This trend is particularly evident in regions such as North Africa, Brazil, and Ethiopia, where *Opuntia* is increasingly cultivated as a multipurpose crop for food, forage, and biomass production (Inglese *et al*. 2017; Naorem *et al.* 2024). The growing demand for sustainable feedstocks in bio-based industries has further contributed to increased interest in *Opuntia* biomass within circular bioeconomy frameworks.

Under appropriate agronomic management, *Opuntia* spp. can achieve relatively high annual biomass yields, reflecting both intrinsic physiological adaptations and improved cultivation practices. In Mexico, official agricultural statistics report that nopal (*Opuntia* spp.) production reached approximately 891,821 tons from 12,799 hectares in 2019, corresponding to an average yield of about 71 tons per hectare. This increase in productivity, achieved with only a modest expansion in cultivated areas over the last decade, suggests the role of technological improvements and farm management practices in enhancing biomass availability for sustainable valorization strategies (SIAP 2019).

A key advantage of *Opuntia* spp. as a biomass feedstock is its potential for continuous availability of harvestable material throughout the year, as cladodes can be collected at different developmental stages without significantly compromising plant viability. Fruits and their by-products, including peels and seeds, contribute substantially fraction of the biomass pool, generating multiple fractions suitable for integrated valorization. Beyond their quantitative availability, these biomass fractions exhibit a broad functional diversity, as cladodes and derived polysaccharides have been traditionally and industrially used for food, feed, water treatment, soil restoration, and material applications, highlighting their potential versatility as renewable resources. This steady, diversified, and multifunctional biomass supply can support process schemes focused on the recovery of polysaccharides, fibers, and other functional components relevant to biotechnological applications and the development of bio-based materials (Guevara-Arauza 2021; Ali *et al.* 2024).

Environmental Resilience and Low-Input Agricultural Systems

One of the most relevant agronomic advantages of *Opuntia spp*. is their high tolerance to drought, salinity, and low soil fertility, which allows their cultivation on degraded or marginal lands unsuitable for conventional crops. As CAM plants, *Opuntia* species exhibit elevated water-use efficiency through nocturnal CO_2 fixation combined with daytime stomatal closure, effectively reducing water losses under arid and semi-arid conditions (Hernandez *et al*. 2024).

Opuntia spp. not only tolerate water scarcity but also offer useful ecosystem services, including soil stabilization, erosion control, and carbon sequestration, thereby strengthening their role in low-input agricultural systems and strategies for mitigating climate change. Recent reports indicate that these species are no longer limited to conventional desert environments but are increasingly cultivated in regions characterized by cooler or more variable climatic conditions, reflecting their broad adaptive capacity under changing environmental scenarios (Hernandez *et al*. 2024).

Collectively, these attributes have positioned *Opuntia* spp. as strategic crops within circular economy and sustainable agriculture frameworks. Their ability to generate substantial biomass under resource-limited conditions supports their use as reliable feedstocks for green processing technologies and integrated biomass valorization schemes, while avoiding direct competition with staple food crops or intensive, water-dependent agricultural systems (Hernandez *et al*. 2024).

CHEMICAL COMPOSITION OF *OPUNTIA* SPP. BIOMASS

The chemical composition of *Opuntia* spp. biomass supports its growing relevance as a renewable resource for bioproducts and green technologies. Different plant organs, including cladodes, fruits, peels, seeds, and flowers, exhibit distinct compositional profiles that influence their functional and technological applications. *Opuntia* biomass is characterized by a high content of structural and soluble polysaccharides, moderate protein levels and a diverse range of secondary metabolites, which influence its appropriateness for specific extraction processes and industrial applications (Sáenz *et al*. 2004; Inglese *et al*. 2017; Ali *et al.* 2024).

Primary Metabolites: Carbohydrates and Fibers

Carbohydrates constitute the dominant fraction of *Opuntia* spp. biomass, comprising both structural and non-structural components. Cladodes are particularly rich in soluble dietary fibers, such as mucilage and pectic polysaccharides, as well as insoluble fractions including cellulose and hemicellulose (Medina-Torres *et al.* 2003; Sáenz *et al*. 2004). These polysaccharides exhibit high water-binding capacity and rheological functionality, which support their use in hydrogel systems, edible films, and biopolymer matrices, especially when extracted using aqueous or mild green extraction methods that preserve their molecular structure and functionality (Rodríguez-González *et al*. 2014; Sánchez-Vega *et al*. 2020).

Mucilage from *Opuntia ficus-indica* is characterized by a complex, high-molecular-weight heteropolysaccharide structure, resulting in viscosity, gel-forming ability, and emulsifying properties relevant to food, pharmaceutical, and biomaterial applications (Rodríguez-González *et al*. 2014). These characteristics position mucilage as a promising candidate for green extraction processes and development sustainable material formulations, where functional integrity is critical.

Lignocellulosic components present in mature cladodes and seeds have attracted considerable interest as feedstocks for biorefinery schemes, including the recovery of cellulose and fermentable sugars for bio-based materials and energy applications. In such systems, pretreatment and fractionation processes are key determinants of yield, conversion effectiveness and downstream processing performance (Hernandez *et al*. 2024, Varela Pérez *et al.* 2024)

Secondary Metabolites: Betalains, Phenolic Compounds, Flavonoids and Terpenoids

Beyond its macromolecular constituents, *Opuntia spp*. biomass contains a wide array of secondary metabolites that provide functional attributes relevant to bioproduct formulation. Betalains, including betacyanins and betaxanthins, are responsible for the characteristic pigmentation of fruits and contribute to natural coloring capacity with antioxidant stability, making them suitable for use as natural colorants and functional additives in food systems and biodegradable materials (Andreu *et al*. 2018).

Phenolic compounds and flavonoids are distributed across different plant organs, particularly in cladodes, fruit peels, and seeds. These compounds are associated with antioxidant performance, oxidative stability, and protective effects in food systems and bio-based materials (Ramadan *et al*. 2021). Their incorporation into polymeric matrices has been reported to improve shelf stability, UV protection, and functional performance, especially when recovered through solvent-based or green extraction techniques that preserve their bioactivity (Ramadan *et al*. 2021; Medeiros *et al*. 2024).

Terpenoids and other minor constituents have been reported in *Opuntia* tissues, contributing to aroma, hydrophobic interactions, and interfacial properties that can be relevant in composite materials and emulsified systems (Mazri 2021). Polysaccharide-rich fractions such as *O. ficus-indica* mucilage can act as functional platforms that interact synergistically with secondary metabolites, which may improve the performance of sustainable bioproducts (Ramadan *et al*. 2021).

Variability among Species, Plant Organs, and Processing Conditions

The chemical composition of *Opuntia spp*. biomass exhibits considerable variability depending on species, plant organ, agronomic conditions, and processing parameters. Differences between cladodes, fruits, peels, and seeds strongly influence the relative abundance of polysaccharides, fibers, and secondary metabolites, as well as their functional properties (Medina-Torres *et al.* 2003; Sáenz *et al*. 2004)

Cultivation practices further contribute to this variability. Biomass yield and chemical quality are strongly influenced by geographic location, soil type, climate, planting density, irrigation regime, and harvest frequency. Under appropriate agronomic management, *Opuntia* spp. cultivation can be optimized to achieve high productivity while preserving the functional attributes of polysaccharide-rich fractions (Alam-Eldein *et al*. 2021, Naorem *et al.* 2024). Although *Opuntia spp*. is well known for its low water requirements, irrigation practices vary depending on production systems. In commercial cultivation, supplemental irrigation is often applied to improve biomass yield and fruit production, whereas in traditional or marginal systems the crop is frequently grown under rainfed conditions (Inglese *et al*. 2017; Nefzaoui and El Mourid 2010).

Processing conditions also exert a marked influence on biomass composition and performance. Extraction conditions, including method, temperature, solvent system, pH and pretreatment strategies, influence polysaccharide integrity, molecular weight distribution, and the retention of associated bioactive compounds. These factors can directly affect the efficiency of compound recovery and the functional performance of derived materials.

The interplay between chemical composition, extraction methods, and processing conditions is necessary to maximize the recovery and functionality of *Opuntia*-derived compounds, supporting their effective integration into bioproducts, biomaterials and biorefinery systems.

EXTRACTION AND PROCESSING TECHNOLOGIES

The transformation of *Opuntia* spp. biomass into value-added bioproducts depends on the selection of appropriate extraction and processing technologies. *Opuntia* tissues present a complex matrix characterized by high water content, mucilage-rich polysaccharides, lignocellulosic fractions, and diverse embedded secondary metabolites, which require tailored strategies to achieve efficient and selective recovery.

Consequently, the selection of extraction technologies is an important step in determining the efficiency, selectivity and functionality of recovered compounds, influencing their suitability for industrial applications. Both conventional and emerging green extraction approaches have been explored to fractionate *Opuntia* spp. biomass with increasing emphasis on improving sustainability, reducing environmental impact and preserving bioactive compounds. These developments are consistent with circular bioeconomy principles by promoting sustainable processing and the integral utilization of *Opuntia* biomass.

Conventional Extraction Methods

Conventional extraction techniques, including maceration, agitation, heating, Soxhlet, and classic solid-liquid extraction using water or hydroalcoholic solvents, are commonly applied to recover metabolites from *Opuntia* spp. cladodes, fruits and seeds. These approaches remain attractive due to their simplicity, accessibility and relatively straightforward scalability, particularly in industrial contexts.

These techniques are especially effective for extracting water-soluble components such as mucilage, soluble dietary fibers, and other polar compounds, including phenolic compounds (Sáenz *et al.* 2004). Hydroalcoholic extractions are often preferred for the recovery of antioxidant compounds due to their improved solubility and extraction efficiency (Andreu *et al.* 2018). Hot water extraction remains one of the most commonly used approaches for isolating mucilage and polysaccharides because of its compatibility with food-grade and biomaterial applications (Cárdenas *et al.* 1997; Medina-Torres *et al.* 2003).

However, despite their widespread use, conventional extraction methods present several limitations, including long extraction times, high solvent consumption, low selectivity, and the potential degradation of thermolabile compounds due to prolonged exposure to elevated temperatures. These drawbacks are known to compromise process efficiency and limit the recovery of high-value bioactive compounds. As a result, conventional techniques are increasingly regarded as reference methods, while alternative strategies are being developed to overcome these limitations.

Green Extraction Technologies Applied to *Opuntia spp*. Biomass

Green extraction technologies have emerged as alternatives to overcome the limitations of conventional methods with the aim of improving extraction efficiency, reducing solvent consumption and preserving the integrity of bioactive compounds. These approaches aim to enhance mass transfer processes while operating under milder and more controlled conditions.

Microwave-assisted extraction (MAE) has been reported to reduce extraction time while improving the recovery of phenolic compounds and pigments through rapid dielectric heating and enhanced cell wall disruption (López-Salazar *et al.* 2023). Optimization strategies based on statistical and artificial intelligence approaches have further improved extraction efficiency, obtaining high phenolic yields and antioxidant capacity in O. *ficus-indica* cladodes (Oufighou *et al.* 2025). Ultrasound-assisted extraction (UAE) relies on acoustic cavitation phenomena that promote solvent penetration and mass transfer, resulting in higher extraction yields under mild temperature conditions. UAE has been reported to be particularly effective for recovering betalains and phenolic compounds from *Opuntia* fruits, allowing high yields under mild temperature conditions and short extraction times, while enhancing antioxidant and anti-inflammatory activities (Gómez-López *et al.* 2021).

Supercritical fluid extraction (SFE) using carbon dioxide has been applied to *Opuntia* seeds for the recovery of lipid-rich fractions. This technique enables the production of high-quality oils that are typically rich in unsaturated fatty acids, tocopherols and minor phenolic compounds (Al-Naqeb *et al*. 2023). Although conventional Soxhlet extraction can yield higher quantities, SFE can produce extracts with higher purity, absence of solvent residues and improved preservation of thermolabile compounds.

Despite these advantages, the implementation of green extraction technologies remains constrained by factors such as high equipment cost, energy requirements, and challenges associated with large-scale industrial application. Therefore, while these techniques offer clear improvements at the laboratory scale, their industrial feasibility requires further optimization and economic evaluation.

A comparative overview of conventional and green extraction technologies applied to *Opuntia spp*. biomass, including their operating conditions, target compounds, advantages, and limitations, is summarized in Table 1.

Table 1. Comparative Overview of Conventional and Green Extraction Technologies Applied to *Opuntia spp*. Biomass

Extraction Method	Target Fractions	Advantages	Limitations	References
Hot water extraction	Mucilage, soluble polysaccharides	Simple, low-cost, scalable	Long extraction time, low selectivity	Sáenz *et al.* 2004
Hydroalcoholic extraction (often ultrasonic-assisted)	Phenolics, flavonoids, antioxidant fractions	High extraction efficiency for polar bioactives	High solvent consumption, thermal degradation	Andreu *et al.* 2018
Microwave-assisted extraction (MAE)	Phenolics	Rapid extraction, optimized yield, reduced solvent	Equipment cost, limited scalability	Oufighou *et al.* 2025
Ultrasound-assisted extraction (UAE)	Betalains, phenolic compounds, flavonoids	Short extraction time, low temperature, reduced solvent consumption	Scale-up challenge, equipment dependencies	Gómez-López *et al.* 2021

Supercritical fluid extraction (SFE) with CO_2	Seed oils, fatty acids, tocopherols, minor phenolic compounds	Solvent-free extracts, high selectivity, preservation of thermolabile compounds	High equipment cost, limited efficiency for highly polar compounds	Al-Naqeb *et al.* 2023

Pretreatments, Fractionation, and Purification Strategies

Pretreatment, fractionation, and purification strategies are essential to enhance the accessibility, conversion, and recovery of valuable components from *Opuntia spp*. biomass prior to extraction or downstream processing. Due to the high moisture content and polysaccharide-rich matrix of *Opuntia* tissues, mechanical operations such as size reduction, drying, and milling are commonly applied to increase surface area and enhance solvent penetration, resulting in improved extraction efficiency.

Enzymatic pretreatments using cellulases, hemicellulases, and pectinases have been shown to selectively disrupt cell wall components, facilitating the release of soluble fibers, mucilage, and fermentable sugars while preserving functional properties (Garfias-Silva *et al*. 2022; Liu *et al.* 2025). Physicochemical pretreatments, including hydrothermal and mild acid or alkaline treatments, have also been explored to improve polysaccharide accessibility and to integrate *Opuntia* biomass into biorefinery schemes aimed at producing bioethanol, biopolymers, and other bioproducts.

Following extraction, fractionation and purification are important to obtaining ingredients with defined molecular and functional characteristics. Membrane-based technologies such as microfiltration and ultrafiltration have been reported to be effective for separating polysaccharide fractions according to molecular weight while preserving rheological properties and minimizing thermal degradation (Fernández-Martínez *et al*. 2024). Chromatographic and adsorption-based techniques are applied for the enrichment of phenolic compounds and natural pigments when high-purity fractions are required, despite their higher operational costs (Liu *et al.* 2025).

The integration of optimized extraction technologies with appropriate pretreatment and fraction strategies is important to maximize the recovery, functionality and industrial applicability of *Opuntia* spp. biomass within sustainable biorefinery systems.

APPLICATIONS IN BIOPRODUCTS

The increasing availability of *Opuntia* spp. biomass has enabled its incorporation into a wide range of bioproducts derived from renewable resources. Its complex composition, including structural polysaccharides, mucilage, soluble fibers, and secondary metabolites, provides multifunctional properties of interest for industrial bioprocessing. Secondary metabolites naturally present in *Opuntia* biomass, particularly phenolic compounds contribute antioxidant and protective effects that enhance product stability during processing and storage (Andreu *et al*. 2018). These components support applications in food-related systems, functional additives, and fermentation-based processes, aligning with sustainable production models and biomass valorization strategies.

Cladodes, fruits, and seeds of *Opuntia* spp. have been extensively explored as sources of dietary fiber, polysaccharides, and proteins suitable for functional formulations. The high content of soluble fiber and mucilage contributes to viscosity, water retention, and textural modification, enabling their use as natural stabilizers, thickeners, and fat replacers (Medina-Torres *et al*. 2003; Sáenz *et al.* 2004). In addition, secondary metabolites naturally present in *Opuntia* biomass, including phenolic compounds and flavonoids, provide antioxidant protection that enhances product stability during processing and storage without the need for synthetic additives (Andreu *et al*. 2018; Mazri 2021).

One of the most distinctive bioproduct applications of *Opuntia spp*. is the recovery of natural pigments, particularly betalains, which exhibit intense coloration, high water solubility, and antioxidant functionality. These properties make them suitable as natural colorants and stabilizing agents in food and bio-based formulations (Stintzing and Carle 2005). Furthermore, the carbohydrate-rich composition of *Opuntia* biomass supports its use as a substrate in fermentation processes, including the production of bioethanol, organic acids, and other value-added metabolites (Hernández *et al*. 2024). Soluble fibers and mucilage have also shown prebiotic potential by selectively promoting beneficial microbial growth, reinforcing the role of *Opuntia* biomass as a versatile feedstock for integrated bioproduct and biotechnological applications (Nefzaoui and El Mourid 2010).

APPLICATIONS IN BIOMATERIALS

The structural complexity and chemical diversity of *Opuntia spp.* biomass have supported the development of a wide range of bio-based materials with functional and environmental relevance. Polysaccharide-rich fractions, including mucilage, pectins, and cellulose, constitute key building blocks for biomaterial fabrication, while minor secondary components can contribute to stabilization and performance during processing.

Figure 2 illustrates a schematic overview of the valorization pathway of *Opuntia spp*. biomass, showing the transformation of cladodes, fruits, and seeds into functional fractions and their subsequent applications in films, hydrogels, composites, and adsorbent materials. This integrated method demonstrates the potential of *Opuntia* biomass within circular bioeconomy frameworks.

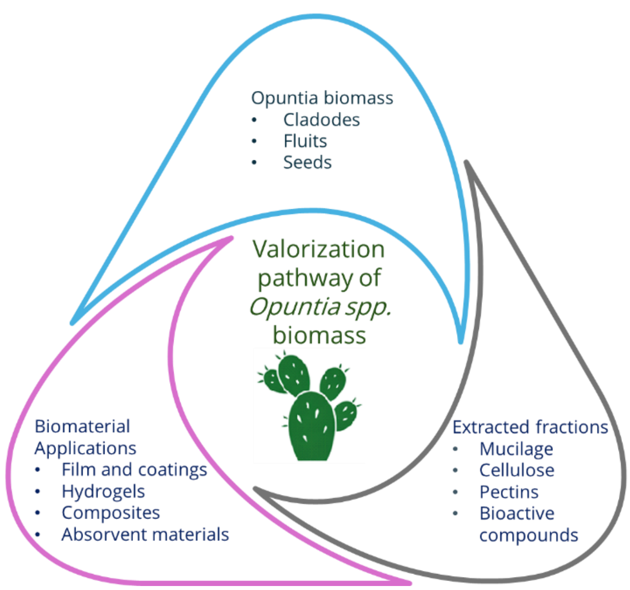

Fig. 2. Valorization pathway of *Opuntia spp*. biomass illustrating the transformation of cladodes, fruits, and seeds into mucilage, pectin, cellulose, and bioactive compound-rich fractions, and their subsequent application in films, hydrogels, composites, and adsorbent materials

Table 2 provides representative examples of biomaterials derived from *Opuntia spp*., highlighting the relationship between biomass fraction, processing strategy, material properties, and final application.

Table 2. *Opuntia*-derived Biomaterials, Processing Methods, Properties, Applications, and Limitations

Biomass Fraction	Processing Method	Material Type	Key Properties	Application	Limitations	Reference
Mucilage (cladodes)	Aqueous extraction, drying	Hydrocolloid matrix	High viscosity, water-binding capacity, pseudoplastic behavior	Thickening agent, film precursor	High moisture sensitivity, low mechanical strength and limited stability	Cárdenas *et al.* 1997; Van Rooyen *et al.* 2024
Mucilage (cladodes)	Aqueous extraction, casting	Edible films	Film-forming ability, flexibility, biodegrad-ability	Edible films and coatings	Weak mechanical resistance, high water vapor permeability, low durability	Sáenz *et al.* 2004; Medeiros *et al.* 2024
Mucilage / pectins	Extraction + thermal treatment	Hydrogels	High swelling capacity, viscoelastic behavior	Controlled release systems	Structural instability, poor mechanical robustness, sensitivity to pH/ionic strength	Medina-Torres *et al.* 2003; Liu *et al.* 2025
Polysaccharides (cladodes)	Film casting + additives	Films and coatings	Barrier properties, gas exchange control	Food packaging	Sensitivity to humidity, need for additives, limited barrier *vs.* synthetic polymers	Sánchez-Vega *et al.* 2020; Medeiros *et al.* 2024
Cellulose fibers	Mechanical/ chemical treatment	Biocomposites	Reinforcement, improved strength	Composite materials	Variability in fibers, interfacial incompatibility, processing complexity	Ginestra *et al.* (2009)
Lignocellulosic biomass	Minimal processing	Natural adsorbent	Sorption capacity, low-cost	Water treatment	Limited adsorption capacity, regeneration challenges, structural degradation	Nefzaoui and El Mourid 2010; Liu *et al.* 2025
Cellulose-rich fractions	Integrated processing	Biocomposites	Mechanical performance and sustainability	Structural materials	Scalability challenges, high processing cost, need for modification	Ali *et al.* (2024); Van Rooyen *et al.* 2024; Liu *et al.* 2025

Polysaccharide-rich fractions, particularly mucilage and pectins, have been extensively explored for edible films, coatings, and hydrogels due to their favorable water-binding, film-forming, and biodegradable properties. Early studies by Cárdenas *et al.* (1997) and Sáenz *et al*. (2004) established the fundamental rheological and film-forming behavior of *Opuntia* mucilage, providing a basis for developments in *Opuntia*-derived biomaterials.

Building on these foundational findings, more recent research has further expanded the application of *Opuntia* polysaccharides and cellulose-rich fractions toward bio-composites and functional materials with improved mechanical performance and environmental compatibility (Ginestra *et al.* 2009; Sánchez-Vega *et al.* 2020; Ali *et al.* 2024). In addition, environmental applications such as the use of raw cladode materials as low-cost natural adsorbents further highlight the multifunctionality of *Opuntia*-derived biomaterials within sustainable and circular bioeconomy frameworks (Nefzaoui and El Mourid 2010).

One of the most promising non-food applications of *Opuntia* biomass is in water treatment systems. Mucilage and polysaccharide-rich extracts exhibit flocculating and adsorptive properties, enabling the potential removal of turbidity, heavy metals, and suspended solids from contaminated water. These materials represent a low-cost, biodegradable alternative to synthetic flocculants, particularly in rural and resource-limited settings (Nefzaoui and El Mourid 2010).

Recent studies have explored chemical and physical modifications of *Opuntia*-derived materials, including crosslinking, incorporation of reinforcing agents and surface functionalization to improve mechanical strength, reduce water sensitivity and enhance adsorption capacity. These modification strategies are particularly relevant for overcoming the inherent limitations of polysaccharide-based materials, such as low mechanical stability and high moisture sensitivity, as highlighted in Table 2. As a result, modified *Opuntia*-based materials can exhibit improved functional performance and broader applicability in biomaterials, including composites, films and adsorbent systems (Ali *et al*. 2024; Van Rooyen *et al*. 2024; Liu *et al*. 2025).

SUSTAINABILITY AND CIRCULAR BIOECONOMY PERSPECTIVE

The increasing pressure on natural resources and the need to reduce environmental impacts have accelerated the transition toward circular bioeconomy models based on renewable biomass. *Opuntia spp*. represents a strategic feedstock due to its high biomass productivity, minimal agricultural inputs, and ability to thrive on marginal lands unsuitable for conventional crops (Nefzaoui and El Mourid 2010; Inglese *et al.* 2017). Its perennial growth habit and high water-use efficiency further support its role as a resilient resource under climate-change scenarios.

Life cycle considerations reported for *Opuntia*-based systems indicate favorable environmental profiles compared with traditional lignocellulosic crops, particularly in terms of water footprint, land use, and greenhouse gas emissions. Low irrigation requirements at the possibility of rainfed cultivation in marginal areas contribute to reduced water demand, although supplemental irrigation can be applied in intensive production systems (Nefzaoui and El Mourid 2010; Inglese *et al.* 2017; Hernadez *et al*. 2024). Limited agrochemical inputs and year-round biomass availability lead to lower energy demand during cultivation and harvesting. The integration of multiple biomass fractions into value-added products enhances process efficiency and improves environmental performance.

A defining advantage of *Opuntia* biomass lies in its suitability for whole-plant valorization. Cladodes, fruits, peels, seeds, and processing residues can be simultaneously exploited for the recovery of polysaccharides, fibers, secondary metabolites, and structural components, thereby reducing the production of waste and supporting zero-waste and biorefinery concepts (Ali *et al.* 2024). Residual fractions can be further used for energy production, soil conditioning, or fermentation substrates, reinforcing material circularity. Low cultivation costs and compatibility with environmentally responsible extraction technologies position *Opuntia*-based systems as competitive and sustainable alternatives for bioproduct and biomaterial manufacturing, particularly in arid and semi-arid regions.

CURRENT LIMITATIONS

Although there is growing interest in *Opuntia* spp. as a renewable feedstock for bioproducts and biomaterials, several scientific, technological and economic challenges remain for large-scale implementation. A major challenge arises from the intrinsic heterogeneity of *Opuntia* biomass, as chemical composition varies markedly among species, cultivars, plant organs, maturity stages and environmental conditions, resulting in inconsistent extraction yields and variable material properties (Sáenz *et al*. 2004; Mazri 2021). This variability has made process optimization, reproducibility, and industrial standardization more difficult. However, this variability can also represent an opportunity rather than solely a limitation, as it enables the selection and optimization of specific cultivars and biomass sources specially designed for targeted applications (Inglese *et al.* 2017).

In addition to compositional variability, the lack of harmonized and standardized methodologies for pretreatment, fractionation and purification represents a critical bottleneck. Most studies focus on isolated biomass fractions rather than integrated biorefinery approaches, leading to incomplete biomass utilization and limiting process efficiency and economic feasibility (Ali *et al.* 2024; Hernández *et al.* 2024). This fragmentation is further reinforced by the disciplinary separation between studies on chemical composition, extraction technologies and material applications, which are often addressed independently rather than within a unified processing framework.

From an industrial perspective, several constraints further limit large-scale deployment. These include challenges related to biomass supply and logistics, particularly the seasonal and region-specific availability of *Opuntia* biomass, as well as the relatively low degree of industrial demand compared to established lignocellulosic feedstocks. Moreover, the economic viability of advanced extraction technologies remains uncertain due to high operational costs, energy requirements and the demand for specialized equipment, which can limit their scalability (Nefzaoui and El Mourid 2010; Ali *et al*. 2024).

Furthermore, most of the available studies remain at laboratory or pilot scale, with limited consideration of scale-up constraints such as solvent recovery, process integration, continuous operation and equipment compatibility. Comprehensive techno-economic analyses and life cycle assessments are still scarce, hindering the evaluation of industrial feasibility and environmental performance (Nefzaoui and El Mourid 2010). The functional stability of *Opuntia*-derived materials represents a critical bottleneck for industrial application. Polysaccharide-based films and hydrogels often exhibit high water sensitivity and limited mechanical strength, while bioactive compounds such as phenolics and betalains can degrade during processing or storage, reducing long-term performance (Medina-Torres *et al.* 2003; Andreu *et al.* 2018).

Addressing these limitations requires a more integrated approach that links biomass composition, with extraction processes and material design within a biorefinery framework. This review has consolidated dispersed knowledge and has highlighted the need for coordinated strategies aimed at improving process integration, standardization and scalability, thus supporting the transition from laboratory-scale research to industrial implementation.

FUTURE PERSPECTIVES

Beyond emerging applications in biomaterials and biorefinery systems, future developments should continue to recognize the central role of *Opuntia spp.* as a food resource. The use of cladodes and fruits in fresh consumption, processed foods, and functional ingredients remains one of the most established and economically relevant applications of this biomass (Inglese *et al*. 2017; Sáenz *et al.* 2004). Future research should further expand its role in functional foods, nutraceuticals, and health-oriented formulations, while integrating these applications within sustainable and circular production systems (Nefzaoui and El Mourid 2010; Hernández *et al.* 2024).

Future research on *Opuntia* spp. biomass should prioritize integrated and scalable processing strategies that enable its efficient valorization within biorefinery frameworks. Improving the standardization of extraction and fractionation processes will be essential to ensure reproducibility and facilitate industrial implementation.

Emerging approaches such as nanostructuring and encapsulation strategies offer promising opportunities to enhance the functionality and stability of *Opuntia*-derived compounds. These strategies are particularly relevant to overcome the inherent limitations of *Opuntia*-derived materials, including the low mechanical strength of polysaccharide matrices and the instability of bioactive compounds such as phenolics and betalains. Nano- and micro-encapsulation systems can improve the protection of sensitive compounds against environmental degradation, control their release, and enhance their integration into biomaterials and bio-based formulations (Medeiros *et al*. 2024; Fernández-Martínez *et al. 2024).*

The incorporation of *Opuntia*-derived polysaccharides into composite and structured systems has shown potential to improve mechanical properties and expand the applicability of these materials (Van Rooyen *et al.* 2024). Further research should also address techno-economic feasibility, life cycle assessment and process integration to support the transition from laboratory-scale studies to industrial applications. Advancing toward an integrated, sustainable and multifunctional utilization of *Opuntia* biomass will be key to fully realizing its potential within circular bioeconomy systems.

CONCLUSIONS

This review has highlighted the significant potential of *Opuntia spp.* biomass as a sustainable resource for both food applications and the development of bioproducts and biomaterials. Its well-established role as a food source through cladodes and fruits for fresh consumption, processed products and functional ingredients, remains a central and economically remains a central and economically relevant application. At the same time, its rich composition in polysaccharides, mucilage and bioactive compounds underpins its functional performance in advanced applications such as films, hydrogels, composites and adsorbent systems. However, important challenges persist, including biomass variability, lack of process standardization, limited integration of extraction and processing technologies, and constraints related to material stability and mechanical performance, which together with economic and scale-up barriers restrict large-scale implementation. A key insight emerging from biorefinery approaches that enable the simultaneous valorization of multiple biomass fractions. Futures progress will depend on the development of scalable green processing technologies, standardized methodologies and advanced material design strategies, which will be essential to fully exploit the potential of *Opuntia* biomass within circular bioeconomy frameworks.

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