

Summary

This doctoral thesis aims to develop an innovative process, investigating the extraction of polysaccharides from *Opuntia ficus-indica* and exploring the potential for biogas production and agricultural applications through a series of interconnected studies, culminating in an economic analysis for the industrial scale-up of the process.

Chapter 1 presents a brief introduction on sustainability, green chemistry and green engineering, key themes throughout the discussion. *Opuntia*, its distribution, and its potential from the perspective of possible industrial applications are also introduced.

Chapter 2 explores the development of an extraction process for polysaccharides from *Opuntia* using green extraction methods. Ultrasound Assisted Extraction (UAE) with acidified water was selected for optimization. The extraction conditions such as Solid-Liquid ratio, pH, temperature, and time, were optimized using Design of Experiment (DOE) methodology and Response Surface Methodology (RSM). The optimized extraction conditions—Solid-Liquid ratio of 1:10 (w/v), pH 2.5, temperature of 65°C, and an extraction time of 20 minutes—allow for an extraction yield of 11.32 ± 0.25 % dw, comparable to the predicted value of 12.07 ± 1.7 %. The extract was found to be primarily composed of galacturonic acid, arabinose, and galactose, with a low esterification degree (42.84 ± 0.48 %). Furthermore, the extract exhibited significant antioxidant properties, with an anti-radical activity of 95.56 % at a concentration of 2 mg/mL. These results highlight *Opuntia* pads as a valuable source of functionalized polysaccharides with potential applications in cosmetics and other industries.

Chapter 3 investigates the potential of anaerobic digestion (AD) for converting the residue from UAE extraction into biogas. Initial trials with fresh *Opuntia* biomass proved unsuitable for AD due to the presence of polymers that are not easily biodegradable by the bacteria involved in the process. However, UAE residue was found to be a promising feedstock for biogas production, and further optimization was carried out by applying various pretreatment strategies (acidic, alkaline, and alkaline with hydrogen peroxide) to improve its biodegradability. Among the pretreatment strategies, the Alkaline Hydrogen Peroxide (AHP) treatment significantly improved methane production, underscoring the importance of pretreatment in optimizing biogas yields from *Opuntia* residues. This chapter establishes the feasibility of using *Opuntia* biomass as a renewable bioenergy resource and provides insights into how specific pretreatment methods can improve methane production.

Chapter 4 investigates the use of the digestate from anaerobic digestion as a sustainable alternative to chemical fertilizers. The study analyzes the chemical composition, nutrient availability, and phytotoxicity of digestate derived from the UAE residue. Greenhouse tests using lettuce (*Lactuca sativa* L.) demonstrated that digestate has strong potential as an organic soil improver with optimal nutrient ratios for plant growth. This chapter emphasizes the potential of digestate to enhance soil quality, reduce the reliance on chemical fertilizers, and promote sustainable agricultural practices in line with European Union regulations.

Chapter 5 addresses the challenges associated with scaling up the extraction and biogas production process for industrial applications. The design of an industrial facility capable of processing 3000 tons of fresh cladodes annually is presented. The facility includes sections for pretreatment, extraction, extract recovery, solvent recirculation, and anaerobic digestion. Key considerations such as mass and energy balance, equipment sizing, and operational efficiency are discussed.

Chapter 6 focuses on the economic evaluation of the proposed industrial process. It examines fixed and variable costs, economic indicators such as revenue and Break-Even Point (BEP), and the role of economies of scale in reducing production costs. This chapter also integrates the economic assessment with environmental impact analysis using Life Cycle Assessment (LCA), evaluating the trade-offs between process efficiency and environmental sustainability. The results provide a comprehensive perspective on the financial and environmental feasibility of the industrial-scale production of *Opuntia*-based polysaccharides, biogas, and digestate.

Overall, this thesis provides a comprehensive approach to the sustainable utilization of *Opuntia ficus-indica*, from the extraction of valuable polysaccharides to the generation of renewable energy and the use of waste by-products as eco-friendly fertilizers. The findings contribute to the development of innovative, sustainable processes that can be applied to various industries, including cosmetics, agriculture, and bioenergy.