Chapter 44
Opuntia spp. in Biogas Production

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Abstract Safe environment and clean energy are among the most important green chemistry fundamentals. The world economy depends mainly on fossil fuel as a source of energy, and due to limited natural resources and uncontrolled pollution, the world is looking for alternatives that can meet the basic requirements of a clean and safe life. Using alternative sources such as biogas as an energy source can provide a solution to world energy problems. Biogas is produced through anaerobic digestion of organic matter, which is converted into combustible gas rich in methane. Biogas generation is one of the cheapest methods of producing energy on the spot from readily available resources. Nonedible agriculture crops and/or waste are among the essential biomass sources to produce biogas. Biomaterials produced from *Opuntia* species showed great potential as a source of biomass in the last years. Plants that belong to this genus can tolerate drought and poor soil fertility and require low maintenance. *Opuntia* biomass has been considered an excellent sub-

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strate alone or in combination with other organic waste materials. This chapter discusses the most recent research on *Opuntia*'s different species in biofuel production and their potential as an alternative energy source.

Keywords Environment · Biofuel · Biomass · Energy · Clean energy · Green chemistry

Abbreviations

AD	Anaerobic digestion
CH_4	Methane gas
kWh	Kilowatt per hour
L ha^{-1} yr^{-1}	Liter per hectare per year
t ha^{-1}	Tonne per hectare
TS	Total solids
VS	Volatile solid

1 Introduction

Uncontrolled use of chemicals leads to drastic climate changes, representing one of the most critical challenges facing the world economy and the future sustainable development agenda. The world tends to move towards a green economy to reduce the harmful effects of the current industrial activities, especially in the energy sector. The green economy aims to reduce environmental risks and ecological scarcities, aiming for sustainable development without degrading the environment. The energy sector relies on fossil fuel, and the global annual energy demand of over 12 billion tons of oil equivalent results in the emission of 39.5 Gigatons of carbon dioxide (Gt-CO_2), and the annual CO_2 emission would increase in the future (Abas et al., 2015). The CO_2 emission could be minimized by decreasing fossil fuels and replacing it with renewable ones such as biomass or improvement of energy efficiency in all human activities in different ways. Biomass energy utilizes biological waste organic materials for the production of heat or electricity. Fuelwood, charcoal, and animal dung continue to be essential sources of bioenergy in many parts of the world, and, to date, wood fuels represent by far the most common sources of bioenergy (Ruane et al., 2010).

Biodegradable waste could be an excellent source to produce useful energy, and at the same time leading to waste minimization. The waste treatment was recognized to produce biofuel and electricity introduced in many countries. The feedstock's organic fractions are degraded mostly into CH_4, CO_2, and digested residues (Barbosa et al., 2001). Production of methane-rich biogas through anaerobic digestion of organic waste materials provides a versatile carrier of renewable energy, as methane can be used in replacement for fossil fuels in both heat and power generation and as a vehicle fuel, thus contributing to mitigate the emissions of greenhouse gases and slowing down the climate change.

Approximately 50% of the total energy consumed in Africa is obtained from fuelwood. However, there are several disadvantages related to this type of fuel, including adverse health effects resulting from the accumulation of indoor smoke, deforestation, and the time-consuming process of wood collection, which is dangerous from an environmental point of view and labor-intensive (Roopnarain & Adeleke, 2017). It was reported that the biogas project was proposed in Namibia is the digestion of the common reed (*Phragmites australis*), and recently, two small-scale biogas projects on a water treatment plant and a landfill have already been initiated in Namibia. Both are the Clean Development Mechanism (CDM) projects (Roopnarain & Adeleke, 2017).

2 *Opuntia* Distribution and Uses

The *Opuntia* genus (*sensu stricto*) is endemic to America. It belongs to the Cactaceae family and includes over 181 species comprising, based on morphological traits, a total of 29 series (Guzmán et al., 2003). It is also well known as the cactus pear plant or nopal. Prickly pear is a fast-growing cactus growing in dry, arid, and rocky plaed pasture land and degraded guarigues throughout North and South America. They are also distributed in the Mediterranean basin, Middle-East, South Africa, India, Thailand, and Australia. Some *Opuntia* species and cultivars are currently cultivated in several world regions in America, Africa, Asia, Europe, and Oceania (Labra et al., 2003). Many *Opuntia* species have been declared by some countries across Africa and Australia as invader plants (Brutsch & Zimmermann, 1993).

Opuntia species are drought-resistant fodder and easily growing with a little attention. *Opuntia* is used mainly for fruit production, and as a source of food for humans and animals. The tender stems (nopalitos) are consumed as greens in some countries such as Mexico. The young cladode is consumed as a vegetable, the cactus pear is consumed as fresh fruit, flowers, and mature cladodes low lignified are used as forage. The mucilages showed interesting biological activities and used for pharmaceutical and cosmetic products. Several pharmacological activities have been reported and showed interesting activities against different human pathologies (Peña-Valdivia et al., 2008; Sáenz et al., 2004; Cárdenas et al., 1997).

The crop for fruit production of *Opuntia* generates high amounts of residues, i.e., premature fruits and exceeding cladods, that are removed for increasing the plant vigour. Additionally, the limited uses in the food industry, low lignin content, and its high productivity of plant biomass in arid regions are important factors enabling the cultivation of prickly pear for energy purposes in semi-arid areas (Weiland, 2003). Different countries, including Brazil, Italy, Kenya, Botswana, South Africa, and Ethiopia, have implemented prickly pears on a large scale in wastelands. This can enable bioenergy production without disrupting food supplies and hence sustainable energy supply for the future (Santos et al., 2016; Belay & Ali, 2018; Roopnarain & Adeleke, 2017). The cladodes are an excellent source of carbon and can be used to balance the digestion of protein-rich wastes such as slaughterhouse wastewater (Panizio et al., 2020).

3 Composition

The common raw materials used for the production of biofuel, e.g., sugar cane and straw from different crops are consist of cellulose, hemicellulose, and lignin as main constituents, in addition to small amounts of phenols, proteins, minerals, starch, fatty acids, oils, waxes, tannins, and resins. The biomass from prickly pear cladodes has a different chemical structure from previously mentioned materials with high pectin levels and relatively low levels of cellulose and lignin (Sáenz et al., 2004). The non-fibrous carbohydrates are the most important portion of prickly pear biomass, mainly represented by soluble sugars, polysaccharides, organic acids, and other types of reserve carbohydrates pectins. The chemistry of *Opuntia* is not fully covered; however, different secondary metabolites have been reported. Cladode chemical composition such as carbohydrates 64–71%; 3–7% (dry/wet basis), lipids 1–4%; 0.2% (dry/wet basis), and proteins 4–10%; 0.5–1% (dry/wet basis) showed variations depending on different factors. Younger cladodes show higher carbohydrate, protein, and water contents (Stintzing & Carle, 2005). Calcium oxalate, among other inorganic salts, contributes to the high ash content (8.5–23.7%) in *O. ficus-indica* cladodes (Contreras-Padilla et al., 2011).

3.1 Sugar Content

Opuntia stems contain readily fermentable, water-soluble carbohydrates (3–7% fresh mass fractions). Total sugars amounted to 40–42% of the materials' dry biomass obtained by the direct drying of the fresh raw materials (Stintzing et al., 2005). Glucose is the major sugar; however, galactose, arabinose and xylose are present (Santos et al., 2016; Kuloyo et al., 2014; Yang et al., 2015). *Opuntia* fruit contains 6–14% (fresh weight), mainly glucose and fructose (Berat & Turker, 2005; El Kossori et al., 1998). To high monosaccharides' concentration in the biomass pretreated with either yeast cells (fermentation) or chemical hydrolysis using acidic/basic conditions like HCl/NaOH at high temperature (80 °C) is required. However, these chemical methods decrease the water-soluble sugars due to chemical degradation (Calabrò et al., 2018).

3.2 Mucilages and Pectins

Both mucilages and pectins are complex carbohydrate polymeric structures and form colloidal solutions in water. They differ from each other in terms of the chemical structure and physical properties (Karawya et al., 1980). Extraction of mucilages takes place using mild conditions and under neutral conditions; however, pectins require heating for 2 h at different pHs. Mucliages have low uronic acid and high sugar content than pectins. Different studies demonstrated a high ratio of arabinose, xylose, and rhamnose (Goycoolea & Cárdenas, 2003).

Pectin is a carbohydrate fraction of biomass-derived materials and functions as an intercellular and intracellular cementing material. It is a polymer with a polygalacturonic acid backbone of α-1, 4 linked D-galacturonic acid units. Sidechains usually contain neutral sugars, such as L-rhamnose, galactose, and arabinose. Besides, pectin may contain other sugars, like glucose, to improve its gel-forming properties (BokelmAn & Ryan, 1985). *Opuntia* total pectin has concentration range of 0.13% to 2.64% in wet basis (1% to 23.8% in dry-weight basis). *O. robusta* showed high pectin content (3.30/26.6 wet/dry basis) in comparison with *O. ficus indica* (1.91/13.8) (Villarreal et al., 1963). The full enzymatic hydrolysis of prickly pectins showed a mixture of galacuronate (56.3), galactose (6.5), arabinose (5.6), xylose (0.9), and rhamnose (0.5) (Stintzing & Carle, 2005).

The mucilages are responsible for the ability of the Cactaceae to retain water even under unfavorable climatic conditions (Saag et al., 1975; Goldstein & Nobel, 1991). The mucilage chemical structure contains variable amounts of neutral sugars such as arabinose, galactose, rhamnose, and xylose. The presence of galacturonic acid was also reported (Srivastava & Pande, 1974; Sáenz et al., 2004). The mucilage of *O. ficus indica* is composed of 24.6–42% arabinose; 21–40.1% galactose; 8–12.7% galacturonic acid; 7–13.1% rhamnose and 22–22.2% xylose (Trachtenberg & Mayer, 1981; Nobel et al., 1992).

3.3 Other High-Molecular-Weight Compounds

O. ficus-indica have high amorphous and paracrystalline (disordered) cellulose, and low content of crystalline cellulose, suggesting its lignocellulosic biomass would be even more readily hydrolyzable into fermentable sugars than would biomass from traditional herbaceous or woody feedstocks (Yang et al., 2015). The non-fibrous nature of cladode reflected from the prickly pear low content of cellulose (3%–13%), hemicellulose (up to 8%), and lignin (up to 14%). This represents a significant difference from lignocellulosic materials that commonly presents fiber content over 50%, with cellulose ranging from 25 to 50% (Ben-Thlija, 1987; Malainine et al., 2003). The lignin mass fractions in *O. ficus-indica* dry bagasses (12.3%) were substantially lower than those for woody feedstocks (21–32%; e.g., poplar, eucalyptus, and pine; 20–30% sugarcane). Feedstocks with reduced lignin mass fractions might display reduced recalcitrance during biofuel production (Ragauskas et al., 2014; Cardona et al., 2010).

4 The Potential of *Opuntia* as a Source of Bioenergy

Prickly pear biomass can be converted by anaerobic bacteria to produce biogas. Anaerobic digestion is a complex biochemical process of degradation of organic matter in the absence of oxygen, and it is intended for the stabilization of organic matter to produce biogas and biofertilizer. Biogas generated in the process usually contains about 60% CH4, 35% CO_2, and 5% a mixture of H_2, N_2, NH_3, H_2S, CO, O_2, and volatile amines. This gas can be used as fuel to generate thermal and electrical energy. The resulting biofertilizer has essential plant nutrients such as N, P, K, and micronutrients that can be applied to the soil as fertilizer.

The average biomass productivity of prickly pear was studied on a large production scale in five locations in Brazil as one of the parameters to estimate biofuels' potential production. The study included two varieties of *O. ficus indica* (palma gigante and redonda) and *Nopalea cochenillifera* ("palma miúda"). The average fresh biomass productivity was nearly 90 t ha^{-1} yr^{-1} (Santos et al., 2016). The same group estimated the potential of biogas production from prickly pear biomass theoretically using the average dry biomass productivity of 7.9 t ha^{-1} yr^{-1}, the conversion rate of volatile solids (VS; 91%) of 517 m^3 t^{-1} VS^{-1} 3717 m^3 ha^{-1} yr^{-1} of biogas is expected to be generated. The potential of electricity generation with biogas was theoretically expected, and an average of 4646 kWh ha^{-1} yr^{-1} was also estimated for electrical energy. This amount (from 1 ha of prickly pear) could produce biomass to generate electricity sufficient to meet the annual consumption of about two homes (Santos et al., 2016).

Obach and Lemus (2006) estimated high production (23,400 KWh ha^{-1} $yr^{-1)}$. The author's calculation was based on the average production of 300 ton ha^{-1} yr^{-1} production of 58 m^3 t^{-1} SV^{-1} of biogas (with 52% methane) and a generation of 1.5 kWh m^{-3} biogas. Another similar and large-scale study conducted in Italy, cultivation of 159 10^3 ha prickly pear, produced an average of 3849 m^3 ha^{-1} $yr^{-1}$of biogas from which ~342 ton ha^{-1} yr^{-1} of biomethane could be extracted, or 67,038 MWh of electric energy and 70,390 MWh of thermal energy could be generated. The data was close to the second study by Obach and Lemus (Comparettia et al., 2017). These values were very close to traditional energy crops such as maize (5780 m^3 CH_4 ha^{-1}), alfalfa (3995 m^3 CH_4 ha^{-1}), and fodder beet (5800 m^3 CH_4 ha^{-1}) (Weiland, 2003).

O. ficus-indica biomass was evaluated for biogas production in Kenya. The plant was cultivated on a large scale under various planting densities on marginal land blocks (900 m^2/experiment). The methane production varies between 578 and 1860 m^3 per ha, depending on planting density during a 4-months growth period (Krümpel et al., 2020).

5 Optimization of the Biogas Production

The biogas production efficiency from the cladods biomass alone using AD are low when compared to co-digestion. Mixing the clados with animal manure improved the biogas production (Uribe et al., 1992; Varnero et al., 1992; Varnero & López, 1996; Varnero & García de Cortázar, 1998). The biogas production of slaughterhouse wastewater was improved by co-digestion of the of slaughterhouse wastewater (75%) with *O. fícus indica* (25%) under semi-continuous conditions (Panizio et al., 2020). The green algae *Scenedesmus* sp. biomass is not an adequate substrate for anaerobic digestion due to its low biodegradability and low biogas yield. The co-digestion of *O. maxima* (75%), and *Scenedesmus* sp. (25%) based on VS content improved methane yield compared to both substrates' mono-digestion yielding up to 308 L CH_4 kg VS^{-1}. Co-digestion enhanced the anaerobic digestion process and avoided inhibiting the low C/N ratio of microalgae (Ramos-Suárez et al., 2014).

O. ficus indica is an ideal plant for African arid regimes as a potential bioenergy source. A short acidic aerobic pretreatment (9 h) of *O. ficus indica* biomass before anaerobic digestion yielded 123% higher methane yield when compared to that without pretreatment. The aerobic pretreatment suggests that there was increased hydrolysis with retreatment (Myovela et al., 2019). The results were further supported by Calabrò et al. (2018) and showed enhancement of methane production using the acidic pretreatment (HCl) compared with thermal and alkaline treatments.

O. ficus-indica grows abundantly in the northern part of Ethiopia. The co-digestion of *O. ficus indica* fruit peel with cow dung in a ratio of 1:3 under mesophilic conditions (38 °C) using batch digester showed enhancement of biogas production (Gebrekidan et al., 2014). The pH has a direct effect on the quality of the produced biogas. The optimum conditions were found to be at pH = 6. The fermentation of different manure/prickly pear mixtures ratios showed the importance of maintaining a pH 6 or higher. At lower pH levels, CO_2 becomes dominant and the combustibility and energy content largely reduced. Increasing the proportion of manure in the mixture and using cladodes older than 1 year keep the neutral or basic pH, produce methane-rich biogas (methane content higher than 60%) (Varnero & López, 1996; Varnero & García de Cortázar, 1998).

6 Bio-Ethanol Production

Few studies have been conducted on the conversion of *Opuntia* biomass to bioethanol. The production of bioethanol from cactus biomass still beyond the expected level. The biomass's high-water content and the low total solids are the main reasons directly related to the low yield of bioethanol. The cladode biomass's viscosity, due to pectin presence, can be decreased using pectinase in the enzyme cocktail. A mixture of pectinase and cellulase enzymes was necessary for pectin solubilization, and the complete release of sugars (Grohmann et al., 1995). Enzyme mixtures consisting of cytolase, pectinex, rapidase, and viscozyme were used to hydrolyze *Opuntia* cladode mucilage to improve its extractability and release of sugars (Kim et al., 2013). Pretreatment of fresh or dried *O. ficus-indica* cladodes with cellulase enzyme and acid slightly improved sugar release and ethanol yields above those of non-pretreated material; however, ethanol yields remained low at ~1.4% w/v (Retamal et al., 1987).

Under non-aerated conditions, separate hydrolysis (using 1.5% H_2SO_4) and fermentation of *O. ficus-indica* cladodes biomass using *Kluyveromyces marxianus* and *Saccharomyces cerevisiae* resulted in similar ethanol yields of ~2.6% w/v (Kuloyo et al., 2014). In oxygen-limited cultures, *K. marxianus* exhibited almost double the ethanol productivity compared to non-aerated cultures. The obtained results showed an improvement over earlier attempts. The authors recommended hydrolysis of the biomass and to use of pectinase enzyme to reduce the viscosity of the slurry and increase the release of fermentable sugars to attain an economically viable ethanol yield of >4% w/v (Kuloyo et al., 2014; Wingren et al., 2003).

Hydrolyzed fresh and dried biomass had similar glucose, xylose, and galacturonic acid concentrations. The enzymatic hydrolysis using *Saccharomyces cerevisiae* (33 °C, 8 h) for the biomass from *Nopalea cochenillifera* and *O. stricta* (partially dried, 30% TS) produced ethanol 29.4 and 37.5 g L^{-1} biomasses, respectively (Alencar et al., 2020). The estimated potential of ethanol production for the three prickly pear varieties studied in Brazil is in the range of 1490–1875 L ha^{-1} yr^{-1}. These values are lower than those reported for the main energy crops used for ethanol production, such as sugar cane (5300–9400 L ha^{-1} yr^{-1}), sugar beet (5000–6000 L ha^{-1} yr^{-1}) or cassava (3600 L ha^{-1} yr^{-1}) (Santos et al., 2016). However, prickly pear can produce ethanol in semi-arid zones, where those crops cannot be cultivated. Moreover, the water consumption per unit of ethanol produced from prickly pear cladodes should be lower for the prickly pear than other crops used today.

7 Conclusion

This chapter focuses on the production of biogas from the *Opuntia* plant. The process of anaerobic digestion of the *Opuntia* plant results in biogas production and a nutrient-rich digestate. In a broad spectrum, these species are well known for an extraordinary ability to produce biomass in soil and climate conditions, which are unfavorable for most plant species, in part due to their high water use efficiency. Soon, given the prospect of water scarcity, this fact must be evaluated by the biofuel industry. Furthermore, several studies are needed to be conducted and evaluated, more consistently, both the sustainability of biomass production for ethanol and biogas production, especially for the newly emerged prickly pear diversities.

For biogas production, despite its potential and significance to arid regions, very little research data is available about prickly pear anaerobic digestion, and more research has to be conducted. For ethanol production, it is necessary to enhance the steps of biomass pretreatment, wherein pH must be near neutral for the application of biological processes, the high viscosity of the cladode biomass slurry should be reduced and the fermentable carbohydrate concentration in the hydrolysate should be increased. Hence it is important to produce an eco-friendly, economically viable process for ethanol concentration of at least 4% (w/v) from lignocellulose feedstock.

Due to global warming increasing in recent times, there is currently a huge demand for renewable energy and the prospects of more limited water resources, and the potential use of prickly pear cladodes for biofuel production deserves to be investigated. It faces numerous technological challenges at all stages of production. From an agricultural point of view, cultivation in the field requires much improvement in management practices for planting and harvesting systems, especially with the cropping operations' mechanization. The conversions of the biomass into biofuels still need ground breaking research.

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