ENHANCING METHANE PRODUCTION FROM CASSAVA STARCH: COMPARATIVE ANALYSIS OF EXTRUSION PRETREATMENT IN SINGLE-STAGE AND TWO-STAGE ANAEROBIC DIGESTION

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ABSTRACT

The anaerobic digestion (AD) of starch-based feedstocks poses a challenge due to the complex semi-crystalline structure of starch, which can impede efficient methane (CH_4) production. This study explored the effects of extrusion pretreatment on the performance of single-stage and two-stage anaerobic digestion (AD) processes using cassava starch (CS) as feedstock. Extrusion pretreatment significantly improved the single-stage AD process, reducing the adaptation phase from 41 to 23 days and increasing the 63-day CH_4 production by 42%, reaching 3135 ± 322 NmL CH_4/L_{medium}. In contrast, extrusion pretreatment did not have a significant impact on the two-stage AD process, which already had inherent advantages of reducing the methanogenic adaptation phase to just 3 days, shortening the digestion time by at least 78% (from 63 to 14 days), and increasing the overall CH_4 productivity by 305% or more, reaching 2966 - 3063 NmL CH_4/L_{medium}. The two-stage process also produced a purer biogas (around 82% CH_4) with an energy potential of around 14 kJ/gCOD, in addition to generating hydrogen as a clean energy byproduct. While extrusion improved biogas production in the single-stage AD, the two-stage AD process proved to be a more promising approach for efficient CH_4 generation and clean energy recovery from CS.

Keywords: Anaerobic digestion. Methane. Cassava starch. Extrusion. Two-stage biogas production.

1 INTRODUCTION

The rising global energy demand, depletion of fossil fuel reserves, and the negative environmental impacts of fossil fuels have driven the search for renewable and sustainable energy sources. Biogas, primarily composed of methane (CH_4), is a promising alternative, suitable for generating electricity, heating, cooling, and transportation. It can be produced via anaerobic digestion (AD) in biodigesters, landfill gas recovery systems, and wastewater treatment plants.[1] Biogas production offers numerous benefits, such as reducing greenhouse gas emissions, improving waste management, and enhancing soil fertility.[2]

Starch-based crops like cassava are emerging as valuable biomass feedstocks for biogas production.[3] The OECD-FAO agricultural outlook predicts a significant increase in cassava utilization for biofuel by 2028.[4] Despite its potential, the complex structure of starch could hinder hydrolysis, the rate-limiting step in AD, necessitating pretreatment methods to enhance biogas yield. Various pretreatments like thermochemical methods have shown effectiveness in improving CH_4 yields.[5] However, extrusion, a thermo-mechanical pretreatment, despite being promising for starch-based feedstocks, has rarely been applied in biogas production. Previous research by our team introduced a novel dry-extrusion pretreatment for cassava starch, improving its properties[6] and hydrogen production during dark fermentation.[7] This study explores the impact of extrusion pretreatment on CH_4 production from cassava starch in both single-stage and two-stage AD processes, hypothesizing that extrusion will enhance biodegradability and methane production. The study also compares the energy potential and biogas purity from the different processes.

2 MATERIAL & METHODS

The study utilized cassava starch (CS) with 10% moisture content, provided by Embrapa Agroindústria de Alimentos as feedstock for the AD process. Sugarcane bagasse (SB), donated by Raízen, milled and sieved to a 2 mm particle size was used as mechanical aid for the CS dry-extrusion pretreatment process at a CS:SB mixture ratio of 1:0.25 as described in our previous work.[6] The extrusion was carried out using a co-rotating twin-screw extruder under previously optimized conditions (129°C, 132 rpm) to enhance CS pretreatment. Anaerobic sludge from a sewage treatment facility served as the inoculum, with its characteristics determined following APHA standards.[8] For single-stage AD, untreated or extruded-CS was anaerobically digested in batch reactors at 35°C with pH adjusted to 7.0, while for two-stage AD, a first-stage H_2 production from untreated- or extruded-CS through dark fermentation (DF) in batch reactors at 35°C and pH 5.5 was followed by a second-stage methanogenesis of the resultant hydrogen production effluents (HPE) in batch reactors at 35°C and pH 7.0. The reactor pressure was measured using the reactor's manometer, and the normalized gas volume was calculated using the isothermal expansion equation and the internal energy conservation postulation for ideal gases. The H_2 and CH_4 production kinetics were evaluated using the modified Gompertz equation (3) at a 95% confidence interval, where, H represents biogas production volume (NmL/L_{medium}), H_{max} is the maximum specific volume of the biogas produced (NmL/L_{medium}), R_{max} is the maximum biogas production rate (NmL/L_{medium}/day), λ is the adaptive phase (h), and e is the Euler number (2.71828).

$$H(t) = H_{max} \cdot exp\left\{-exp\left[\frac{R_{max} \cdot e}{H_{max}}(\lambda - t) + 1\right]\right\} \quad (3)$$

3 RESULTS & DISCUSSION

The results showed that extrusion pretreatment significantly enhanced CH_4 production from CS in a single-stage AD process by reducing the adaptation phase from 41 to 23 days and increasing the total CH_4 production in 63 days by 42%, from 1832 ± 175 NmL CH_4/L_{medium} to 3135 ± 322 NmL CH_4/L_{medium}. Untreated-CS showed slow progress during the digestion (Figure 1a) due to starch's complex structure, impeding hydrolysis. The improvements observed for extruded-CS might be a result of starch crystallinity reduction and increased water solubility of starch by extrusion pretreatment, which has been shown in previous studies to facilitate the microbial degradation of starch.[7]

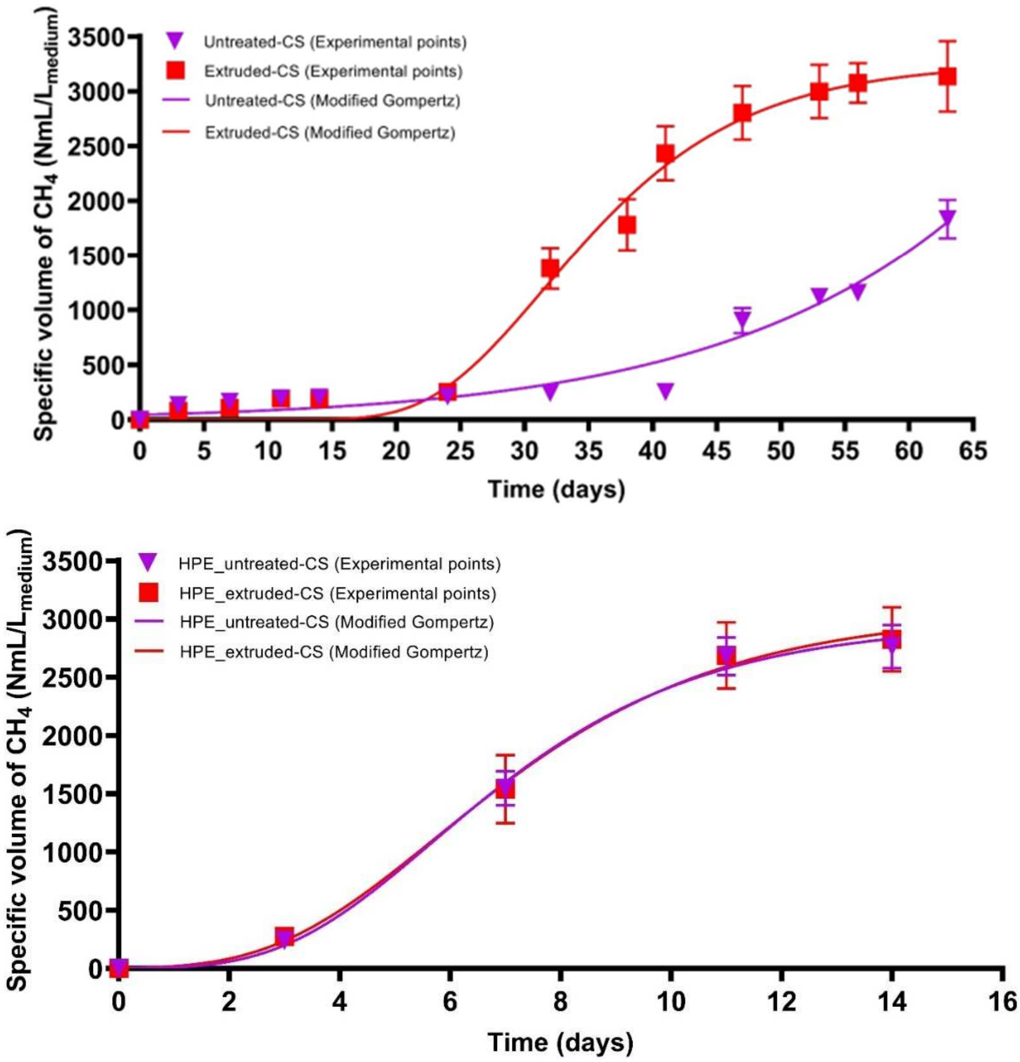

Figure 1 The kinetics of methane (CH_4) production from (a) single-stage anaerobic digestion (AD) of untreated- and extruded cassava starch (CS) and (b) second-stage methanogenesis of the H_2 production effluents (HPE) obtained from the first-stage dark fermentation of untreated- and extruded-CS in a two-stage AD process.

The two-stage AD process, with the separation of the acidogenesis (H_2 production) phase from the methanogenesis phase, was found to have advantages over the single-stage process, particularly in reducing digestion time and increasing biogas purity. Extrusion pretreatment increased H_2 production rates by 38% (from 80.4 to 111.1 NmLH_2/L_{medium}/h) in the first stage and reduced the fermentation lag phase by 59% (from 13.6 to 5.6 h), reaching a maximum H_2 production of 3201 NmL H_2/L_{medium}. However, it had no significant effect on CH_4 production in the second stage, with a maximum CH_4 production volume of 2966 - 3063 NmL CH_4/L_{medium} for both untreated- and extruded-CS on day 14 (Figure 1b). Both untreated and extruded-CS achieved over 92% reduction in COD and near-complete VFA reduction (96-100%), demonstrating the process' efficiency.

Furthermore, the increase in CH_4 production volume, productivity, and yield observed with the second-stage methanogenic process represent at least 1276%, 1276%, and 1487% higher values than those observed in the single-stage AD of untreated-CS and extruded-CS in 14 days, which were still in the adaptive phase. Additionally, the total digestion time was reduced by at least 78%, from 63 days to 14 days, when using HPE from the first stage as feedstock for the second-stage methanogenesis.

Extrusion pretreatment significantly enhances CS hydrolysis, benefiting both single-stage anaerobic digestion (AD) in terms of CH_4 production and the first-stage H_2 production by reducing the adaptive phase time and increasing the production rate. However, the source of the HPE used in the second-stage methanogenesis does not affect the CH_4 production profile (Figure 1b). This lack of influence is due to the fact that hydrolysis is not needed for the second-stage methanogenesis with HPE, as HPE typically contains volatile fatty acids (VFA), which are direct substrates for methanogenesis.

Further advantages of the two-stage AD process include increased CH_4 content and overall productivity. The adaptive phase of the AD process can be shortened by at least 87% (from 23 days to 3 days), and the overall productivity can be increased by at least 305% (from 70 $NmLCH_4/L_{medium}$/day to 237.5 $NmLCH_4/L_{medium}$/day) when using HPE in the second-stage process. Maximum CH_4 productivity in the second-stage process reached 384 - 402 $NmLCH_4/L_{medium}$/day, compared to 137 $NmLCH_4/L_{medium}$/day in the single-stage AD with extruded-CS. The CH_4 content in the final biogas mixture also improved significantly, with approximately 82% CH_4 in the second-stage methanogenesis compared to 49% - 57% in the single-stage AD.

Finally, the two-stage AD also improved the 14-day CH_4 energy yields, increasing from 0.84 - 0.87 kJ/gCOD in the single-stage to 13.8 - 14.1 kJ/gCOD in the second-stage methanogenic stage, similar to the 63-day yield of 15.66 kJ/gCOD from the single-stage AD of extruded-CS. Overall, extrusion pretreatment can improve biogas production from CS in a single-stage AD, while the two-stage AD is a more promising approach for efficient CH_4 production and clean energy generation from CS.

4 CONCLUSION

This study investigated the effects of extrusion pretreatment on the AD of CS, in both single-stage and two-stage AD systems. Extrusion pretreatment enhanced the biodegradability of CS in the single-stage AD process, reducing the adaptive phase and increasing the 63-day CH_4 production. In contrast, extrusion pretreatment did not significantly impact the two-stage AD process, which already had inherent advantages over the single-stage process, such as a shorter methanogenic adaptation phase, reduced digestion time, and higher biogas purity, with H_2 as an additional clean energy byproduct. Overall, while extrusion pretreatment can improve biogas production from CS in a single-stage AD, the two-stage AD is a more promising approach for efficient CH_4 production and clean energy generation from CS.

All the results presented in this document are part of a recently published paper.[9]

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