

A Review on Biogas Potentials from Maize Cob under Varying Pretreatment Temperatures

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Abstract

Maize cob, a lignocellulosic agricultural residue, holds great promise as a feedstock for biogas production. However, its structural complexity necessitates pretreatment to enhance biodegradability and methane yield. This review explores the impact of varying pretreatment temperatures on biogas potential, focusing on lignocellulosic breakdown, microbial digestibility, and process efficiency. An analysis of some studies provides insights into optimal pretreatment temperatures, associated mechanisms, and challenges in scaling up for industrial applications. Pretreatment significantly influences methane yield by improving substrate hydrolysis rates. Studies report a 50-100% increase in biogas production following optimal thermal pretreatment. It was found that inadequate lignin removal and prolonged process duration are associated with both LTP and MTP. But, HTP offers higher accessibility to biomass due to effective deconstruction of cellulose-hemicellulose-lignin complex with high potential for scale-up. However, these advantages are associated with adverse counter-productive processes such as excess inhibitory products generations and high energy demand. For the HTP to be adaptive, these processes must be balanced.

Keywords: Maize-Cob, Biogas, Pretreatment, Temperature, Lignocellulose.

Introduction

Biogas production from agricultural residues such as maize cobs represents a sustainable approach to renewable energy generation and waste management (Angelidaki et al., 2009). Maize cobs are rich in cellulose and hemicellulose, which serve as fermentable substrates, but the presence of lignin necessitates pretreatment to improve enzymatic and microbial accessibility (Zheng et al., 2014). Temperature is a critical parameter influencing the efficiency of pretreatment methods, such as thermal, chemical, and combined approaches (Hendriks & Zeeman, 2009). Maize cobs are a complex agricultural waste typically consisting of cellulose (30-45%), which is a crystalline polymer of glucose monomers, hemicellulose (20-35%) a heterogeneous polymer of pentoses and hexoses and importantly the lignin (15-25%), a complex aromatic polymer that inhibits enzymatic hydrolysis (Sun & Cheng, 2002). Pretreatment disrupts this matrix, enhancing the digestibility of cellulose and hemicellulose (Kumar et al., 2009).

The production of biogas from lignocellulosic biomass, such as maize cobs, involves complex biological, chemical, and physical processes. This framework explores the interrelationship between pretreatment temperature and biogas yield, guided by theories of biomass degradation, microbial activity, and energy conversion efficiency. Fundamental principles include lignocellulosic biomass structure, pretreatment theory, microbial kinetics, thermal energy and reaction kinetics, biogas yield optimisation, sustainability and energy balance and feedstock-specific responses. According to Hendriks & Zeeman (2009), maize cobs consist of cellulose, hemicellulose, and lignin. Pretreatment thus modifies these components to enhance enzymatic hydrolysis and microbial digestibility. Mosier *et al* (2005) pointed out that pretreatment aims to alter the biomass structure by breaking down lignin, solubilizing hemicellulose, and increasing cellulose accessibility but further argued that varying temperatures impact the extent of these modifications. Anaerobic digestion relies on a consortium of microorganisms, including hydrolytic, acidogenic, acetogenic, and methanogenic microbes. It is well established that pretreatment influences substrate availability and microbial effectiveness (Weiland, 2010).

The Arrhenius equation suggests that higher temperatures accelerate chemical reactions, including the breakdown of complex polymers into simpler sugars. However, excessive temperatures may produce inhibitory by-products, such as furfural and HMF (Taherzadeh & Karimi, 2008). Jørgensen (2009) reported that the theoretical maximum biogas yield depends on the carbon-to-nitrogen ratio and the efficiency of substrate conversion into methane. Pretreatment temperature determines the balance between enhanced hydrolysis and inhibitor formation. Essentially, the net energy gain from biogas production must account for the energy inputs during pretreatment. Low and moderate temperatures are energy-efficient but may result in lower yields, while high temperatures enhance yields but increase energy costs (Mussatto *et al.*, 2010). Also, the effectiveness of pretreatment varies with biomass characteristics. Thus, maize cobs, with their high cellulose content, require optimized temperature protocols for maximum biogas potential (Chen *et al.*, 2007). In this paper, biogas potentials from maize cob will be reviewed under different pretreatment temperatures (low, moderate and high temperatures).

Methodology

This is a review paper and the source of data used is primarily the peer reviewed articles published by reputable journals. These journals are mostly obtained from Google scholar website using combined terms comprising 'effects of temperature on biomass pretreatment' and 'low temperature pretreatment'.

Effect of Pretreatment Temperatures

Low-Temperature Pretreatment (<100°C):

Pretreatment at low temperatures primarily target hemicellulose, making it more accessible for enzymatic hydrolysis. While lignin disruption is minimal, the partial

solubilisation of hemicellulose improves overall microbial activity during anaerobic digestion. For instance, pretreatments at temperatures between 70-90°C have shown an increase in biogas yields by approximately 20-30% compared to untreated maize cobs (Zheng *et al.*, 2014). Advantages associated with low temperature pretreatment include energy efficiency, minimized inhibitory compounds, preservation of fermentable sugars, reduced equipment cost and environmental benefits.

Low-temperature pretreatment (LTP) methods require less energy, reducing overall processing costs and therefore improving sustainability. Low temperatures produce fewer inhibitory by-products (furfural, HMF), making the downstream anaerobic digestion process more effective. Mild conditions help retain hemicellulose-derived sugars, which can be utilized by microorganisms in biogas production. Lower temperatures eliminate the need for high-pressure and high-temperature equipment thereby reducing capital investments. Interestingly, processes at low temperatures often require fewer chemicals, resulting in a lower environmental footprint. Moreover, due to its low-temperature processes with less energy demand, it more convenient and sustainable for decentralized or small-scale operations.

Notwithstanding the prevailing advantages, there are several drawbacks associated with LTP. These shortcomings include incomplete lignin removal, reduced biogas yields, longer processing time, limited effectiveness on recalcitrant biomass and potential for enzymatic inhibition. Low temperatures are insufficient for breaking down lignin, limiting the accessibility of cellulose and hemicellulose for enzymatic hydrolysis (Hendriks & Zeeman, 2009). While cost-effective, the incomplete disruption of lignocellulosic structures may lead to moderate biogas yields compared to higher-temperature methods (Jørgensen, 2009). Low-temperature methods often require extended treatment times to manifest effects on biomass structure (Mussatto *et al.*, 2010). Biomass with high lignin content may not respond effectively to low-temperature pretreatment, requiring supplementary or alternative methods (Zheng *et al.*, 2014). In some instances, by-products from hemicellulose solubilisation, such as acetic acid, may likely interfere with enzymatic activity and microbial digestion (Kumar *et al.*, 2009).

Moderate-Temperature Pretreatment (100-180°C):

Moderate-temperature pretreatment (MTP) involves heating lignocellulosic biomass to temperatures ranging from 100°C to 180°C, often in the presence of steam, water, or mild chemical additives. This treatment disrupts the crystalline structure of cellulose, partially solubilizes hemicellulose, and alters lignin structure, improving enzymatic access to polysaccharides. The hydrothermal conditions favour autohydrolysis, where water acts as a reactant to cleave hemicellulose into fermentable sugars without requiring strong chemicals (Chen *et al.*, 2020). Additionally, the higher temperature enhances the

breakdown of ester linkages and glycosidic bonds within the biomass matrix (Liu *et al.*, 2021).

MTP includes steam explosion, dilute acid, and alkaline pretreatments. It is associated with enhanced lignin solubilisation and cellulose accessibility, thus, facilitate hemicellulose degradation into degradable sugars, thereby improving methane yields. Pretreatment at 120-160°C achieves optimal biogas yields, balancing energy input and substrate degradation (Chen *et al.*, 2007). Studies have shown that steam explosion at 140°C can increase methane production by up to 65% compared to untreated samples (Hendriks & Zeeman, 2009). At these temperatures, the combination of heat and pressure enhances the breakdown of lignocellulosic bonds. For example, dilute acid pretreatment at 130°C significantly reduces lignin content, resulting in a 45% increase in enzymatic hydrolysis (Zheng *et al.*, 2014). While moderate-temperature pretreatment is effective, it may generate inhibitors such as acetic acid and formic acid, which need to be mitigated through washing or detoxification steps (Kumar *et al.*, 2009). Interestingly, moderate-temperature processes are more energy-efficient than high-temperature methods, and they offer a favourable balance between biogas yield and operational costs (Sun & Cheng, 2002).

In summary, MTP can improve biomass accessibility, minimize energy requirements, cuts down inhibitory by-products and preserves fermentable sugars (Li *et al.*, 2023; Wang *et al.*, 2022; Xiao *et al.*, 2021; Zhao *et al.*, 2020). Incomplete removal of lignin remained a major limitation of this method as the moderate temperature is not adequate to fully remove lignin, which may limit the accessibility of cellulose in recalcitrant feedstocks (Sun *et al.*, 2021). Moreover, the milder conditions require longer reaction times to achieve the desired structural modifications, potentially increasing operational costs (Zhao *et al.*, 2020), and lastly, the effectiveness of MTP varies with biomass type, necessitating specific protocols for different feedstocks (Chen *et al.*, 2020).

Moderate-temperature pretreatment is preferred in scenarios where energy efficiency and the preservation of fermentable sugars are critical. It is particularly suitable for biomass with moderate lignin content, where complete delignification is not essential. The balance between cost, energy input, and biogas yield makes this approach attractive for industrial applications interest on sustainability and scalability (Liu *et al.*, 2021; Wang *et al.*, 2022).

High-Temperature Pretreatment (>180°C):

At temperatures above 180°C, hemicellulose is extensively hydrolysed into fermentable sugars, and lignin undergoes partial depolymerisation. For instance, pretreatment at 200°C with dilute sulphuric acid increased methane yield by 85% compared to untreated maize cobs (Mosier *et al.*, 2005). Autoclaving, concentrated acid hydrolysis, and ammonia fibre expansion could potentially and effectively delignify and structurally disrupt maize cobs. High temperatures break down lignin and hemicellulose, exposing cellulose for microbial degradation (Saha & Cotta, 2008). Studies have reported that autoclaving maize cobs at

190°C with alkaline solutions enhanced biogas production by 70% due to efficient lignin removal (Chen *et al.*, 2007). High energy demand is conceptualised in Figure 1.

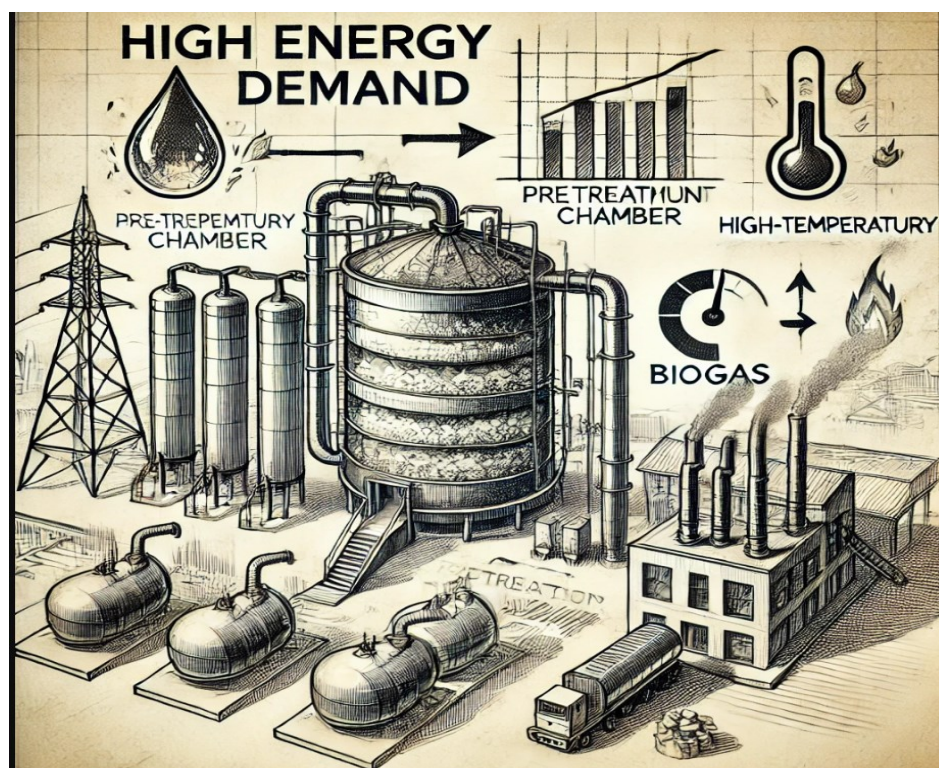


Figure 1: High energy demand biogas plant

Major advantages of high temperature pretreatment (HTP) include enhanced lignin degradation, increased hydrolysis rates, improved biogas, high potentials for scale-up and reduction of recalcitrance. High-temperature pretreatment effectively disrupts the lignin structure, improving the enzymatic accessibility of cellulose and hemicellulose (Mosier *et al.*, 2005). This delignification significantly enhances the efficiency of downstream biogas production processes. At high temperatures (>180°C), hemicellulose is extensively hydrolysed into digestible sugars, thus facilitating microbial digestion and improving methane yield (Saha & Cotta, 2008). High-temperature processes, such as steam explosion and ammonia fibre expansion, are well-studied and have demonstrated scalability for industrial applications (Hendriks & Zeeman, 2009). Biomass with high lignin content responds effectively to high-temperature treatment, overcoming challenges associated with more resistant feedstocks (Jørgensen, 2009).

However, there are certain bottlenecks associated with HTP which hampers its wide applications. High energy demand, formation of inhibitory substances, requirements for expensive equipment, feedstock specific optimisation and environmental concern are affecting its suitability for use. The energy required to maintain temperatures above 180°C

increases operational costs, reducing the overall net energy gain of the process (Taherzadeh & Karimi, 2008). High-temperature processes can lead to the formation of degradation products, such as furfural, HMF, and phenolic compounds, which inhibit microbial activity during anaerobic digestion (Palmowski & Müller, 2003). High-pressure systems required for these pretreatments increase capital costs and maintenance complexity (Hendriks & Zeeman, 2009). Not all biomass types respond uniformly to high-temperature pretreatment; process parameters must be tailored for different lignocellulosic materials, complicating operational standardization (Chen *et al.*, 2007). The use of strong acids or alkalis in some high-temperature pretreatment methods can generate waste streams that require proper neutralization and disposal, adding to environmental and economic burdens (Mussatto *et al.*, 2010).

While high-temperature pretreatment offers significant advantages in improving biogas yields and processing recalcitrant biomass, its application is constrained by economic and environmental considerations. The balance between energy inputs and outputs is a critical factor for its feasibility, especially when compared to low- or moderate-temperature alternatives. Furthermore, while scalability and efficiency are promising, the inhibitory compounds formed during these treatments necessitate additional detoxification steps, potentially offsetting the benefits. Future developments should focus on integrating renewable energy sources to offset high energy costs and advancing inhibitor mitigation techniques to enhance microbial compatibility.

Conclusion

Pretreatment significantly influences methane yield by improving substrate hydrolysis rates. Studies report a 50-100% increase in biogas production following optimal thermal pretreatment. It was found that inadequate lignin removal and prolonged process duration are associated with both LTP and MTP. But, HTP offers higher accessibility to biomass due to effective deconstruction of cellulose-hemicellulose-lignin complex with high potential for scale-up. However, these advantages are associated with adverse counter-productive processes such as excess inhibitory products generations and high energy demand. For, the HTP to adaptive, these processes must balance.

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