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PRODUÇÃO SUSTENTÁVEL DE BIOHIDROGÊNIO E BIOMETANO A PARTIR DA DIGESTÃO ANAERÓBIA DE RESÍDUOS DA CADEIA DE PROCESSAMENTO E COMERCIALIZAÇÃO DA BANANA

CINTIA CRISTINA DA COSTA FREIRE

Tese apresentada ao Instituto de Pesquisa em Bioenergia de Rio Claro, Universidade Estadual Paulista, como parte dos requisitos para obtenção do título de Doutor em Ciências.

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"*Não se encontra a paz evitando a vida*", *Virginia Woolf.*

RESUMO

A crescente demanda por soluções sustentáveis no setor agroindustrial e alimentício tem incentivado pesquisas sobre o aproveitamento de resíduos orgânicos para geração de bioenergia. Nesse cenário, resíduos da cadeia de processamento e comercialização da banana foram estudados como substratos para digestão anaeróbia, visando produzir biohidrogênio ($bioH_2$) e biometano ($bioCH_4$). A investigação englobou estudos de biodigestão de bananas impróprias para consumo e também da água residuária do processamento industrial da banana (ARPB). Além disso, técnicas de delineamento experimental e metodologia de superfície de resposta visando otimizar variáveis operacionais (temperatura, pH e relação substrato/inóculo) dos biorreatores e técnicas de digestão anaeróbia em sistemas de estágio único (produção direta de $bioCH_4$ em biorreator metanogênico) e duplo estágio (produção sequencial de $bioH_2$ e $bioCH_4$) para a ARPB foram avaliadas. Nos ensaios de fermentação dos resíduos de comercialização da banana, a alta disponibilidade de açúcares de fácil fermentação resultaram em uma produção de $bioH_2$ 265,47 mL $bioH_2$/gSTV. Com relação à fermentação da ARPB, a produção máxima de 210,82 NmL $bioH_2$/g TC foi obtida com a codigestão de 2,0 g TC/L do substrato com esgoto sintético. Em contrapartida, um maior rendimento de produção de $bioH_2$ da ARPB (241,5 NmL/gCT) foi obtido nas condições 37,5 °C; pH 5,75; S/I de 2,35 (ponto central do delineamento experimental) no estudo de otimização das variáveis operacionais, sem a necessidade de codigestão com esgoto sintético, o que evidenciou o planejamento experimental como uma técnica eficaz para a maximização da produção de $bioH_2$. Para as duas configurações reacionais avaliadas para o tratamento da ARPB visando a produção de $bioCH_4$, o maior rendimento de biometano foi obtido para o sistema de estágio único (602 $NmLCH_4$/gDQO), resultando em um maior aproveitamento energético (24,41 MJ/kgDQO). Em contrapartida, o ensaio que compõe o segundo estágio de biodigestão da ARPB apresentou um rendimento de 340 $NmLCH_4$/gDQO e aproveitamento energético de apenas 19,44 MJ/kgDQO. Com base nestes resultados, a valorização dos resíduos da cadeia de processamento e comercialização da banana por meio da digestão anaeróbia tem se mostrado como uma estratégia sustentável que pode aliar o tratamento eficiente de resíduos à geração de bioenergia, contribuindo para a mitigação dos impactos ambientais e para o fortalecimento da economia circular no setor agroindustrial.

PALAVRAS-CHAVE: Resíduos da bananicultura; biometano; biohidrogênio; digestão anaeróbia; recuperação energética.

ABSTRACT

The growing demand for sustainable solutions in the agricultural and food industries has driven research into using organic waste to generate bioenergy. In this context, residues from the banana processing and commercialization chain were investigated as substrates for anaerobic digestion to produce biofuels such as biohydrogen (bioH_2) and biomethane (bioCH_4). This research included studies on the biodigestion of bananas that were unsuitable for consumption, as well as the banana processing wastewater (BPW). Additionally, the use of experimental design techniques and response surface methodology to optimize the operational variables (temperature, pH, and substrate/inoculum ratio) of bioreactors were evaluated, as well as anaerobic digestion in single-stage (single production of bioCH_4 in a methanogenic bioreactor) and two-stage (sequential production of bioH_2 and bioCH_4 in different bioreactors) systems for ARPB. During fermentation assays with banana residues, the abundance of easily fermentable sugars resulted in the production of 265.47 mL of bioH_2 per g TVS. Regarding the fermentation of BPW, the maximum production of 210.82 NmL of bioH_2/g TC was obtained through the co-digestion of 2.0 g TC/L of substrate in synthetic sewage. However, a higher bioH_2 production yield (241.5 NmL/gTC) was obtained at 37.5 °C, pH 5.75, and an S/A of 2.35 (central point of the experimental design) in the BPW fermentation optimization study. These results demonstrated that the experimental design is an effective method for maximizing bioH_2 production. Regarding the two reaction configurations evaluated for treating BPW to bioCH_4 production, the single-stage system had the highest biomethane yield (602 NmLCH_4/gCOD) and energy recovery (24.41 MJ/kgCOD). On the other hand, the BPW biodigestion in the two-stage system showed a yield of 340 NmL CH_4/g COD and an energy recovery of 19.44 MJ/kg COD. These results demonstrate that valorizing waste from the banana processing and distribution chain through anaerobic digestion is a sustainable strategy that combines efficient waste treatment with bioenergy generation. This approach contributes to mitigating environmental impacts and strengthening the circular economy in the agro-industrial sector.

KEYWORDS: Banana residues; biomethane; biohydrogen; anaerobic digestion; energy recovery.

SUMÁRIO

CONSIDERAÇÕES INICIAIS

O presente trabalho foi estruturado com o objetivo de apresentar de forma detalhada os resultados obtidos ao longo da pesquisa de doutorado, organizados no formato de capítulos. Cada um desses capítulos aborda, de maneira independente, as análises e experimentos realizados para cada uma das hipóteses levantadas para este estudo, conforme descrito no Quadro 1. O Capítulo 3 obteve desdobramento em um artigo científico intitulado como "*Unravelling the Biohydrogen Production Potential from a Co-Digestion Process of Banana Processing Wastewater and Synthetic Sewage by Anaerobic Fermentation: Performance Evaluation and Microbial Community Analysis*", publicado na revista internacional *Waste and Biomass Valorization*. O conteúdo deste artigo foi incorporado à presente tese em sua íntegra, mantendo-se fiel à versão publicada na referida revista científica.

QUADRO 1. Estrutura da tese de doutorado na temática "Produção sustentável de biohidrogênio e biometano a partir da digestão anaeróbia de resíduos da cadeia de produção e consumo da banana".

DESCRIÇÃO/HIPÓTESE	OBJETIVO	POSIÇÃO	TIPO
H1 - Apesar de os resíduos da cadeia de produção e consumo da banana apresentarem potencial para serem eficientemente aproveitados para produção de diferentes biocombustíveis, há uma lacuna significativa na literatura quanto à sua exploração para a obtenção sustentável de biogás e biohidrogênio por meio da digestão anaeróbia.	• Contextualizar a relevância econômica e o volume da produção da fruta, evidenciando o problema ambiental da geração de resíduos, reforçando a necessidade de soluções sustentáveis para o aproveitamento desta biomassa residual; • Realizar uma análise bibliométrica da produção científica relacionada à digestão anaeróbia de resíduos da banana, identificando tendências e oportunidades de pesquisa.	Capítulo 1	Artigo de revisão
H2 - O inóculo obtido a partir dos resíduos da comercialização da banana, produzidos em mercado local de Rio Claro – SP, quando empregado em reatores fermentativos, possui maior eficiência na degradação do resíduo e produção de biohidrogênio quando comparado ao lodo granular obtido de reator UASB para tratamento de resíduos de avicultura.	• Avaliar as características físico-químicas dos resíduos da comercialização da banana; • Obter inóculo a partir do resíduo da banana por meio da incubação do caldo fermentativo do resíduo enriquecido com meio de cultivo semi-definido para a fermentação; • Avaliar a produção de biohidrogênio e metabólitos solúveis a partir da fermentação escura dos resíduos da banana utilizando inóculo autóctone e alóctone.	Capítulo 2	Artigo empírico
H3 - A água residuária do processamento da banana (ARPB) é um substrato promissor para a produção de biohidrogênio;	• Avaliar a produção de biohidrogênio em reatores batelada alimentados com diferentes concentrações de ARPB; • Avaliar o perfil taxonômico e funcional da biomassa fermentativa sob efeito das diferentes concentrações de ARPB testadas.	Capítulo 3	Artigo empírico *(Publicado)*
H4 - Ferramentas de delineamento experimental podem auxiliar na maximização da produção de biohidrogênio a partir da água residuária do processamento da banana.	• Maximizar a produção de biohidrogênio a partir da fermentação da água residuária do processamento da banana; • Avaliar a influência das variáveis temperatura, razão substrato inóculo e pH inicial na produção de biohidrogênio; • Avaliar o perfil taxonômico e funcional da biomassa fermentativa nas condições operacionais mais favoráveis para a produção de bioH_2.	Capítulo 4	Artigo empírico
H5 - Ensaios de produção de biometano alimentados com o efluente fermentativo obtido de reatores utilizados para a produção de biohidrogênio possuem maior aproveitamento energético quando comparados aos ensaios utilizando o resíduo bruto.	• Avaliar a produção de biometano utilizando ARPB bruta (estágio único); • Avaliar a produção de biometano em reatores batelada utilizando os efluentes da fermentação da ARPB (ensaio de segundo estágio); • Avaliar o aproveitamento energético e a composição da comunidade microbiana dos ensaios de biodigestão em estágio único e em dois estágios.	Capítulo 5	Artigo empírico

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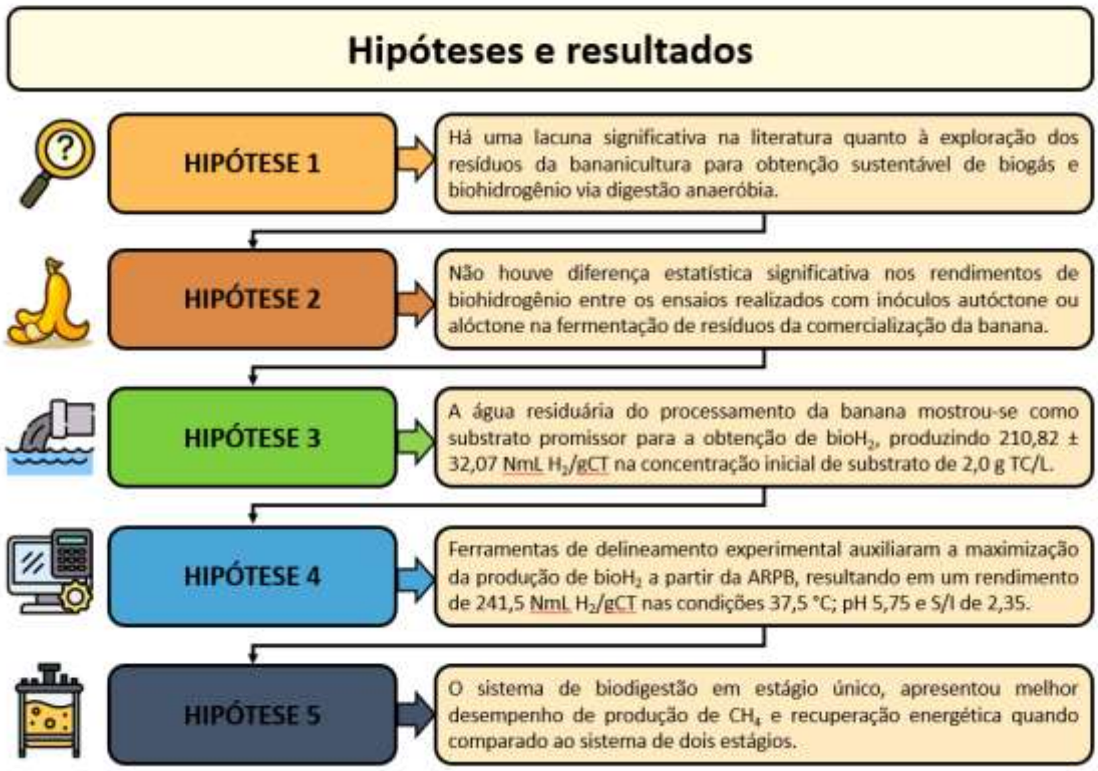
CONSIDERAÇÕES FINAIS

Este estudo investigou o potencial dos resíduos gerados ao longo da cadeia de comercialização e consumo da banana, incluindo águas residuárias e frutos descartados comercialmente, como substrato para digestão anaeróbia visando à obtenção de biometano e biohidrogênio. A partir das hipóteses levantadas, foi possível validar, por meio de diferentes abordagens teóricas, procedimentos experimentais e análises estatísticas as possibilidades do aproveitamento dessa biomassa residual para obtenção dos produtos de valor agregado a partir da digestão anaeróbia. O diagrama que representa visualmente as hipóteses e principais resultados obtidos está representado na Figura 1.

Figura 1. Diagrama das hipóteses e principais resultados relacionados à digestão anaeróbia dos resíduos da cadeia de processamento e comercialização da banana, com foco na produção de biometano e biohidrogênio.



A primeira hipótese sugere que, apesar do potencial dos resíduos da banana para a recuperação energética, há uma lacuna significativa na literatura quanto à exploração destes resíduos para obtenção sustentável de biogás e biohidrogênio via digestão anaeróbia. A abordagem teórica realizada enfatiza que, embora o Brasil seja um dos maiores produtores da fruta, há uma escassez na produção científica do país e também a nível global sobre produção sustentável de biogás e biohidrogênio a partir dos resíduos da cadeia produtiva da banana nos últimos 25 anos. Os países que possuem abundância desta matéria-prima enfrentam desafios com o descarte de resíduos, o que torna mais urgente a busca por processos de aproveitamento energético mais eficientes, baratos e sustentáveis. Além disso, essa demanda pode servir como incentivo estimular governos e instituições a investir em pesquisa e infraestrutura voltada às práticas de economia circular.

Para a segunda hipótese que propõe que o inóculo obtido a partir dos resíduos da comercialização da banana pode apresentar maior eficiência na degradação do substrato e na produção de biohidrogênio quando comparado ao lodo granular de reator UASB, foi verificado não houve diferença estatística significativa nos rendimentos de biohidrogênio entre os ensaios realizados com os diferentes inóculos. Além disso, verificou-se que o consórcio de fonte externa, aliado ao substrato contendo polpa e casca, é uma estratégia promissora por permitir o aproveitamento integral do resíduo e não estar limitado a necessidade de condições estéreis.

A terceira hipótese que sugere que a água residuária do processamento da banana pode ser utilizada como substrato promissor para a produção de biohidrogênio foi confirmada nos testes fermentativos em batelada, de forma que os maiores rendimentos foram obtidos com concentração inicial de 2,0 g TC/L (210,82 ± 32,07 NmL H_2/gCT). Conforme diferentes concentrações de substrato foram oferecidas, observou-se alteração nas rotas metabólicas, evidenciando a influência direta das condições iniciais de alimentação no processo fermentativo.

A quarta hipótese que sugere que ferramentas de delineamento experimental poderiam auxiliar na maximização da produção de biohidrogênio a partir da ARPB foi validada, uma vez que os modelos estatísticos permitiram identificar as melhores condições operacionais para o processo. A melhor resposta prevista pelo modelo para o rendimento de bioH_2 (243,78 NmL/gCT) foi retornada nas condições: temperatura 42,9°C, pH inicial de 6,29 e S/I de 2,15. A validação do ponto central do delineamento experimental (37,5 °C; pH 5,75; S/I de 2,35) resultou experimentalmente em um rendimento de produção de bioH_2 de 241,5 NmL/gCT, resultado muito próximo ao máximo previsto pelo modelo.

Os resultados experimentais para os ensaios metanogênicos em diferentes configurações (estágio único e dois estágios) contrariam a quinta hipótese levantada, que sugere que ensaios de produção de biometano alimentados com o efluente fermentativo obtido de reatores utilizados para a produção de biohidrogênio podem possuir maior aproveitamento energético quando comparados aos ensaios utilizando o resíduo bruto. Os resultados confirmaram que o sistema de estágio único, alimentado com ARPB bruta, apresentou melhor desempenho na produção acumulada e rendimento de biometano, maior aproveitamento energético e maior taxa de remoção de matéria orgânica.

Diante dos resultados obtidos, conclui-se que os resíduos da cadeia de comercialização e consumo da banana, em virtude de sua composição rica em carboidratos facilmente degradáveis, podem ser utilizados como substratos em processos de digestão anaeróbia para obtenção de biometano e biohidrogênio.