



BIOMASS AND BIOENERGY CONFERENCE

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FÁBIO MINORU YAMAJI and FRANCIANE ANDRADE DE PÁDUA

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ABOUT THE EVENT

The Biomass and Bioenergy Conference will bring together the world's leading biomass and bioenergy references to present and discuss perspectives, solutions and their impacts in Brazil and the world.

The aim of the conference is to promote the meeting of professionals, researchers, research centers, companies and universities to talk about the use and application of biomass in all its forms and its importance in society, encouraging scientific research and development through lectures and presentations.



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SPEAKEARS



Workshop I - Experimental design and data analysis with Jamovi
Dr. Marina Moura Morales
Embrapa Forestry



Workshop II - BioCalc: the carbon credit calculator for solid biofuels
Dr. Antonio Carlos Farrapo Junior and Dr. Diogo Aparecido Lopes Silva
Federal University of São Carlos (UFSCAR)



Workshop III - Generative AI tools in scientific research
Dr. Roberto A. Martins
Federal University of São Carlos (UFSCAR)



Biomass & Bioenergy: Pathways to clean energy transition
Dr. Manuel Garcia-Perez
Washington State University



The role of Brazilian Biorenewables National Laboratory (LNBR) in the context of Brazil's energy transition
Dr. Mário Tyago Murakami
Brazilian Center for Research in Energy and Materials (CNPq)



The future of Sustainable Aviation Fuel (SAF)
Dr. Manuel Garcia-Perez
Washington State University



Implementing innovation in the use of byproducts through a collaborative approach in rural regions
Dr. Mery A. Perez
Memorial University of Newfoundland



Effect of bark blending with wood on ash fusion
Dr. Kenji Koido
National Institute for Environmental Studies



Fast-growing biomass for renewable energy
Dr. Marina Moura Morales
Embrapa Forestry



Bioinspired catalysts for biomass to biofuel conversion: A South African perspective
Dr. Busiswa Ndaba-Vatsha
University of South Africa



Hydrothermal carbonization for waste management, energy production and nutrient recovery
Dr. Fabiano Bisinella Scheufele
Federal University of Technology - Parana (UTFPR)



Forestry "waste" to applications and potential of marine "waste"
Dr. Kelly Hawboldt
Memorial University of Newfoundland



Lignocellulosic waste: development and innovation in obtaining bio-oil
Dr. Lisiane dos Santos Freitas
Federal University of Sergipe (UFS)



Biochar and slag fertilizer application on the growth and biomass yield of willow
Dr. Tsuyoshi Yamada
Forestry and Forest Products Research Institute (FFPRI)



Potential of sugarcane biochar for electrochemical energy storage and conversion
Dr. Izabela Irena Rzeznicka
Shibaura Institute of Technology

AWARD-WINNING PAPERS

Poster



Carla Vitoria dos Santos de Vechi

Development of green solvent-based extraction protocol for microbial lipids



Lenilson Afonso dos Santos

Defatted Spent Coffee Grounds-Derived Activated Biochar for Free Fatty Acid Removal from Waste Cooking Oil Toward Sustainable Biodiesel Production



Alisson Lara de Carvalho

Energy Potential of Açaí Seed (*Euterpe sp.*) Biochar Obtained by Torrefaction and Conventional Pyrolysis



Enrico de Mello Castellucci

Ethyl esters Production via Direct Transesterification of biomass Oleaginous Fungi Cultivated in Agro-Starchy Wastewaters



Joice Mörs

Development and Evaluation of a Prototype for the Removal of Carbon Dioxide (CO₂) and Hydrogen Sulfide (H₂S) from Biogas Using Microalgae

Oral



Sarha Lucia Murillo Franco

Integrated Techno-Economic and Environmental Evaluation of Fast Pyrolysis of Raw and Defatted Spent Coffee Grounds: A Case Study in Brazil



Gabriel de Figueiredo da Costa

Citrus Waste Valorization Through Supercritical CO₂ Extraction of Limonene



Millos Julián Enrique Jinete Torres

Effect of Torrefaction Atmosphere on the Combustion Performance of Sugarcane Bagasse Briquettes



Jorge Eduardo Infante Cuan

Optimization of the SAF Supply Chain via the ATJ Route: A Techno-Economic and Environmental Assessment in Brazil Using Sugarcane, Corn, and Agave Biomass



Samuel Brito de Lima Arruda

Sulfamethoxazole removal by adsorption using biochar obtained from coconut residues and *Terminalia catappa*

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BIOMASS AND BIOENERGY CONFERENCE

ABSTRACT



Algae

BIOMASS POTENTIAL OF *CYANOBIMUM* SP. CACIAM 16 AND *Merismopedia* sp. CACIAM 33 AS SOURCES OF PIGMENTS AND ANTIOXIDANTS

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Cyanobacterial biomass emerges as a sustainable alternative to first and second-generation biomass sources. Cultivation of cyanobacteria does not require arable land or potable water, as these microorganisms can grow with minimal space and nutrients. Furthermore, they present high photosynthetic efficiency, which allows for high growth rates and biomass productivity. The resulting biomass is attractive for the production of high-value metabolites such as phycobiliproteins (PBPs), carotenoids and phenolic compounds. This work evaluated the potential of biomass from two Amazonian strains, *Cyanobium* sp. CACIAM 16 and *Merismopedia* sp. CACIAM 33, as sources of pigments and antioxidants. Strains were grown in BG-11 medium for 30 days (13:11 h photoperiod; 24 ± 2 °C). Biomass productivity was determined gravimetrically; PBPs were extracted in 0.1 M phosphate buffer and quantified by spectrophotometry; antioxidant activity was measured by ABTS⁺ radical reduction. CACIAM 16 showed higher biomass productivity ($21.11 \pm 2.52 \text{ mg} \cdot \text{L}^{-1} \cdot \text{d}^{-1}$) compared to CACIAM 33 ($15.33 \pm 1.33 \text{ mg} \cdot \text{L}^{-1} \cdot \text{d}^{-1}$). *Cyanobium* sp. exhibited superior levels of total PBPs ($25.70 \pm 3.97 \text{ mg} \cdot \text{g}^{-1}$) and phycocyanin ($18.91 \pm 2.91 \text{ mg} \cdot \text{g}^{-1}$) than *Merismopedia* sp. (17.55 ± 0.43 and $13.20 \pm 0.23 \text{ mg} \cdot \text{g}^{-1}$, respectively). In the ABTS assay, *Cyanobium* sp. demonstrated antioxidant activity approximately twice as high ($443.26 \pm 10.65 \text{ } \mu\text{molTE/g}$) as *Merismopedia* sp. ($202.10 \pm 3.31 \text{ } \mu\text{molTE/g}$). The differences between the strains were statistically significant ($p \leq 0,05$). These results indicate that both strains, particularly CACIAM 16, are promising biomass sources for pigment and antioxidant production with potential industrial applications.

Keywords: Cyanobacteria; Biomass; Phycobiliproteins; Antioxidants; Bioprospecting

BIOPROSPECTING OF THE MICROALGAE *Synechococcus nidulans* IN MIXOTROPHIC CULTIVATION USING CASHEW BAGASSE EXTRACT AIMING AT THE PRODUCTION OF BIOACTIVE COMPOUNDS

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Microalgae cultivation has gained prominence due to the ability of these microorganisms to produce bioactive compounds with broad biotechnological applicability. However, the high production cost and limited exploration of species require strategies to make their use viable. This study aimed to biochemically characterize the biomass of the microalgae *Synechococcus nidulans*, cultivated under autotrophic and mixotrophic conditions, using cashew bagasse extract (CBE) as an organic carbon source at concentrations of 0.5%, 1.5% and 2.5% (v/v). Cell growth and biomass obtained were evaluated regarding chemical composition, higher calorific value (HCV) and thermogravimetric analysis (TGA). The crops with CBE showed higher biomass yield. The crop with 2.5% (v/v) of CBE reduced the ash content by 25.9% and increased the carbohydrate content by 28.5%, compared to the control. Despite the reduction in the lipid ($13.22\% \pm 0.25\%$) and carotenoid ($10.02 \text{ mg.g}^{-1} \pm 4.33 \text{ mg.g}^{-1}$) contents, the increase in biomass compensated for the lower specific yields. The protein content was high in the crop with 2.5% of CBE ($54.07\% \pm 3.59\%$). The results demonstrate that *S. nidulans* has potential for industrial application, being viable for its production in mixotrophic culture with agroindustrial residues. Furthermore, its high HCV indicates energy potential as a substitute for conventional solid biomass, contributing to the production of bio-oil and reduction of CO₂ emissions. Thus, biofuels derived from microalgae present themselves as a promising alternative to meet global energy demand.

Keywords: Biomass, microalgae, *Synechococcus nidulans*, cashew bagasse, mixotrophic growth

EFFECT OF THE INTERACTION BETWEEN pH AND NITROGEN CONCENTRATION ON BIOMASS AND LIPID PRODUCTION OF *Pantanelinema rosaneae* CACIAM 18 FOR BIODIESEL PURPOSES.

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The demand for renewable energies drives the search for sustainable feedstocks. Cyanobacteria, possessing metabolic plasticity, stand out as platforms for biodiesel production due to their ability to grow in diverse environments and accumulate lipids. In this study, the cyanobacterium *Pantanelinema rosaneae* CACIAM 18 was cultivated under different conditions of pH (4, 8, and 12) and nitrogen concentration (0, 17, and 34 mM), using Response Surface Methodology (RSM) to evaluate the interactive effects on biomass and lipid productivity. The results revealed a strong interaction between the factors, showing that the maximum biomass productivity (7.2 g/L) was achieved at pH 4 with 17 mM of N, whereas the highest lipid accumulation (23% of dry weight) occurred under nitrogen stress (0 mM) at pH 12. The predictive analysis of the biodiesel, based on the fatty acid profile, indicated that its ignition quality (Cetane Number > 63) and oxidative stability (Iodine Value < 44) exceed international standards. However, the cold flow properties proved to be unfavorable under most conditions. Notably, the strain demonstrated a robust ability to modulate the medium, converging the pH from initial ranges (4 and 12) to a final value of around nine. *Pantanelinema rosaneae* CACIAM 18 possesses dual potential, as a feedstock for high stability biodiesel, whose quality is modulated by the pH and nitrogen interaction, and as an agent for bioremediation of environments with extreme pH levels.

Keywords: Cyanobacteria, Biodiesel, Nitrogen, pH, Bioremediation

EVALUATING THE EFFECT OF DIFFERENT CULTIVATION CONDITIONS ON THE POTENTIAL OF *Pantanalinema rosanae* CACIAM 18 BIOMASS FOR PALMITOLEIC ACID PRODUCTION.

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Palmitoleic acid, a monounsaturated fatty acid with several desirable functional properties for various cosmetic, pharmaceutical, and energy applications, is found in the human body and in some oleaginous plant species. The difficulty in finding cultivable plant sources increases production costs and reduces commercial viability. In this context, cyanobacteria emerge as a biomass source with high potential for obtaining value-added products, such as fatty acids. These microorganisms exhibit easy laboratory cultivation and rapid growth, which are desirable characteristics for industrial production. Fatty acid synthesis in cyanobacteria can be directed by modifying cultivation conditions. This study evaluated the influence of temperature (25°C and 30°C) and culture medium (ASM-1 and BG-11) on lipid production and the palmitoleic acid content in the cyanobacterium *Pantanalinema rosanae* CACIAM 18. The objective was to optimize the concentration of palmitoleic acid in the produced lipid. The results showed that the highest lipid production (32.5%) occurred in ASM-1 medium at 30°C. Conversely, the highest palmitoleic acid content (40.8%) was achieved in BG-11 medium, also at 30°C. The study demonstrates that *Pantanalinema rosanae* CACIAM 18 is a promising source for obtaining palmitoleic acid, with a content higher than that of traditional sources. Future steps may include evaluating isolation methodologies, conducting mutagenicity and cytotoxicity tests, and exploring possible applications for this fatty acid.

Keywords: *Pantanalinema rosanae*, Biomass, Palmitoleic acid, Cyanobacteria

POTENTIAL OF MICROALGAE CULTIVATION FOR CARBON SEQUESTRATION AND STOCK ASSOCIATED WITH BIOFERTILIZER PRODUCTION

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Scenedesmus obliquus stands out for its rapid growth and resistance to adverse conditions, making it ideal for large-scale cultivation. Its ability to thrive at high CO₂ concentrations makes it a promising alternative to carbon sequestration. It can be used to produce biofertilizers, which are a more sustainable solution than chemical fertilizers. In this study, *S. obliquus* was cultivated in a *mixing board* tank with a weekly injection of 595 g of CO₂ from flue gas, resulting in a production of 0.16 g/L. The resulting biofertilizer contained 50% organic carbon and essential nutrients (N, P, and K). An experiment with maize using six treatments and five replications revealed that treatments T2 (biofertilizer with inorganic P and K) and T4 (inorganic NPK) demonstrated superior agronomic performance. Treatment T2 stood out for its ability to increase the carbon content in the soil, whereas T4 reduced these levels. With 75.6% fixation of the injected CO₂, *S. obliquus* immobilized 7.42 g of carbon per 5.84 g of biofertilizer applied. These results indicate the potential of microalgae to mitigate CO₂ emissions and promote sustainable agriculture.

Keywords: *Tetradasmus obliquus*; Maize; CO₂ fixation

TWO-STAGE CULTIVATION OF THE MICROALGA *Chlorella fusca* LEB 111 USING THE PHYTOHORMONE INDOLE-3-ACETIC ACID AND NITROGEN REDUCTION FOR ASSESSMENT OF AVIATION FUEL APPLICATIONS

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Microalgae can produce bioproducts, such as neutral and polar lipids, which are of great interest to the energy sector due to their potential for biofuel production. However, their application faces challenges, particularly high production costs. Thus, strategies like two-stage cultivation are promising approaches. This study evaluated the influence of supplementation with the phytohormone indole-3-acetic acid (IAA) and nitrogen reduction in the two-stage cultivation of the microalga *Chlorella fusca* LEB 111, focusing on increasing biomass and lipid content. In the first stage, IAA was added at different times (0, 5, and 10 days) and concentrations (0.01 and 0.1 mg L⁻¹). Subsequently, the second stage was conducted with nitrogen concentration reductions of 50%, 75%, and 87.5%. After cultivation, oil was extracted from the microalgal biomass and characterized by FTIR, NMR, TGA, and fatty acid profile. The results showed that the highest lipid content and final biomass productivity were achieved in the condition with 0.01 mg L⁻¹ IAA supplementation on day 0 and with an 87.5% nitrogen reduction (37.3% and 42.0 mg L⁻¹ d⁻¹, respectively). This condition also resulted in a 67% reduction in lipid production cost compared to the control. The characterization results highlighted the potential of the condition involving 0.01 mg L⁻¹ IAA supplementation on day 0 combined with an 87.5% nitrogen reduction for biofuel production. In conclusion, microalgal biomass represents a promising and sustainable resource for biofuel production, contributing to the mitigation of climate change caused by fossil fuel dependence.

Keywords: Microalgae biomass; Biofuels; Cost analysis; Lipid enhancement; Lipids content.

The background is a vibrant green with a large, stylized, semi-transparent letter 'B' in the center. To the left of the 'B', there are several overlapping circular shapes in shades of yellow and green, resembling oil droplets or bubbles. The overall composition is modern and clean.

Bio-oil

ALTERNATIVE ROUTES FOR COFFEE WASTE VALORIZATION: SOLVENT EXTRACTION AND PYROLYSIS

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Brazil is the world's largest coffee producer and the use of coffee production waste is crucial, accounting for at least 30% of all production. Faced with the imminent energy crisis, alternative routes to renewable fuels are being sought. This study analyzed two methodologies for extracting bio-oils from coffee waste (husks and grounds), comparing the Soxhlet and pyrolysis methods in terms of bio-oil energy potential and electricity consumption. The results showed that although Soxhlet extraction has a higher yield, pyrolysis produced compounds with higher calorific value. In terms of industrial scalability, pyrolysis revealed significant advantages, including less dependence on organic solvents, processing without extensive pre-treatment and the potential for decentralized energy systems in coffee-growing regions, despite the high initial investment. It is concluded that both methodologies are efficient, with the choice depending on the final objective, with pyrolysis more advantageous for energy applications due to its higher calorific value and better viability for industrial scale.

Keywords: Renewable Energy; Scalability; Calorific Value; Biorefinery; Thermochemical Conversion.

ANALYSIS OF THE EFFICIENCY OF HYDROTHERMAL CARBONIZATION IN IMPROVING THE ENERGY CHARACTERISTICS OF BIO-OIL FROM RICE HUSK BIOMASS

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Hydrothermal carbonization (HTC) is a promising technology for converting lignocellulosic biomass into solid biofuels with higher energy value. This study evaluated the effect of HTC at different temperatures (180°C, 200°C, and 220°C) on the chemical composition, energy properties, and structure of rice husks, using FTIR analysis to investigate functional changes. The results showed that increasing the temperature promoted significant modifications in the biomass. A progressive reduction in holocellulose content was observed, from 49.02% in the raw biomass to 39.17% at 220°C, accompanied by an increase in lignin from 34.89% to 49.77%. An increase in fixed carbon was also observed, from 16.35% to 19.79% in the most severe condition. The gross calorific value (GCV) increased from 17.22 MJ/kg (natural biomass) to 18.67 MJ/kg at 240 °C, demonstrating energy enrichment. Conversely, the yield rate (R%) decreased from 100% to 63.27%, indicating mass losses related to the removal of more reactive fractions, such as hemicelluloses and some cellulose. These transformations resulted in more aromatic, less oxygenated, and potentially more stable hydrochars. FTIR analyses confirmed the selectivity of the process, evidencing the formation of carbon-enriched structures suitable for applications in bioenergy, adsorbents, and pyrolysis pretreatment. It is concluded that higher temperatures favor hydrochars with better energy quality, albeit with lower yields, an aspect that should be considered in process optimization.

Keywords: Biomass; Hydrothermal Carbonization; Bio-oil; Energy; Sustainability

CHARACTERIZATION OF FICUS AND NIM PRUNING FOR APPLICATION IN PYROLYSIS PROCESS

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Urban afforestation plays an essential role in cities, but the maintenance of green areas generates large volumes of pruning waste that are generally unused. Species such as Nim (*Azadirachta indica*) and Ficus (*Ficus benjamina*), common in public streets, produce waste classified as lignocellulosic biomass, with potential for renewable energy generation in compliance with UN climate criteria. This study aimed to chemically characterize these biomasses and the bio-oils obtained via micro pyrolysis, to evaluate their potential for producing value-added chemical compounds. Proximate, extractive, CHN O, EDX, TGA, and lignocellulosic composition analyses were conducted. Pyrolysis was carried at 700 °C under an N₂ atmosphere, and the bio-oils were analyzed by GC-qMS. The biomasses showed low moisture content (6.7% for Nim and 2.5% for Ficus), and high volatile matter (85.4% and 70.9%, respectively), favorable characteristics to the process. The higher heating value was 17.1 MJ kg⁻¹ for Nim and 14.1 MJ kg⁻¹ for Ficus. TGA indicated the thermal behavior and optimal degradation temperature. Nim showed high lignin content (62.5%), favoring phenol production. In the bio-oils, phenols predominated (72.2% Nim and 56.7% in Ficus), while Ficus also showed high levels of linear hydrocarbons (26.6%). These results indicate the feasibility of converting pruning waste into high-value bio-based products. The predominance of phenols, particularly in Nim, indicates potential for applications in the chemical industry (e.g., polymer synthesis) and the pharmaceutical industry (e.g., production drugs with analgesic properties). This work advances the field of biomass utilization and supports the development of low-carbon technologies aligned with UN climate goals.

Keywords: *Azadirachta indica*; *Ficus benjamina*; pyrolysis; bio-oil; GC-qMS

CO-PYROLYSIS OF GREEN COCONUT FIBERS WITH POLYMERS: ENHANCED THE QUALITY OF PRODUCED BIO-OIL AIMING BIO-FUEL PRODUCTION

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Co-pyrolysis of residual biomass with plastics emerges as a promising alternative for sustainable energy generation, mainly due to the environmental impact and the possibility of obtain biofuels and bioproducts. Biomass is recognized as a renewable resource while plastic waste poses an environmental challenge due to its high volume and low recycling rate. By merging these residues in a thermal conversion process, both can be transformed into biofuels, thereby reducing improper disposal and promoting the circular bioeconomy. In this study, bio-oils obtained from fast co-pyrolysis in a microscale fixed-bed reactor were chemically analyzed using gas chromatography (GC/MS) for compound identification. Green coconut fibers were collected, deposited on the soil, exposed to environmental factors for 30 days, and subjected to pyrolysis. The samples were characterized by proximate and elemental analysis, high heating value (HHV) and thermal gravimetric analysis (TGA). Mixtures of this biomass with polymers (PP, HDPE, and LDPE), were pyrolyzed and the bio-oils were chromatographically analyzed. The analysis of resulting bio-oils revealed that the mixture containing 25% of each of the three polymers and 25% of biomass was the most effective, reducing phenols and furans, and eliminating ketones.

Keywords: Green Coconut; Plastics; Co-pyrolysis; Bio-oil; Sustainability.

DEVELOPMENT OF GREEN SOLVENT-BASED EXTRACTION PROTOCOL FOR MICROBIAL LIPIDS

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The transition toward a circular bioeconomy necessitates sustainable processes, especially in bioproducts extraction. Microbial lipids and carotenoids, such as torularhodin and beta-carotene, are high-value pigments sustainably produced through lignocellulosic biomass fermentation in biorefineries. These compounds offer significant potential for diverse industrial and health applications. However, conventional extraction solvents pose toxicity risks and environmental concerns, highlighting the need for alternatives aligned with green chemistry principles. This study aimed to develop and evaluate a sustainable extraction protocol using green solvents to recover lipids and carotenoids from *Rhodospiridium toruloides* yeast, replacing chloroform and enhancing bioproduct recovery. *R. toruloides* strain UFMG-CM-Y2896 was cultivated in synthetic medium comprising xylose ($30\text{g}\cdot\text{L}^{-1}$), glucose ($4\text{g}\cdot\text{L}^{-1}$), yeast extract ($2\text{g}\cdot\text{L}^{-1}$), MgSO_4 ($1\text{g}\cdot\text{L}^{-1}$), $(\text{NH}_4)_2\text{SO}_4$ ($2\text{g}\cdot\text{L}^{-1}$), and KH_2PO_4 ($3\text{g}\cdot\text{L}^{-1}$), incubated at 28°C and 200rpm for 96 hours. For compound extraction, 200 mg of dry biomass was macerated with a green solvent and methanol mixture (2:1 v/v). Green solvents tested included D-limonene, ethyl acetate, and anisole, with chloroform used as control. The protocol involved incubation, sonication, addition of saturated NaCl solution, and centrifugation for phase separation. Lipid quantification was performed gravimetrically, while carotenoids were analyzed through HPLC. All green solvents demonstrated superior lipid productivity compared to chloroform, notably ethyl acetate ($1.04\text{g}\cdot\text{L}^{-1}\cdot\text{h}^{-1}$), achieving a 5.7-fold increase over chloroform ($0.18\text{g}\cdot\text{L}^{-1}\cdot\text{h}^{-1}$) and retaining the qualitative carotenoid profile, including torularhodin and beta-carotene. The study validates green solvents, particularly ethyl acetate, as sustainable alternatives to chloroform for lipid and carotenoid extraction, contributing to efficient, environmentally responsible biorefineries and valorizing agro-industrial residues.

Keywords: Sustainable extraction, green solvents, microbial lipids, carotenoids, *Rhodospiridium toruloides*.

FLUID CATALYTIC CRACKING CO-PROCESSING OF BIO-OIL AND FOSSIL FEEDSTOCKS: IDENTIFICATION OF POLAR COMPOUNDS BY ESI(+)-ORBITRAP HRMS

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Co-processing in fluid catalytic cracking (FCC) units is a promising approach to integrating renewable feedstocks, such as bio-oils, into conventional refining, thereby reducing fossil fuel dependency and greenhouse gas emissions. Understanding the molecular composition of co-processed products is crucial for identifying valuable fractions and optimizing treatment strategies. This study aimed to evaluate the biogenic contribution of pinewood bio-oil in co-processed FCC streams with fossil-derived vacuum gas oil (VGO), using Orbitrap high-resolution mass spectrometry with positive electrospray ionization [ESI(+)-Orbitrap HRMS]. The FCC feeds comprised 100% fossil (LP0), 95:5 fossil/bio-oil (LP5), and 90:10 fossil/bio-oil (LP10) blends. Data processing was performed using Composer v1.5 and Thermo Xcalibur™. The ESI(+)-Orbitrap HRMS allowed for the detection of polar compounds such as amines, amides, ketones, ethers, and esters. As the proportion of bio-oil increased, there was a corresponding rise in the content of oxygenated compounds. For example, LP0 contained 5.5% of the O-class compounds, with a double bond equivalent (DBE) of 10, primarily associated with fluorenone derivatives. With the bio-oil inclusion, LP5 and LP10 exhibited 21.2% and 30.4% of O-class compounds, respectively, with DBE values ranging from 3 to 15, associated with derivatives of lignin materials, such as tetrahydrofuran, tetrahydropyran, furan, pyran, and fluorenone. Additionally, O2-class compounds were exclusively detected in the co-processed liquid products, with DBE values ranging from 3 to 14. These were mainly identified as diones or ethers linked to aromatic rings. The use of HRMS supported the identification of compounds that may require further upgrading or treatment.

Keywords: Co-processing bio-oil; FCC; Orbitrap HRMS

INTEGRATED LIQUEFACTION AND PYROLYSIS OF COCONUT RESIDUE: A SUSTAINABLE APPROACH FOR HIGH-VALUE CHEMICALS

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Green coconut residue, an abundant and underutilized resource in Brazil's Northeast region, exhibits significant potential as a lignocellulosic biomass to produce bioproducts. This study investigated an integrated valorization pathway through acid liquefaction followed by fast pyrolysis, focusing on the sequential and selective thermal conversion of biomass constituents. Initially, the biomass underwent liquefaction using 2-ethylhexanol as the solvent and *p*-toluenesulfonic acid (pTSA) as the catalyst, yielding 42.8% liquid fraction and 57.2% solid residue. Analytical results indicated that the liquefaction residue was carbon-enriched and exhibited condensed structures, typical of humins. Subsequently, the solid residue was subjected to fast pyrolysis at 500 °C. GC/qMS analysis of the bio-oil composition revealed a predominance of important oxygenated compounds, including levoglucosenone and phenols, demonstrating that the liquefaction-derived material still retains valuable fractions of interest. The results demonstrate the potential of the integrated liquefaction and pyrolysis approach as a promising pathway for the valorization of green coconut residue, in alignment with the biorefinery concept. This strategy enables maximized biomass utilization, promoting the selective conversion of its constituents into high-value-added compounds, such as phenols and versatile chemical intermediates. Furthermore, it significantly contributes to reducing the environmental burden associated with improper waste disposal, representing a step forward toward the complete utilization of lignocellulosic waste and the development of more circular, sustainable, and environmentally responsible processes.

Keywords: Sustainability, Levoglucosenone, Phenols, GC/qMS

PERFORMANCE OF CANOLA HYBRIDS UNDER DIFFERENT WATER CONDITIONS AND SOWING DATES FOR BIOFUEL PRODUCTION

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Canola (*Brassica napus* L. var. *oleifera*) is an oilseed crop with high energy value and great potential for biofuel production due to the high content and quality of the oil in its seeds. In semiarid regions, its introduction is promising, although yield may be affected by water availability and sowing date. This study aimed to evaluate the performance of canola hybrids in terms of oil content under different sowing dates and irrigation levels, seeking to optimize the production of raw material for biofuels under the edaphoclimatic conditions of the semiarid region of Minas Gerais, Brazil. The experiment was conducted in the field using a randomized complete block design with split-split plots. Three sowing dates (April 25, May 11, and May 25, 2023), three irrigation levels (100%, 70%, and 40% of crop evapotranspiration – ET_c), and three hybrids (Diamond, Hyola 575 CL, and Nuola 300) were tested, with three replications. The plots measured 15 m², with 0.5 m row spacing and a density of 20 seeds/m. Oil extraction was performed by triple hot mechanical pressing. The highest oil yields were obtained from the earliest sowing date (36.2%) and from irrigation levels of 100% (32.6%) and 70% of ET_c (32.0%). Among the hybrids, Diamond and Nuola 300 significantly outperformed Hyola 575 CL. These findings demonstrate that delayed sowing and water deficits reduce oil content, highlighting the importance of efficient irrigation management and sowing schedule in semiarid regions.

Keywords: *Brassica napus*, biofuels, oil yield, renewable energy, semiarid region.

PRODUCTION OF PHENOLIC-ENRICHED BIO-OIL FROM GRAPE SEEDS: EFFECTS OF MICROWAVE PRETREATMENT AND CATALYTIC PYROLYSIS

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The study investigated the microwave pretreatment of grape seeds (*Vitis vinifera*), followed by catalytic pyrolysis, to produce bio-oil enriched with phenolic compounds. The pretreatment was conducted under varying conditions of temperature (80–160 °C), pH (2–12), and power (300–900 W), using a Box-Behnken experimental design. The results indicated that neutral conditions (pH 7), a temperature of 160 °C, and low power (300 W) favored holocellulose removal, resulting in a higher concentration of reducing sugars (16.42 g·L⁻¹) and enrichment of bio-oil with phenols. The catalytic pyrolysis was carried out using catalysts developed with Nb₂O₅, LaCoO₃, and either WO₃ or MoO₃. The catalyst containing MoO₃ (Cat2542) demonstrated high selectivity for phenolic compounds, with a reduction in oxygenated compounds and an increase in the relative phenol content (93.46%). The study highlighted the potential of using catalysts to improve bio-oil quality, making the process safer and more efficient, even in inert atmospheres. It was concluded that microwave pretreatment and the use of specific catalysts represent a promising approach for the valorization of residual biomass.

Keywords: Phenols; Renewable resources; Biomass valorization; Catalytic pyrolysis.

BIO-OIL PRODUCTION BY FAST MICRO PYROLYSIS OF URBAN TREE PRUNING WASTE (ARACAJU/SE/BRAZIL): GAS-CHROMATOGRAPHIC CHARACTERIZATION

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This study describes the profile of bio-oil produced by fast micro pyrolysis of urban pruning from Ficus and Indian Neem trees in the city of Aracaju (Sergipe/Brazil). Pruning samples were characterized through preliminary analyses such as ultimate and proximate, mineral (EDX) and thermogravimetric (TGA) analyzes, besides high heating value (HHV) and lignocellulosic profile. These analyses confirmed characteristics of these biomasses, mainly the high content of volatile compounds, corroborating to submit the biomasses to a pyrolysis to produce bio-oil. Fast micro pyrolysis was conducted at 700°C, based on TGA information's (maximum mass loss). Bio-oils were analyzed by gas chromatography / mass spectrometry (GC/MS), producing slightly different profiles. The ficus bio-oil sample presented a greater number of compounds (83 compounds) compared to the neem bio-oil (48 compounds). Phenols were predominant in both bio-oils, but ficus showed a higher phenols content (73.2%), compared to neem (56.7%). The second predominant chemical class was ketones (19.5%) for neem, while was hydrocarbons (26.4%) for ficus. Similarly, the majority compound in the ficus bio-oil were guaiacol, followed by phenol, vinyl guaiacol and syringol, while in the neem sample, they were syringol and its propenyl derivative, followed by 3,5-dimethoxy-acetophenone, vinyl guaiacol and iso-eugenol, confirming the main differences in samples.

Keywords: Pruning trees; pyrolysis; GC/MS; bio-oil

SIMULATION, TECHNICAL-ECONOMIC EVALUATION AND RISK ANALYSIS OF THE PURIFICATION OF EUCALYPTUS BARK BIO-OIL OBTAINED BY THE FAST PYROLYSIS PROCESS

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Biomass, a renewable resource derived from organic matter, can be transformed into value-added products through fast pyrolysis—a thermochemical process that generates solid, liquid, and gaseous fractions. The primary product, bio-oil, is a complex mixture rich in high-value chemical compounds that can be isolated via extraction and distillation. Integrating process simulation with techno-economic and risk analyses offers a comprehensive framework for evaluating the technical and economic feasibility of such recovery processes. This study aimed to simulate the separation and purification of valuable compounds from bio-oil produced via fast pyrolysis of eucalyptus bark. The process was modeled using the Aspen Plus® simulator, incorporating key unit operations such as liquid-liquid extraction and fractional distillation. The simulation results confirmed the successful recovery of target compounds, particularly syringol and trans-3,4-dimethoxycinnamic acid, with notable purity levels and an overall solvent recovery efficiency of 89.55%. The economic assessment demonstrated the process's viability, indicating high internal rates of return and short payback periods, even in scenarios involving substantial capital investment. Risk and uncertainty analyses, performed through Monte Carlo simulation, reinforced the robustness and reliability of the project under varying operational and economic conditions. Overall, the findings support the implementation of bio-oil purification systems as a promising and feasible strategy for producing renewable chemical intermediates from lignocellulosic biomass.

Keywords: Aspen Plus, lignocellulosic biomass, thermochemical conversion.

SUSTAINABLE BIOCATALYSIS WITH *Rhizopus oryzae*: EFFECT OF SUBSTRATE CONCENTRATION ON THE PRODUCTION OF FREE FATTY ACID CONCENTRATES

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The enzymatic hydrolysis of vegetable oils is a promising strategy for producing free fatty acid (FFA) concentrates with applications in the food, pharmaceutical, and biofuel industries. Employing lipolytic whole cells of *Rhizopus oryzae* as a biocatalyst offers a sustainable alternative, as the fungal biomass naturally expresses active, immobilized lipases, eliminating costly separation steps, reducing waste, and enabling reuse. This study assessed *R. oryzae* cells for converting olive oil into FFAs, focusing on how substrate concentration influences hydrolysis yield. The fungus was cultivated in liquid medium containing 3 % (v/v) olive oil at 30 °C and 180 rpm for 72 h. The resulting biomass was used directly in hydrolysis reactions at 40 °C, pH 6.0, mechanical stirring at 600 rpm, 200 U of hydrolytic activity, and 3 % (w/v) gum arabic as emulsifier. Two substrate emulsions (25 % and 50 % v/v olive oil) were evaluated over 24 h. The highest conversion occurred with 25 % oil, yielding 618.6 mM FFAs and 68.29 % hydrolysis, whereas 50 % oil produced 532.2 mM FFAs and 58.75 % hydrolysis. FFA release kinetics showed rapid conversion during the first 8 h, followed by a slowdown, more pronounced at the higher substrate load. Linearization of FFA concentrations from the first 8 h allowed calculation of initial reaction rates: 42.06 mM h⁻¹ for 25 % (R² = 0.97) and 27.35 mM h⁻¹ for 50 % (R² = 0.97). The superior rate at 25 % suggests that excess oil may inhibit enzymatic activity or restrict substrate diffusion. These findings confirm the feasibility of using *R. oryzae* biomass as a biocatalyst for producing FFA concentrates and highlight the need to optimize substrate concentration to maximize hydrolysis efficiency.

Keywords: Biocatalysis; Lipase; Enzymatic hydrolysis

THERMAL LIQUEFACTION OF MACAUBA ALMOND CAKE: A PROMISING PATHWAY FOR HIGH-YIELD BIOCRUDE PRODUCTION FROM LIPID-RICH BIOMASS

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This study investigated the bioenergy potential of macaúba (*Acrocomia aculeata*) almond cake as a raw material for biocrude production via thermal liquefaction. Thermal liquefaction using ethanol (both anhydrous and hydrated) yielded high conversion rates (81% to 82.1%) and significant biocrude yields (approximately 60%), attributed to the high lipid content of the biomass. The biocrude produced was of excellent quality, with an HHV of approximately 33 MJ.kg⁻¹, low moisture content (0.25% to 0.56%), and high energy recovery (73.9%). Elemental analysis showed a carbon content of 69% and an O/C ratio of 0.20, indicating greater thermal stability and lower corrosivity. Gas chromatography coupled with mass spectrometry (GCMS) identified a predominance of esters (above 98%), such as ethyl 9-octadecenoate, resulting from the esterification of fatty acids. These results highlight almond cake as a promising raw material for the production of sustainable biofuels, with the potential to replace fossil fuels and contribute to the energy transition.

Keywords: biocrude; thermal liquefaction; ethanol; almond cake, *Acrocomia aculeata*

The image features a green fuel pump nozzle and hose in the foreground, angled towards the bottom right. The background is a solid green color with a circular inset in the center showing a blurred image of a fuel pump. The word "Biodiesel" is written in large, white, bold letters across the center of the image.

Biodiesel

A PHASE EQUILIBRIA STUDY FOR VALORIZING GLYCEROL FROM BIODIESEL PRODUCTION THROUGH SOLVENT EXTRACTION OF ODORIFEROUS COMPOUNDS

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Glycerol (1,2,3-propanetriol) is an important building block for sustainable industry. Due to a surplus of bioglycerol, caused by the rapid increase in biodiesel production, its purification process is relevant for adding value to this biodiesel coproduct. Usually, bioglycerol is purified by vacuum distillation, although it is a costly and energy-intensive process. Conversely, solvent extraction could be an interesting alternative for extracting compounds with similar solubility, such as short-chain oxygenated compounds, which correspond to the odoriferous compounds present in crude bioglycerol. Considering that solvent extraction is subjected to the liquid-liquid equilibria (LLE) this work reports phase equilibria data of a pseudoternary model system, which comprises glycerol plus water 16% w/w (as the diluent), ethyl acetate (as the solvent) and butyric acid (as the solute), at 303.2 K and 94.5 kPa. Ethyl acetate was able to extract the target solute with notably high selectivity (in range of 218 – 334 in terms of mass fractions). The binary interaction parameters of both NRTL and UNIQUAC models were adjusted within the LLE experimental data and resulted in root-mean-square deviations of 0.29% and 0.27%, respectively, for predicting equilibrium compositions. These results show potential for applying solvent extraction in bioglycerol purification. Considering milder distillation (in terms of temperature and pressure) is employed, the feasibility of biodiesel production might be enhanced, promoting a sustainable bioeconomy.

Keywords: Biodiesel; Bioglycerol; Phase equilibria; Solvent extraction; Bioeconomy.

APPLICATION OF BIPHASIC CULTIVATION UNDER THE INFLUENCE OF NITROGEN AND LIGHT QUALITY ON BIOMASS AND LIPID ACCUMULATION BY *Nostoc* sp. CACIAM 21 FOR BIOFUEL PRODUCTION

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The search for new sustainable sources of biomass and lipids for bioenergy production can be achieved through the cultivation of cyanobacteria. However, low productivity still represents a significant challenge to the feasibility of biofuel production from biological processes. In this context, the present study evaluated the effect of biphasic cultivation on maximizing biomass and lipid production by the cyanobacterium *Nostoc* sp. CACIAM 21. This was carried out through different concentrations of sodium nitrate (0 g/L, 0.75 g/L, and 1.5 g/L) in the first phase, and the manipulation of different light-emitting diodes (blue, red, and white) and photoperiods (partial and continuous) in the second phase. The intermediate sodium nitrate concentration (0.75 g/L) showed a significant promoting effect on the growth of CACIAM 21, resulting in biomass production of 4.85 g/L and productivity of 0.21 g/L/day. Meanwhile, the highest lipid accumulation (38.10% w/w) was observed under red light with a continuous photoperiod (24 h), with palmitic acid (C16:0) standing out, representing 32.92–44.67% of the total fatty acids across the different treatments. Furthermore, the lipid profile obtained under red light and continuous photoperiod demonstrated physicochemical characteristics favorable for biodiesel production. Therefore, the results indicate that the application of biphasic cultivation directly influenced the biosynthesis of biomass and lipids by *Nostoc* sp. CACIAM 21, highlighting the potential of this strategy for sustainable biofuel production.

Keywords: Biofuels; cyanobacteria, fatty acids, optimization, two-stage.

BIODIESEL PRODUCTION FROM FUNGAL SINGLE CELL OIL: ELECTRONIC NOSE AS INNOVATIVE TOOL FOR REACTION MONITORING

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This study aimed to evaluate the olfactory profile of biodiesel and Single Cell Oils (SCO) extracted from the biomass of the filamentous fungus *Mucor circinelloides*. The microorganism was cultivated in an aerated and stirred bioreactor containing 700 mL of medium with sugarcane hydrolysate (composed of 64% glucose and 36% xylose), totaling 40 g/L of total sugars, inoculated with 1×10^5 spores/mL. Cultivation conditions were pH 4.5, temperature of 26 °C, stirring at 250 rpm, aeration at 1.5 vvm, and duration of 120 hours, with monitoring and control of pH and dissolved oxygen. After cultivation, the biomass was separated by centrifugation and directly used in transesterification, without prior lipid extraction. The reaction was conducted in a stainless-steel pressurized reactor at 250 °C, 300 rpm, for 6 hours, using ethanol as the acylating agent and the HPMo/NbO₂ catalyst. For the olfactory profile analysis, an electronic nose was employed, with 10 readings performed. The product exhibited properties compliant with ANP standards, highlighting a kinematic viscosity of 4.85 mm²/s and density of 0.885 g/cm³. Biodiesel formation was confirmed by nuclear magnetic resonance (H1NMR) spectroscopy. The conversion of oil into ethyl esters was monitored by changes in the sample's olfactory profile. The results correlate with a predictive model previously developed for this purpose. It was found that these olfactory profile changes could, in the future, replace chromatographic analysis, potentially enriching the process with real-time analysis.

Keywords: Biodiesel, Single Cell Oil, Eletronic nose, Biocatalysis

CANOLA CULTIVARS UNDER WATER DEFICIT AND LATE SOWING: IMPACTS ON LIPID COMPOSITION AND BIODIESEL POTENTIAL

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Canola oil (*Brassica napus* L.) is a promising feedstock for biodiesel production due to its high oleic acid content and good oxidative stability. However, these attributes are influenced by agronomic factors such as sowing date, water management, and genetic material. This study evaluated, under field conditions, the combined effects of three sowing dates (April 25, May 11, and May 25, 2024) and three irrigation levels (100%, 70%, and 40% of crop evapotranspiration) on the lipid profile of three canola cultivars (Diamond, Hyola 575 CL, and Nuola 300), aiming at biofuel production. The experiment was arranged in a randomized complete block design with a split-split plot scheme and three replications. Oil was extracted by hot maceration (200 °C), and fatty acids were determined by gas chromatography. Oleic acid (C18:1) was predominant in all cultivars. Late sowing combined with water deficit increased monounsaturated fatty acids and reduced polyunsaturated ones, enhancing the oil's oxidative stability. It is concluded that the integrated management of sowing date and irrigation can optimize the quality of canola oilseed biomass for bioenergy purposes, although attention must be paid to the grain yield of each cultivar.

Keywords: *Brassica napus* L.; oleic acid; biofuel; water management; bioenergy

EVALUATION OF IMMOBILIZATION OF *PSEUDOMONAS FLUORESCENS* LIPASE IN SBA-15 FOR APPLICATION IN BIODIESEL SYNTHESIS

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Lipase is an enzyme of great industrial importance, involved in lipid hydrolysis and enantioselective esterification and hydrolysis reactions with high yield and enantio-excess. To enhance its activity and facilitate recovery, its immobilization on heterogeneous substrates is necessary. Among the materials that can be used for lipase immobilization, mesoporous silica nanoparticles are efficient for immobilizing lipases due to their stability, controlled texture, and easy surface functionalization. Therefore, the objective of this work was to evaluate the synthesis and characterization of mesoporous silica SBA-15 as a support for the immobilization of *Pseudomonas fluorescens* (AK) lipase and its application in biodiesel production, aiming to enhance enzymatic stability and catalytic efficiency in the process. SBA-15 was synthesized and characterized by XRD, SEM, FTIR, and surface area analysis using the B.E.T. method. Lipase AK was immobilized by adsorption on SBA-15 and used in biodiesel production by transesterification of babassu oil with ethanol. The synthesis of SBA-15 was efficient, as evidenced by the diffraction pattern typical of mesoporous silica and high surface area (BET = 643 m²/g), indicating a well-ordered mesoporous structure. The immobilization of lipase AK on SBA-15 was successful, maintaining significant enzymatic activity (1,216.73 U/g), confirming the effective functionalization of the bioadsorbent. Furthermore, the biodiesel produced met commercial standards, with ester conversion exceeding 95%, confirming the efficiency of the enzymatic catalyst in the formation of the main fatty acid esters.

Keywords: biodiesel, lipase AK immobilization, SBA-15.

FROM AGRO-INDUSTRIAL WASTE TO RENEWABLE ENERGY: PEQUI SEED OIL AS A BIOFUEL FEEDSTOCK

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Agro-industrial residues pose significant socio-environmental challenges due to inadequate disposal. Their reutilization in sustainable production systems to generate value-added products is highly attractive for biorefineries and directly supports the United Nations Sustainable Development Goals, contributing to climate change mitigation and a renewable energy transition. Pequi (*Caryocar brasiliense*) is a fruit native to the Brazilian Cerrado with notable economic and social importance for local populations, particularly smallholder farmers engaged in extractive activities. However, its seeds feature a complex morphology with numerous spines, resulting in substantial agro-industrial waste. The pequi seed is particularly promising due to its high oil content (45–50%) rich in free fatty acids. This study proposes a renewable diesel production route using oil extracted from pequi seeds and a commercially available NiMo/Al₂O₃ heterogeneous catalyst in a hydrotreatment reaction conducted in a continuous-flow reactor for 1 hour at 400 °C under 25 bar H₂. FTIR and NMR analyses indicate efficient hydrogenation of unsaturations and effective oxygen removal from the feedstock, while GC-MS chromatograms reveal a hydrocarbon mixture ranging from C₈ to C₂₀, confirming the quality of the resulting fuel. The green diesel obtained from pequi seeds demonstrates strong potential as a decentralized energy source for small communities and as an alternative feedstock for biofuel production, addressing domestic energy demand while promoting sustainable biorefinery practices. This approach advances Brazil's emerging new biofuel programs and offers an integrated solution for valorizing agro-industrial residues, supporting both energy security and environmental sustainability.

Keywords: Pequi seeds; Green diesel; Circular economy; Biorefinery

GREEN DIESEL PRODUCTION FROM RENEWABLE FEEDSTOCKS – SIMULATION AND COST OPTIMIZATION

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The accelerating impacts of global warming highlight the urgency of adopting sustainable fuels. Green diesel, produced through the hydrodeoxygenation of vegetable oils or animal fats, is a promising drop-in replacement for fossil diesel. To ensure economic feasibility, process optimization is crucial for enhancing design and operation. This work simulates and optimizes the production cost of a hydroprocessing plant for green diesel from various vegetable oils and fats. The process was modeled in Aspen Plus using literature data for typical unit operations, and costs were estimated using the Aspen Process Economic Analyzer, combined with correlations. The optimization was carried out using particle swarm optimization (PSO), implemented in Python and connected to Aspen, to minimize the total cost. The problem had constraints related to diesel quality specifications and was solved for different feedstocks. Results show that used cooking oil and beef tallow achieve the lowest minimum selling price (1.98 US\$/L and 2.30 US\$/L for 1 ton/h of oil), mainly due to lower feedstock costs. For these feedstocks, the required capacity of the isomerization/cracking unit was smaller, as their fatty acid profiles allowed compliance with diesel standards with less severe upgrading. In contrast, soybean, cottonseed, and Jatropha oils demanded higher hydrogen consumption, significantly increasing operating costs. These results underscore the significant impact of feedstock selection on both economic considerations and process design. Future work should address detailed reaction kinetics, seasonal variability in feedstock availability, and blending strategies to enhance process flexibility and robustness.

Keywords: Renewable diesel, Hydroprocessing, Hydrotreatment

HYDROTREATMENT OF WASTE COOKING OIL AND SOYBEAN OIL FOR GREEN DIESEL: CATALYST REUSABILITY AND CIRCULAR ECONOMY IMPLICATIONS

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The growing need for the sustainable and efficient use of resources is essential to mitigate environmental impacts. In this context, the concept of circular economy combined with biorefineries plays a strategic role in the development of biofuels that contribute to greenhouse gas reduction, waste valorization, and diversification of the energy matrix. This work investigates the production of green diesel from a heterogeneous NiMo/Al₂O₃ catalyst using waste cooking oil, comparing its performance with refined soybean oil and evaluating the reusability of the catalyst in consecutive reactions. Hydrotreatment reactions were conducted at 400 °C and 25 bar of H₂ for 1 h. FTIR, NMR, and GC-MS analyses confirmed that triglycerides in both feedstocks underwent hydrodeoxygenation, decarbonylation, and decarboxylation, leading to a complex mixture of hydrocarbons within the typical range of diesel fuels. Importantly, the results demonstrated that waste cooking oil yields products with physicochemical properties comparable to those obtained from refined soybean oil, highlighting its potential as an alternative feedstock. In addition, the possibility of catalyst reuse was shown to be a promising route for reducing production costs while maintaining efficiency, reinforcing the economic feasibility of the process. These findings are particularly relevant for Brazil, where soybean oil remains the dominant raw material for industrial biofuel production. Expanding the use of residual oils not only reduces dependency on food-based feedstocks but also aligns with the United Nations Sustainable Development Goals. This approach underscores the role of green diesel from waste biomass as a viable solution within the framework of a circular economy.

Keywords: Green diesel; Hydrotreatment; waste oil; catalyst

MAGNETIC POROUS CARBON AS AN ADSORBENT OF GLYCEROL REMOVAL IN THE BIODIESEL PURIFICATION PROCESS

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Due to environmental degradation and rapid depletion of fossil fuel resources, biodiesel has emerged as an alternative source of renewable fuel derived from vegetable oils, animal fats, and waste oils. During biodiesel production, impurities such as glycerol are formed, which prevents its immediate use and, consequently, the biodiesel needs to be purified. In the biodiesel purification process, adsorbents are used to remove these impurities without the use of potable water. The present study aimed to assess the performance of a magnetic porous carbon composite synthesized from phenol, formaldehyde, and 30 wt% of *kraft* lignin. The material synthesized was characterized in terms of surface morphology (MEV) and surface area (BET). The adsorption tests were based on previous studies and were conducted with an adsorbent concentration of 7.5 mg. mL⁻¹ at 30, 35, 40, and 50°C for 90 min, under agitation in a shaker at 120 rpm. The results showed that the adsorbent was able to remove about 82.9% of glycerol without changing the material's physical properties. The biodiesel characterization revealed the viscosity ranged from 4.09 to 4.19 cSt, index acid ranged from 0.03 to 0.05 (mgKOH.g⁻¹), and the maximum value of free glycerol content was 0.0034%, meeting the standard requirements of ANP N°920/2023. The thermodynamic study indicate that the adsorption process is spontaneous, validating the characterization results and demonstrating the adsorbent capacity of the material synthesized in the dry washing purification process of biodiesel.

Keywords: Biodiesel, Adsorbent, Dry Washing, Glycerol

RENEWABLE PATHWAYS: A BIBLIOMETRIC REVIEW OF SCIENTIFIC PRODUCTION OF GREEN DIESEL AND BIOJET FUEL (2015–2025)

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The study presents a bibliometric review of scientific production on green diesel and biojet fuel between 2015 and 2025, considering the role of drop-in biofuels in the energy transition. A total of 813 publications were identified, with growth until 2022, reflecting rising interest. The most cited keywords were “diesel”, “emission”, “fuel”, and “engine”, emphasizing emissions and engine performance. Production is concentrated in Energy, Engineering, Environmental Sciences, Biotechnology, and Chemistry, highlighting the multidisciplinary character of the topic. India leads in publications, followed by Malaysia, the USA, China, and Brazil, indicating geographic decentralization and the role of emerging countries. Main thematic areas include biomass production and conversion, feedstocks such as vegetable oils and ethanol, environmental impacts, and technological applications. Growing attention is given to hydrotreatment, pyrolysis, catalysts, and alternative feedstocks such as microalgae. Among the most cited studies, research on camelina, hydrodeoxygenation of vegetable oils, and wastewater remediation integrated with fuel technologies stand out, showing progress toward low-impact and viable solutions. The methodology included defining keywords, data collection, refinement, analysis in VOSviewer, and interpretation, mapping gaps, trends, and contributions to research policies. Results emphasize the relevance of renewable fuels to the climate crisis and the need for interdisciplinary efforts and public policies. A patent review in the WIPO database identified 41 results, of which only five directly address green diesel production. These focus on non-edible vegetable oils, sustainability, and byproduct recovery, dependent on metal catalysts. Most patents are from China and the USA, consistent with their publication leadership.

Keywords: Biofuel; biorefinery; pyrolysis; hydrotreatment, VOSviewer

SEQUENTIAL OPTIMIZATION MODEL FOR UTILITY MINIMIZATION IN HYDRODEOXYGENATION OF SOYBEAN OIL

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The growing demand for renewable fuels represents a challenge, requiring efficient and economically competitive processes to replace fossil-derived alternatives. Among the available technological routes, the hydrodeoxygenation (HDO) of vegetable oils has emerged as one of the most promising pathways. A key barrier to the large-scale deployment of this process lies in its high energy requirements, which directly affect production costs and environmental performance. This work proposes the application of a sequential optimization model developed in GAMS/CPLEX to improve the energy efficiency of a green fuel production plant using soybean oil as the primary feedstock. Thermodynamic and process data are obtained from rigorous simulations in Aspen Plus v15, considering a feed capacity of 1000 kg/h of soybean oil. The optimization framework is formulated as a Mixed-Integer Programming (MIP) problem, where the objective function is the minimization of external utility demands (hot and cold). The model includes constraints to ensure thermodynamic feasibility, energy balances, and minimum approach temperatures, as well as binary decisions representing the allocation and activation of heat exchangers. Unlike conventional energy integration approaches, the sequential optimization strategy enables the systematic adjustment of process variables while respecting feasibility limits, exploring trade-offs between utility consumption and process design. The study also provides a basis for future expansion toward multi-objective optimization, incorporating both energy and cost considerations. By adopting this approach, the research aims to contribute to the development of more flexible, efficient, and competitive renewable fuel production technologies, supporting the transition toward a low-carbon energy matrix.

Keywords: Sequential Optimization; Hydrodeoxygenation; Green Diesel

SIMULATION OF A BIODIESEL PRODUCTION PLANT IN A FIXED-BED REACTOR WITH HETEROGENEOUS CATALYST: WASH WATER CONSUMPTION EVALUATION

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Biodiesel is a biofuel obtained through the transesterification reaction of vegetable oils and alcohols, consolidating itself as a strategic alternative in the face of fossil fuel depletion and increasing demands for environmental sustainability. In Brazil, its use has been promoted by public policies that mandate its blending with fossil diesel since 2004, reaching 15% v/v in 2025, with prospects for further increases in the coming years. Currently, the predominant biodiesel production method is homogeneous alkaline transesterification in batch mode. Although this process achieves high yields, it requires several purification steps, generating large volumes of wastewater. Heterogeneous catalysts have emerged as an alternative, offering technical and environmental advantages such as catalyst reuse, easier purification of fatty acid methyl esters (biodiesel), and reduced wastewater generation. This study aimed to simulate and evaluate a pilot-scale biodiesel production route using soybean oil and methanol in a fixed-bed reactor with the $\text{Ca}(\text{C}_3\text{H}_7\text{O}_3)_2/\text{CaCO}_3$ catalyst. The route was simulated in *Aveva Process Simulation* software, incorporating transesterification kinetics reported in the literature. The process considered a feed of 260 kg/h of soybean oil and methanol, with a mass ratio of 1:20, and the reaction conducted at atmospheric pressure and 60 °C. The developed process flowsheet included the design of a fixed-bed reactor, two flash distillation columns, a decanter, and a liquid–liquid extraction column. The results demonstrated that the process required only 0.14 L of wash water per liter of biodiesel produced, yielding approximately 150 kg/h of biodiesel.

Keywords: Biodiesel; Heterogeneous transesterification; Fixed-bed reactor; Process simulation; Wash water.

UTILIZATION OF 1-BUTYL-3-METHYLIMIDAZOLIUM HYDROXIDE AS CATALYST IN THE TRANSESTERIFICATION OF OILSEEDS

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The growing demand for sustainable energy sources has intensified research into biodiesel production through environmentally friendly processes. Ionic liquids have emerged as promising catalysts due to their low volatility, thermal stability, and recyclability. This study aimed to evaluate the performance of the ionic liquid 1-butyl-3-methylimidazolium hydroxide ([Bmim][OH]) as a catalyst in the transesterification of different lipid matrices, such as soybean oil, castor oil, and residual oils and fats. The ionic liquid was synthesized and applied in transesterification reactions under varied conditions, including different oil-to-alcohol molar ratios, catalyst concentrations, reaction times, and temperatures. In addition, a pressurized reactor (Parreactor) was employed to explore the influence of higher pressure and temperature on biodiesel production. The products were characterized by Fourier-transform infrared spectroscopy (FTIR) and proton nuclear magnetic resonance (¹H NMR). Initial experiments suggested that the synthesized [Bmim][OH] had limited catalytic activity, with little to no conversion detected. Control tests with potassium hydroxide (KOH) indicated that not only the catalyst but also the reaction conditions contributed to the poor performance. In experiments carried out in the pressurized reactor, the formation of ethyl esters was observed, although conversion remained incomplete, suggesting that higher temperatures and optimized conditions are required to achieve significant yields. Although [Bmim][OH] demonstrated lower performance compared to conventional catalysts, its potential as a sustainable and recyclable alternative remains relevant. The results highlight the need for further optimization of both catalyst synthesis and reaction parameters, especially under pressurized conditions, to advance the applicability of ionic liquids in biodiesel production.

Keywords: Biodiesel; Ionic liquid; [Bmim][OH]; Transesterification; Green catalysis

The image features a green background with a large, irregular circular cutout. Inside this cutout, there is a composite image. The top half shows an industrial facility with a tall smokestack and large storage tanks under a blue sky. The bottom half shows a large pile of wood chips or biomass. The word "Bioenergy" is written in white, bold, sans-serif font across the center of the cutout, overlapping both the industrial and biomass images.

Bioenergy

ARTIFICIAL INTELLIGENCE IN THE ASSESSMENT OF LAND LEASE FEASIBILITY FOR THE SUGAR-ENERGY SECTOR IN THE ALTA PAULISTA REGION, BRAZIL

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This study proposes the use of Artificial Neural Networks (ANNs) to classify the feasibility of land leasing by sugar-energy plants in the Alta Paulista region. The model receives seven input variables—such as pH, organic matter, distance to the plant, lease cost, expected productivity, production cost, and the share of leasing in the total cost—to classify each sample as either “viable” (class 1) or “not viable” (class 2). The network architecture consists of one hidden layer with 10 neurons and two output neurons, responsible for the binary decision-making process. The data were collected through questionnaires answered by experts in the sector, forming the dataset used for training, validation, and testing of the ANN. The classification results are illustrated through confusion matrices. In the training set, the model achieved 100% accuracy for both classes. During validation, an accuracy rate of 85% was observed, with a few classification errors. The overall matrix (including all data) demonstrated excellent performance, with a total accuracy of 97%, correctly classifying the majority of the samples.

Keywords: Artificial Neural Networks (ANNs), Land leasing feasibility, Sugar-energy plants, Classification accuracy

BIODIESEL PRODUCTION THROUGH HETEROGENEOUS BIOCHEMICAL CATALYSIS: COMPARISON BETWEEN NOVOZYM® 435 AND *Cercospora kikuchii* LIPASE IMMOBILIZED ON RICE HUSK

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This work focuses on comparing two heterogeneous biocatalysts for biodiesel synthesis, seeking a more economical and sustainable catalytic alternative. The reactions were carried out using palm kernel oil as the lipid feedstock and anhydrous ethanol as the acylating agent. The catalysts employed in this study were *Cercospora kikuchii* lipase immobilized on rice husk and immobilized *Candida antarctica* lipase B (Novozym® 435). Experiments were conducted in a jacketed cylindrical glass reactor at 50 °C under constant magnetic stirring for 96 hours. Biodiesel purification was performed by centrifugation to recover the catalyst, followed by glycerol adsorption assisted by ultrasound at 45 °C using *Chamotte clay* as the adsorbent material. After adsorption, another centrifugation step was performed to remove the adsorbent material. The product was then subjected to rotary evaporation at 80 °C for 40 minutes to eliminate residual ethanol. Biodiesel formation was confirmed by FTIR and NMR spectra. The kinematic viscosity of the biodiesel was 4.5 mm²/s for Novozym® 435 and 5.0 mm²/s for *Cercospora kikuchii* lipase, values within the range established by ANP for biodiesel, which is 3.0 to 5.0 mm²/s. The results indicate that the lipase immobilized on rice husk showed performance comparable to the commercial biocatalyst, reinforcing its potential as a lower-cost alternative for biodiesel production.

Keywords: biocatalysis; biodiesel; lipase.

BIOINSPIRED CATALYSTS FOR BIOMASS TO BIOFUEL CONVERSION: A SOUTH AFRICAN PERSPECTIVE

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The depletion of fossil fuels and the demand for a reduction in carbon footprint warrants the exploration of more sustainable energy sources. Biofuels such as bioethanol and biogas are promising fossil fuel alternatives for circumventing the current energy crisis. However, these technologies still require high operational costs, resulting in low production volumes. Among the catalysts used, nanoparticles have the potential to significantly improve microbially-driven biofuel production technologies. This could emanate from their unique properties, such as high catalytic active sites and surface area-to-volume ratio. Therefore, their effects when combined with microorganisms for biofuel production need further exploration. In our work, we elucidated the role that biosynthesized nanoparticles play during production of biomass-derived biogas and bioethanol to benefit South African small-holder farmers during winter seasons and chemical fuel industries, respectively.

Keywords: Nanoparticles: catalysts: microorganisms: biogas: bioethanol: biofuels

CARBON DOT NANOTECHNOLOGY AND DIGESTATE FERTILIZATION ENHANCE CORN NUTRITIONAL PROFILES FOR BIOFUEL APPLICATIONS

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The optimization of corn nutritional profiles for biofuel feedstock requires innovative fertilization strategies that enhance both sustainability and crop performance. This study evaluated the effectiveness of carbon dot nanofertilizers and digestate fertilization on corn (*Zea mays* L.) nutritional composition, critical for biofuel applications. A randomized field experiment was conducted comparing nine fertilization treatments including conventional NPK fertilizer, carbon dot nanofertilizers (Q-arbolina, Q-702010), anaerobic digestate, and combined carbon dots with digestate treatments (D-arbolina, D-702010). Plant tissue samples were analyzed for nitrogen, phosphorus, potassium content, and key nutritional parameters relevant to biofuel conversion efficiency. Carbon dot treatments significantly enhanced phosphorus assimilation by 95-160% compared to conventional fertilization, with Q-arbolina reaching 1.29 g/kg and D-arbolina achieving 1.72 g/kg dry weight versus control values of 0.66 g/kg. The Q-702010 treatment showed the highest bioenergetic optimization, with nitrogen content of 23.92 g/kg dry weight and superior potassium uptake of 33.12 g/kg. Digestate treatments demonstrated superior sustainability metrics while maintaining competitive nutritional profiles, with digestate alone achieving 1.66 g/kg phosphorus content. The carbon dot-digestate combinations improved biofuel conversion parameters significantly, with Q-702010 achieving the highest ethanol potential of 411 L/t (7% increase over control) and superior calorific value of 18.4 MJ/kg. Estimated starch content increased from 68.5% in control to 73.2% in Q-702010 treatment, representing a 7% improvement in biofuel feedstock quality. Carbon dot nanotechnology combined with digestate fertilization represents a breakthrough approach for optimizing corn nutritional profiles in biofuel feedstock production. This sustainable strategy enhances key nutritional parameters while reducing dependence on synthetic fertilizers.

Keywords: carbon dots, nanofertilizers, digestate, corn nutrition, biofuel feedstock, sustainable agriculture, ethanol potential

DECIPHERING THE ROLE OF MIRNA-TARGET GENE MODULES IN THE CROSS-TALK BETWEEN BIOMASS PRODUCTION AND WATER DEFICIT IN THE MODEL POACEAE SETARIA ITALICA.

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In the context of climate change, abiotic stress events are becoming more frequent, impacting plant development and biomass production, ultimately affecting crop survival, yield, and biofuel productivity. Plants have evolved genetic mechanisms to regulate these responses, including post-transcriptional regulation by microRNAs (miRNAs). These short non-coding molecules regulate gene networks by forming miRNA–target gene modules, which are associated with several biological processes, including drought response. We identified miRNA–target modules related to biomass production under water deficit in *Setaria italica*, a drought-tolerant C4 grass with high water-use efficiency. *In silico* analyses were performed using Illumina small RNA and mRNA sequencing data from a water deficit experiment. We identified 171 mature miRNAs, including 15 conserved, 4 known, and 152 novel ones, mostly derived from intergenic (66%) and intronic (20%) regions. Expression analysis revealed 23 differentially expressed miRNAs, predominantly upregulated. A total of 3,271 target genes were predicted and functionally annotated using Mercator categories. Targets were mainly associated with pathways related to cell wall organization, carbohydrate metabolism, secondary metabolism, and redox homeostasis—highlighting genes such as cellulose synthases, sucrose-phosphate synthases, and phenylpropanoid-related enzymes. Seventeen categories were significantly overrepresented, including those involved in mRNA degradation (NOT11), histone methylation, and stress responses. Degradome sequencing validated 21 miRNA–target interactions, involving genes linked to redox regulation (superoxide dismutases), lipid degradation (phospholipase D), and transcriptional control (BBX transcription factors). Enrichment analysis confirmed these pathways as significantly overrepresented. Overall, our results suggest that miRNAs play key regulatory roles in biomass-related and stress-responsive pathways in *S. italica* under drought conditions.

Keywords: abiotic stress, monocots, post-transcriptional regulation, *Setaria italica*, drought

DETERMINING THE TRANSGRESSION LEVELS OF THE NATIONAL ENERGY SECTOR IN THE CONTEXT OF PLANETARY BOUNDARIES ASSESSMENT

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The Brazilian energy matrix is recognized for its high share of renewable sources. However, even clean energy sources generate environmental impacts, making it relevant to assess whether these effects remain within Earth's carrying capacity. This study quantifies the impact of the national energy sector based on the concept of Safe Operating Space (SOS), considering four planetary boundaries: climate change (short and long term), freshwater use, marine eutrophication, and land use. The methodological approach consisted of two stages. Initially, data from the SCP-HAT platform were used for downscaling, adjusting the national environmental footprint to the share attributable to the energy sector. Subsequently, upscaling was applied using the Gross Value Added (GVA), distributing the environmental limits in accordance with the sector's economic participation. The results indicate that the energy sector exceeds the planetary boundaries allocated for freshwater use by 884.39 times and for land use by 650.82 times. In contrast, CO₂ emissions remain within the established limits, with transgression indices of 0.20 and 0.37. Nitrogen deposition, however, presents a high index (14.96), indicating significant impacts. Despite the predominance of renewable sources, the data reveal substantial environmental challenges, particularly regarding the consumption of natural resources. Therefore, energy transition strategies and environmental management are essential to ensure long-term sustainability.

Keywords: Energy, Safe Operating Space, Planetary Boundaries

FROM MILL RESIDUES TO CLIMATE SOLUTIONS: REPURPOSING PULP AND PAPER INFRASTRUCTURE FOR BIOENERGY — A CASE STUDY OF CORNER BROOK PULP AND PAPER LTD.

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Fossil fuels have powered industrial growth for centuries but have become a primary driver of climate change, pollution, and biodiversity loss. As the shift to low-carbon energy accelerates to address this reality, bioenergy offers promise for hard-to-electrify sectors across the globe. This study assesses the environmental performance of four bark-based biofuels (biodiesel, bio-oil, syngas, and pellets) produced at Corner Brook Pulp and Paper Ltd. (CBPPL) in Newfoundland and Labrador, Canada. Using a Life Cycle Assessment, fossil fuel use was compared with scenarios where locally sourced bark is converted to biofuels using either electricity or bark as the conversion energy. Across multiple indicators, including global warming potential (GWP), all biofuels outperformed fossil fuels, with GWP reductions exceeding 80% in some cases. The findings demonstrate how repurposing existing industrial infrastructure with local biomass resources can accelerate biofuel adoption, lower costs, and deliver substantial climate benefits.

Keywords: biofuels; life cycle assessment; forestry residues; pulp and paper; greenhouse gas emissions; Newfoundland and Labrador, bioenergy

GREENHOUSE GAS EMISSIONS ASSESSMENT IN THE LIFE CYCLE OF BIOPOLYOL

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The valorization of agricultural and agro-industrial biomass residues has garnered attention from the chemical industry due to the rising costs of fossil-derived raw materials and increasing environmental pressure. This study quantifies the greenhouse gas (GHG) emissions across the life cycle of a biopolyol produced from cassava peel and crude glycerol via thermochemical liquefaction. The environmental impact was assessed under the global warming category using the GHG Protocol. Electricity consumption was identified as the main source of emissions, accounting for 99.46% of the total 22.92 kg CO_{2e} per kilogram of biopolyol. These results highlight the need for renewable energy integration to enhance the environmental viability of the process.

Keywords: Global warming; Environmental impact assessment; Lignocellulosic residues; Renewable polyols; Life cycle assessment

INTEGRATED TECHNO-ECONOMIC AND ENVIRONMENTAL EVALUATION OF FAST PYROLYSIS OF RAW AND DEFATTED SPENT COFFEE GROUNDS: A CASE STUDY IN BRAZIL

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In the context of Brazilian environmental policy, the circular economy model is regarded as a vital strategy for promoting sustainability. This model emphasizes the adoption of regenerative production practices, which aim to optimize resource utilization and minimize environmental impact. Coffee is one of the most important commodities in Brazil, consuming a higher percentual part of their production and generating a substantial amount of organic residue, known as Spent Coffee Grounds (SCG), which possesses considerable valorization potential, particularly through thermochemical processes. In this context, the present study evaluates two fast pyrolysis configurations of SCG from an economic and environmental perspective within the Brazilian context. The initial scenario involves the direct pyrolysis of the dry residue, while the second scenario involves a preliminary coffee oil extraction step using ethyl acetate as a green solvent. Both processes were modeled using *Aspen Plus* and evaluated from a life cycle assessment. The findings suggest that the pre-extraction oil scenario exhibited considerably higher economic viability and attained a first-year payback period. Conversely, the conventional scenario was deemed unviable across all evaluated interest rates. From an environmental perspective, both scenarios demonstrated a lower impact on climate change compared to the alternatives explored in the literature. However, the utilization of ethyl acetate has been observed to exert a more substantial impact on categories such as fossil resource depletion. In conclusion, the valorization of SCG through pyrolysis corresponds as a promising small-scale alternative, particularly when integrated with high-value products such as coffee oil.

Keywords: Fast-Pyrolysis, Coffee Oil Extraction, Waste-Valorisation, Circular Economy, Bioeconomy, Spent-Coffee-Grounds.

INTEGRATION OF DIGESTATE IN ENERGY CROP PRODUCTION: A REVIEW OF OPPORTUNITIES FOR SUSTAINABLE AGROENERGY SYSTEMS

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The integration of digestate in energy crop production represents a promising approach toward sustainable agroenergy systems that optimize resource utilization while addressing environmental and economic challenges. This comprehensive review analyzes opportunities and challenges associated with using digestate from cattle manure as fertilizer for energy crop production, based on systematic literature analysis from 2019-2024. The study reveals that digestate presents nutritional composition with 3.5-5.2 kg N/m³, 1.8-2.9 kg P₂O₅/m³, and 2.5-4.1 kg K₂O/m³, with biomass productivity responses varying significantly by climate conditions (15-35% increases compared to conventional fertilization). Integrated systems demonstrate energy efficiency of 79-92% with Energy Return on Investment (EROI) ratios ranging from 25:1 to 50:1 depending on system boundaries and methodological approaches. Environmental benefits include nutrient circularity potential, reduced synthetic fertilizer dependence, and CO₂ emission reductions of 1.8-4.2 t/ha annually. Carbon sequestration rates vary considerably with soil and climate conditions (0.7-1.8 t C/ha/year). Economic viability shows regional variation with Net Present Values ranging from R\$ 1,750-3,800/ha and payback periods of 4.2-6.8 years. Brazil's theoretical potential for digestate production reaches 850-1,200 million m³/year, though practical implementation faces logistical, regulatory, and technical constraints. The technology demonstrates significant potential but requires careful consideration of regional specificities, methodological consistency in assessment approaches, and coordinated policy development for successful implementation.

Keywords: Digestate, Bioenergy, Energy crops, Sustainability, Circular economy

KRAFT LIGNIN DEPOLYMERIZATION BY FENTON PROCESS ASSISTED BY HYDRODYNAMIC CAVITATION

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Lignin is a highly branched and poorly biodegradable macromolecule, largely produced as a byproduct of the pulp and paper industry. Wastewater containing lignin typically exhibits high chemical oxygen demand (COD), posing a threat to aquatic ecosystems. As an alternative treatment, lignin-rich effluents can undergo Advanced Oxidation Technologies (AOTs), such as the Fenton reaction, which involves hydrogen peroxide (H₂O₂) and iron ions. In this study, a Box-Behnken 2³ experimental design was applied to optimize lignin degradation using Fenton processes assisted by hydrodynamic cavitation. Reactions were carried out in a batch reactor (V = 2.5 L), and a kinetic study was performed to evaluate the process efficiency. Results demonstrated that the AOT assisted by hydrodynamic cavitation was highly effective in lignin depolymerization. A quadratic model for lignin concentration (mg/L) showed a correlation coefficient (R²) of 0.918, indicating strong predictive accuracy. Under optimized conditions ([Fe³⁺] = 25.0 mM, [H₂O₂] = 272.9 mM, P = 1.78 atm), 98% lignin conversion was achieved within 2 hours. The chemical structures of the resulting products were analyzed using pyrolysis coupled with gas chromatography–mass spectrometry (Py-GC/MS), identifying monomers and dimers such as benzyl alcohol, guaiacol, 2-methoxy-4-methylphenol, vanillic acid, and syringaldehyde. Furthermore, *Pseudomonas putida* showed growth in culture medium supplemented with low-aromatic-weight lignin molecules after depolymerization, indicating potential for subsequent biotechnological applications

Keywords: Lignin depolymerization, Advanced Oxidation Technologies, Hydrodynamic cavitation, Lignin valorization, *P. putida*

MATHEMATICAL MODELING OF ENZYMATIC OXIDATION OF ABTS BY LACCASE: EFFECTS OF SUBSTRATE AND ENZYME CONCENTRATION, AND PH

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Introduction: Laccases are multicopper enzymes that catalyze the oxidation of phenolic compounds. The oxidation of the substrate ABTS by laccase is used both to measure enzymatic activity and for potential applications in lignin oxidation. This is because the radical formed can oxidize non-phenolic structures in lignin, which is relevant for biomass pretreatment aimed at obtaining value-added products. **Objective:** This study aimed to evaluate the effects of ABTS concentration, Trametes versicolor laccase enzyme concentration, and pH on the ABTS oxidation rate. **Methods:** A full factorial design 2³ was conducted with the factors: ABTS concentration (1 or 2 mM), enzyme concentration (467 or 933 ng/mL), and pH (4.0 or 5.0). Mathematical modeling used a first-order model, considering statistical significance at $p < 0.05$ for coefficients. **Results and Discussion:** Results showed that all three factors significantly influenced the oxidation, with enzyme concentration having the greatest positive effect, followed by ABTS concentration (also positive), and pH (negative effect). The interaction between enzyme and ABTS concentrations was also significant and positive. A curvature test indicated the linear model was initially inadequate to describe the oxidation rate. However, after transforming the response by inverting enzymatic activity, the model fit correctly, removing curvature. **Conclusion:** ABTS oxidation by laccase can be linearly modeled within the studied experimental range, provided that the response variable is the inverse of enzymatic activity.

Keywords: Enzymology, Design of Experiments, Linear model

MAXIMIZING BIOHYDROGEN PRODUCTION BY *Escherichia coli* THROUGH DARK FERMENTATION: THE IMPLEMENTATION OF COMPUTATIONAL METHODS FOR METABOLIC ENGINEERING STUDIES

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The current global socioeconomic context, driven by the use of fossil fuels, has led to significant environmental impacts and an increasingly frequent occurrence of climate change effects. Given this, among the existing alternatives for clean energy generation, biohydrogen production stands out, derived from dark fermentation carried out by bacteria on residual biomass. The three principal metabolic pathways involved in hydrogen production through dark fermentation are well established and thoroughly characterized. Accordingly, using the genome-scale metabolic model of the bacterium *Escherichia coli* (iJO1366) and metabolic engineering simulations in the Python programming language, we aimed to maximize H₂ production by the bacterium through modifications in the fermentative pathways described in the literature. Regarding the formate hydrogen lyase (FHL) pathway, the analyses resulted in a set of enzymatic knockouts responsible for an H₂ yield of 4.23166 mol/mol of glucose consumed and a biomass concentration of 3.10798 g/L. Conversely, by introducing the NAD(P)H:ferredoxin oxidoreductase (NFOR) pathway into the model and inducing an increase in intracellular NADH production, we identified a yield of 6.84 mol H₂ per mol of glucose consumed, four times higher than that observed in the wild-type model (1.66 mol H₂/mol glucose), along with a biomass concentration of 3.08735 g/L. Thus, the computational analyses reinforce the potential of recombinant *E. coli* in biohydrogen synthesis, either through the bacterium's native pathway (FHL) or the introduced pathway (NFOR), serving as a foundation for in vitro experiments aimed at high-rate biofuel production.

Keywords: bioinformatics, biohydrogen, *Escherichia coli*, metabolic engineering

MENTAL HEALTH AND SUSTAINABILITY CULTURE

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Brazil, as a global leader in several fields, including bioeconomy, has developed a healthy economic and policy framework to promote sustainability. This paper aims to focus on the paradoxical and underexplored consequence of this national emphasis, which is the creation of a digitally mediated culture of sustainability that significantly impacts students' mental health. While the success of the Brazilian bioenergy program is irrefutable, its public-facing account on social media has indirectly cultivated a new form of psychological pressure. The prevalent influence of several social media platforms has transformed sustainability, which was supposed to be a set of practices, into a public performance for the highest "like" bidder. This behavior creates a "digital marketplace" in which students feel obliged to demonstrate their eco-consciousness. This expectation generates a profound dissonance for students who ought to be navigating the demanding academic environments. The flawless "green" personas they are overstretched to project in online environments are often at odds with the realities of their daily lives, which may leave little to no time or resources for such activities. Academic literature, unfortunately and unswervingly, displays a high prevalence of mental health issues, including anxiety and depression, among university students. The media-driven pressure to be continually "environmentally nice" and "green" adds a new layer of stress, contributing to what can be labelled as a social burnout. The same policies and market trends that position Brazil as an environmental leader contribute to a social climate where students feel compelled to adopt a sometimes unsustainable lifestyle of constant digital performance.

Keywords: Mental health, sustainability, environmental health education, environmental behavior

POTENTIAL OF BY-PRODUCTS FROM PULP AND PAPER INDUSTRY FOR LOCAL FOOD PRODUCTION THROUGH GREENHOUSE FARMING IN NEWFOUNDLAND AND LABRADOR (NL)

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The pulp and paper industry generates significant by-products, including waste heat, paper mill sludge, wood ash, biochar, and carbon dioxide (CO₂), which are often discarded. This study examines the potential of repurposing these by-products from Corner Brook Pulp and Paper Limited (CBPPL) in Newfoundland and Labrador (NL) to enhance local food production through greenhouse farming. By incorporating by-products into greenhouse operations, the research evaluates their role in improving food security, reducing environmental impact, and advancing sustainable agriculture. Using a qualitative case study approach, the study highlights the environmental, economic, and agricultural benefits of by-product utilization. Key findings indicate that these by-products can significantly lower greenhouse gas emissions, improve soil quality, increase crop yields, and reduce operational costs. Additionally, consumer perspectives also indicate a strong preference for locally grown, sustainable greenhouse produce through by-product use, though affordability remains a concern. Critical success factors include access to resources, financing, and stakeholder collaboration. While the study acknowledges some limitations, such as the inability to assess operational greenhouses using by-products in NL directly, it offers valuable insights for policy and further research. Recommendations emphasize prioritizing low-cost application technologies, long-term soil health impacts, and enhancing waste stream efficiency. Overall, this research demonstrates how industrial by-products can promote circular economy principles, reduce waste, and reinforce local food systems.

Keywords: Biomass, By-products, Excess heat, Greenhouse Production, Newfoundland and Labrador, Forestry.

OPTIMIZATION OF THE SAF SUPPLY CHAIN VIA THE ATJ ROUTE: A TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT IN BRAZIL USING SUGARCANE, CORN, AND AGAVE BIOMASS

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The growing need to decarbonise the aviation sector has driven the development of sustainable aviation fuels (SAFs) produced from renewable feedstocks. This study presents a mixed integer linear programming (MILP)-based optimisation model for the technical, economic, and environmental design of SAF production from various feedstocks. The optimisation-based model implemented in Lingo Software incorporates variables related to mass and energy balances, greenhouse gas emissions, investment and operating costs, and availability and demand constraints. As a case study, the implementation of the system in a regional Brazilian context is analysed, with different biomass resources for ethanol production and ATJ plants. The results show that all of the analysed plants were able to meet the target demand of 5.24 Mt of SAF using available biomass potential. In economic terms, the corn-based plant was the most profitable, with an internal rate of return (IRR) of 52% and the shortest payback time (2.16 years), although it also had the highest Raw Material Cost (7,373 MUSD). The sugarcane plant achieved the highest net present value (NPV) at an interest rate of 8%, at 35,385 MUSD. Meanwhile, the agave option was positioned as a balanced alternative in terms of investment, costs and return, with high expansion potential. From an environmental perspective, the sugarcane plant recorded the lowest net emissions (0.5826 tCO₂/t SAF), representing an 81.5% reduction compared to fossil fuels. By contrast, reductions of 39.2% and 21.8% were observed for agave- and corn-derived SAF, respectively.

Keywords: Biomass, Energy, Ethanol, Mixed-integer linear programming, Sustainability, Renewable fuel.

RECOVERY OF CASSAVA WASTE FOR THE GENERATION OF BIOPRODUCTS AND BIOENERGY: A REVIEW

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In this study we present a review with trends analysis and interpretation data of 72 articles indexed in the Scopus database, investigating the treatments applied to cassava waste for the production of bioproducts and bioenergy, highlighting their importance for the bioeconomy and sustainability. The results indicate that methods such as fermentation, anaerobic digestion, enzymatic hydrolysis, and briquetting are the most used treatments for converting waste into products like ethanol, biogas, and briquettes. The bibliometric analysis revealed continuous growth in publications on the topic, with a higher concentration of studies in China, Thailand, and Brazil. These countries were found to lead research on bioenergy using cassava due to public policies and investments in sustainable technologies. This bibliometric analysis shows that the recovery of cassava waste is a viable alternative for promoting more sustainable industrial practices, contributing to the circular economy and the reduction of environmental impacts of agricultural systems.

Keywords: Bioeconomy, biogas, crop residues, energy efficiency

SUSTAINABLE ETHANOL DEHYDRATION: CHOLINE CHLORIDE-BASED DEEP EUTECTIC SOLVENTS

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Anhydrous ethanol plays a key role in the global energy transition due to its renewable nature and reduced greenhouse gas emissions. While conventional processes rely on monoethylene glycol (MEG) for extractive distillation, deep eutectic solvents (DESs), such as choline chloride:glycerol (ChCl:G), have emerged as greener alternatives due to their low cost, biodegradability, and low volatility. This study proposes the simulation and optimization of an industrial-scale ethanol dehydration process using ChCl:G as entrainer, employing Aspen Plus® coupled with artificial neural network (ANN) optimization. Thermophysical properties of ChCl:G were regressed from experimental data using DIPPR and IK-CAPE models. Moreover, vapor-liquid equilibrium (VLE) were modeled with the Non-random two-liquid (NRTL) model, based on binary interaction parameters obtained by data regression using Barker's modified method. Three configurations were simulated: a base case process with MEG, and two alternatives with ChCl:G—one under atmospheric pressure and another under vacuum conditions. The vacuum-assisted ChCl:G process achieved 16.0% and 66.7% lower energy and solvent flowrate consumption, respectively, as well as 20% lower CO₂ emissions compared to the MEG-based process. Dynamic control using PID regulators showed fast and stable responses to disturbances, validating the operational robustness of the proposed process. In conclusion, ChCl:G offers a promising, sustainable alternative for ethanol dehydration, though challenges in solvent recovery and large-scale cost still need to be addressed for industrial deployment.

Keywords: Anhydrous ethanol; Deep eutectic solvent (DES); Extractive distillation; Aspen Plus®

TECHNICAL-SCIENTIFIC ASSESSMENT OF DARK FERMENTATION TECHNOLOGY FOR HYDROGEN PRODUCTION

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In the current global context of energy transition, hydrogen gas can be a compelling solution to the use of fossil fuels. One of the most promising production methods is dark fermentation, in which anaerobic bacteria decompose lignocellulosic waste. The objective of this work is to present a technical-scientific assessment of the subject. The research was conducted using the Web of Science® and CAS SciFinder® databases. The methodology for the bibliometric analysis was the Methodi Ordinatio, followed by the use of VOSviewer® software. The results indicated that China is the leading country in both scientific research and innovation in this area. The contributions of India and South Korea are also noteworthy. The successful use of various lignocellulosic substrates for hydrogen production, such as rice straw and ground coffee beans, is also observed. However, studies are still conducted only on a bench scale. Dark fermentation technology remains in the technology readiness level 3-4; however, the recent creation of public policies to encourage hydrogen production may boost research and innovation in the field.

Keywords: Circular Economy; Bibliometric Review; Technological Prospecting; Waste-to-energy.

TECHNO-ECONOMIC AND ENVIRONMENTAL OPTIMIZATION OF RENEWABLE HYDROGEN PRODUCTION AND SUPPLY CHAIN FOR OIL REFINING: A CASE STUDY

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This study assessed the technical, economic and environmental feasibility of four technologies for producing renewable hydrogen for use in refineries. The technologies analyzed were ethanol steam reforming (Ethanol_ESR), proton exchange membrane electrolysis (PEM_electrolysis), biomethane reforming of vinasse (Vinhaça_BD_SMR) and wood gasification (GS_WGS). Mixed Integer Linear Programming (MILP) was used to optimize costs and identify the most advantageous alternative. The results indicated that the routes based on biomass and waste (GS_WGS and Vinhaça_BD_SMR) were more economically competitive, with an internal rate of return (IRR) of over 35%, a payback time of 3 years and hydrogen sales prices close to those of gray hydrogen. In contrast, the Ethanol_ESR and PEM_electrolysis technologies faced greater economic challenges. Electrolysis had the highest initial investment and the lowest IRR (9%), with a payback of 14 years. Ethanol_ESR, on the other hand, despite the lower investment, had its performance affected by the high cost of the raw material, resulting in a payback of 7 years. The sensitivity analysis showed that the waste-based routes are less vulnerable to variations in return and sales price. In environmental terms, all the routes showed a negative balance of emissions, with around -462,014.08 tCO₂eq/year, and reduced emissions by more than 60% compared to grey hydrogen, reinforcing their potential for decarbonization and the energy transition. It is concluded that the valorization of agro-industrial waste and the use of biomass are promising strategies for the sustainable production of hydrogen in refineries.

Keywords: Sustainability Emissions Life cycle assessment Economic feasibility

TECHNICAL-ECONOMIC VIABILITY OF NEW GENERATION OF ETHANOL FROM CO₂ IN SUGARCANE BIOREFINERIES

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The pursuit of alternatives providing financial returns and reducing carbon footprint is a major goal for biorefineries. Bioenergy with Carbon Capture and Utilization (BECCU) can transform fermentation CO₂ into additional ethanol and decarbonization credits. This study assesses the electrocatalytic conversion of biogenic CO₂ into fifth-generation ethanol (E5G) in sugarcane biorefineries, integrating production data, techno-economic modeling, and breakeven analysis. Electrocatalysis achieves conversion efficiencies of 40–60%, with favorable cost–benefit outcomes when combined with carbon credit revenues. Results indicate a potential reduction of over 28 GgCO₂ year^{−1} in Brazilian carbon footprint and a revenue increment around 1.5 billion BRL year^{−1}. BECCU is strategic for advancing bioeconomy innovation, contributing to decarbonization targets and climate commitments through circular economy opportunities.

Keywords: circular economy; biogenic CO₂; distilleries; BECCU; E5G

TECHNO-ECONOMIC ASSESSMENT OF BIOENERGY WITH CARBON CAPTURE AND STORAGE FOR BRAZILIAN THERMOELECTRIC POWER PLANTS

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To achieve near-zero carbon emissions in fossil-fueled power plants, one of the viable solutions is to use bioenergy along with carbon capture and storage (BECCS) for the thermoelectric sector in Brazil. This study is conducted to carry out techno-economic assessments for pulverized coal (PC) and natural gas combined cycle (NGCC) power plants by employing BECCS. A comparative analysis of these technologies is presented, followed by the incorporation of carbon capture and storage (CCS) while using bioresources as fuel feedstock for PC and NGCC power plants. The Integrated Environmental Control Model (IECM) software is used to perform the techno-economic assessments, enabling the selection of various operating specifications and the estimation of preliminary environmental, economic, and technical performance parameters for thermoelectric power plants. The retrofitting of CCS technology is then considered, using bioresource-derived fuels for PC and NGCC plants. CCS technologies are selected based on their technology readiness level (TRL). The tool also facilitates emissions assessment and sensitivity analysis. The results include the levelized cost of electricity (LCOE in \$/MWh), the cost of CO₂ captured (\$/tCO₂), and the cost of CO₂ avoided (\$/tCO₂). A sensitivity analysis is conducted to reveal the impact of changes in capacity factor, CO₂ removal efficiency, and fuel prices. The most influential parameters affecting these costs are identified through comparative analysis. This study attempts to evaluate the viability of BECCS due to its environmental and economic benefits for existing power plants in Brazil, meanwhile, emphasizing on technology readiness level (TRL) and the competitiveness of renewable energy technologies.

Keywords: Power Plants; CCS; Bioenergy; IECM; Sensitivity Analysis.

THE INFLUENCE OF SAMPLE PREPARATION OF NON-CONVENTIONAL BIOMASSES AND THEIR BASIC ENERGY PROPERTIES

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Biomass quality can be a parameter for companies to define purchase and sale prices. The objective of this project was to analyze the influence of biomass sample preparation on the results of energy property tests. For this study, stump biomass of *Eucalyptus urophylla* × *E. grandis* was used. The material was quartered and dried in an oven. For particle size reduction, a shredder and a knife mill were used. Four sample preparation treatments were conducted: two focused on high quality, including reprocessing to maximize yield (HQ20 and HQ60, using 20 and 60 mesh sieves); and two focused on high production, with less reprocessing and higher final yield (HP20 and HP60, also using 20 and 60 mesh sieves). In all samples, the higher heating value (HHV), ash content (AC), volatile matter content (VM), and fixed carbon content (FC) were determined. Higher FC values were observed in treatments HP20 (20.2%) and HQ60 (20%). Regarding AC, treatments HP20 and HP60 showed values of 5.8% and 10.8%, respectively, which were lower compared to the other treatments HQ20 (20%) and HQ60 (25.5%). It was found that HQ20 had an HHV of 4250 kcal/kg, higher and statistically different from the others, which showed lower values: HQ60 (3800 kcal/kg), HP60 (3600 kcal/kg), and HP20 (4000 kcal/kg). It was observed that repeated handling increased the heating value, which could be more beneficial for companies in terms of greater material yield.

Keywords: sampling, yield, time, agility and quality

VACUUM-ASSISTED GAS STRIPPING APPLIED TO EXTRACTIVE FERMENTATION FOR BIOETHANOL PRODUCTION FROM SORGHUM

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Ethanol is the most widely used liquid biofuel for transportation, either as a standalone fuel or as a gasoline additive to enhance octane ratings. Brazil is the world's second-largest bioethanol producer, accounting for 28% of global output (118 billion liters) in the 2024 harvest. Among conventional crops, grain sorghum is a starch-rich cereal similar to corn and well-suited for bioethanol production. It offers agronomic advantages such as adaptability to different soils and climates, efficient water use, and strong drought tolerance. Despite being well-established industrially, ethanol fermentation is limited by the toxic effect of ethanol on yeast, resulting in wines with low alcohol content. Extractive fermentation can reduce the inhibitory effects of ethanol on yeast cells by continuously removing ethanol as it is produced, which can significantly enhance ethanol productivity during the fermentation of sorghum hydrolysates. The present study describes the modeling and experimental validation of ethanol production in separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF) processes using vacuum-assisted gas stripping for ethanol removal. Initially, kinetic parameters for saccharification and fermentation were determined individually. Finally, both SHF and SSF assays with ethanol removal were performed in a 2-liter bubble column bioreactor. The proposed model for SHF and SSF processes, based on mass balances for liquefied starch, glucose, and ethanol, demonstrated excellent fit to the experimental data for both conventional and extractive fermentations. Furthermore, the extractive fermentations demonstrated superior performance compared to conventional methods, achieving ethanol productivity values up to 60% higher.

Keywords: Bioethanol from sorghum; extractive fermentation; gas stripping; vacuum; integrated process.

The image features a background of industrial biogas production equipment, including large metal pipes and valves. A semi-transparent green circular overlay is centered on the image. The word "Biogas" is written in large, bold, white letters across the center of the green circle. In the background, there are labels on the equipment: "offen" (open) on a valve handle and "Biogas" with an upward arrow on a pipe. The overall scene is outdoors, with a building and trees visible in the background.

Biogas

A PILOT-SCALE BIOGAS PRODUCTION FOR RURAL COMMUNITIES IN GUYANA

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Guyana is undergoing a transformative shift following the recent discovery of fossil fuel reserves. However, to mitigate the risks associated with oil price volatility and the resource curse, the country must diversify its energy matrix while addressing sustainability challenges. Biogas presents an attractive solution, particularly for rural communities in Guyana, by simultaneously tackling the issues of energy security and waste management. The present study aims at carrying out an experimental evaluation of a pilot scale biogas production facility for households in interior Guyana by using animal manure. The experiments were conducted to produce biogas using locally available waste. A 1000-liter capacity tank was used to process 500-liters of animal manure as the primary feedstock. The manure was mixed with water to form slurry, which was then sealed and left for 30 days under anaerobic conditions to enable biogas generation. The resulting gas was purified by passing it through a series of chambers to increase its methane concentration. This process yielded a total of 18.45 m³ of purified methane. The gas was then utilized in an engine equipped with a tri-fuel kit installed near the facility. These results demonstrate the potential of biogas production for rural energy needs in Guyana. However, the study relied on a single source of feedstock—the Guyana Livestock Development Authority—highlighting the opportunity to expand the initiative by incorporating additional waste sources. The findings of the study demonstrated promising results for biogas production at the facility. However, the production rate could be enhanced by incorporating larger storage facility.

Keywords: Rural communities, Biogas, Animal manure, Guyana,

ANAEROBIC BIODIGESTION IN SWINE FARMING IN BRAZIL: OVERVIEW OF WASTEWATER TREATMENT PRACTICES AND APPLIED STATISTICAL MODELING

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Efficient management of swine waste is essential to reduce environmental impacts and improve energy recovery. This study assessed the current state of wastewater treatment in swine farms in the region of Pará de Minas, Minas Gerais, Brazil, and proposed statistical models to support the operational control of anaerobic digesters. Six farms were surveyed to characterize their treatment systems, with emphasis on the use of biodigesters as a sustainable solution. In a subsequent phase, a laboratory-scale experiment was conducted to analyze correlations between process parameters and develop predictive models. Results indicated a significant potential to expand biogas production in the region by increasing the number of biodigesters and improving the performance of existing systems. However, technological investments are required to support small-scale operations, enhance process control, and increase the efficiency of both wastewater treatment and biogas generation. Among the models tested, the pH vs IA/PA model demonstrated the best performance, with residuals below 1 and full compliance with statistical assumptions. Conversely, the pH vs SP model showed limitations due to non-normality of residuals and smaller sample size. These findings underscore the importance of tailoring models to specific contexts by incorporating additional variables and adopting more robust statistical approaches. The proposed methodology offers a replicable strategy for improving digester monitoring and control, contributing to greater energy efficiency and environmental sustainability in swine production systems.

Keywords: Biogas; Agricultural Waste; Process Control

ANALYSIS AND SIMULATION OF HYDROGEN PRODUCTION FROM BIOGAS THROUGH THE COUPLING OF DRY REFORMING AND WATER-GAS SHIFT REACTORS

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Conventional H₂ production occurs through methane steam reforming (SMR), which uses CH₄ from natural gas and H₂O, generating CO and H₂, followed by the water-gas shift reaction that aims to increase H₂ production. Biogas, abundant in Brazil, stands out as a renewable source of CH₄. From it, dry reforming (DRM) can be adopted, converting CH₄ and CO₂, both major components of biogas, into CO and H₂, but with lower yield than the conventional route. Thus, this work aimed to define a technological route based on the sequential coupling of DRM and WGS reactors for the conversion of biogas into a syngas rich in H₂. For this purpose, a process flow diagram was developed, also incorporating equipment such as heat exchangers, compressors, and separators, and the process was evaluated based on the results of mass and energy balances using AVEVA Process Simulation software. The results were assessed for different reactor temperatures of DRM (800–1200 K) and WGS (550–900 K) in terms of CH₄ conversion, H₂ yield, and CO₂ emission. The results showed that the best temperature combination for the reactors is 1200 and 593 K for DRM and WGS, respectively, at which a 90% conversion of CH₄ is achieved, a production of 0.2 kg H₂/Sm³ biogas, and a mass ratio of 7.8 between emitted CO₂ and produced H₂, demonstrating that at least 1 kg of CO₂/kg H₂ must be captured for it to be considered renewable low-carbon H₂.

Keywords: CO₂ emissions; Hydrogen Production; Methane Reforming;

ASSESSMENT OF BIOGAS PRODUCTION POTENTIAL FROM FERMENTATION EFFLUENT

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Driven by the pursuit of sustainability, the reuse of effluents through anaerobic digestion stands out for producing biogas and reducing the pollutant load of wastes. This study aimed to evaluate the Biochemical Methane Potential (BMP) of an effluent generated during the fermentative process to produce mycelium for human consumption, a residue source scarcely explored as a substrate for anaerobic digestion. The effluent is rich in organic matter and nutrients, resulting from fermentation, and shows promising potential for biogas generation. Initially, the effluent was characterized for chemical oxygen demand (COD), biochemical oxygen demand (BOD), total solids (TS), volatile solids (VS), and pH. The inoculum, sludge from an anaerobic reactor, was acclimated at 37°C for 4 days. BMP assays were conducted in triplicate, in 500 mL anaerobic reactors, sealed, considering 30% of the headspace for biogas accumulation. The inoculum-to-substrate ratio was set based on literature references, adopting a VS substrate/VS inoculum ratio of 0.5. The reactors were connected to bottles containing 15% NaOH solution to capture CO₂, allowing indirect methane quantification by volume displacement. After internal pressure stabilization, biogas was measured for 40 days under mesophilic conditions (37°C). Results indicated a BMP of 17.7 ± 4.5 mL CH₄/g VS, already corrected by the negative control (biogas production only from the inoculum), highlighting the effluent's potential for biogas generation via anaerobic digestion. Despite moderate variation among bottles, the observed performance also underscores this process as a sustainable alternative for residue treatment, aligned with sustainability principles and the circular economy.

Keywords: Biochemical Potential of Methane; Biogas; Fermentative effluent; Anaerobic digestion

BIOFILTERS WITH NATURAL MATERIALS: FOR HYDROGEN SULFIDE REMOVAL FROM BIOGAS

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Anaerobic digestion of residual biomass is a sustainable alternative for treating organic waste and generating clean energy through biogas, which consists mainly of methane and carbon dioxide, along with impurities such as hydrogen sulfide (H₂S), whose removal is necessary for safe and efficient use. Biological desulfurization has gained interest as an alternative for H₂S removal due to its simplicity, scalability, low cost, and minimal environmental impact. In this context, the present study aimed to develop and test a biofilter prototype using *Luffa cylindrica* as a support medium. The system was installed at the University of Vale do Taquari (Univates) and operated for seven days, during which 13.5 m³ of biogas were treated. The biogas composition was monitored with hourly readings at the inlet and outlet of the system, enabling the assessment of desulfurization efficiency. The biofilter showed satisfactory performance in H₂S removal, with average efficiencies ranging from 60–90% and a maximum of 100%, exhibiting initial fluctuations attributed to the adaptation process and microbial colonization of the support medium. From the fifth day onward, a progressive stabilization of efficiency was observed, with lower H₂S concentrations during nighttime periods, possibly related to environmental variations, such as temperature or light, which influence microbial activity and the contaminant removal rate. The prototype demonstrated satisfactory performance, proving the feasibility of using *Luffa cylindrica* in biofilters for biogas desulfurization and indicating that future studies with longer operational periods and detailed environmental and microbiological analyses are needed to optimize performance and process stability on a larger scale.

Keywords: Biogas. Biological desulfurization. Biofilter. *Luffa cylindrica*.

BLACKWATER AS FRESHWATER SUBSTITUTE FOR CATTLE MANURE ANAEROBIC DIGESTION IN BRAZILIAN SEMI-ARID REGIONS: BIOGAS PRODUCTION, BIOFERTILIZER APPLICATION, AND WATER CONSERVATION

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Water scarcity severely constrains biogas production in Brazil's semi-arid regions (approx. 1.03 million km²), where conventional anaerobic digestion demands substantial freshwater. This study evaluated substituting freshwater with pre-treated blackwater for cattle manure anaerobic digestion, assessing its technical feasibility and resource recovery potential. Blackwater and cattle manure were sourced from small rural properties in semi-arid Pernambuco, Brazil. Bench-scale reactors (350 mL) operated mesophilically (36±2°C) over 76 days, testing four blackwater dilution ratios (25%, 50%, 75%, 100% v/v). Biogas production kinetics were analyzed using the modified Gompertz model. Optimal blackwater (50% v/v) achieved a 45% methane increase, reaching 312.4 mL CH₄ g⁻¹ VS. The maximum biogas potential observed was 1,581.7 mL g⁻¹ VS with 25% blackwater addition. Digestate showed enhanced nutritional profiles (N: 560.0 mg L⁻¹ TKN; K: 89.6 mg L⁻¹), suitable for agriculture, with heavy metal levels within WHO limits. This approach yielded substantial water savings (8-10 L/kg processed manure) while maintaining comparable biogas yields. These findings highlight a viable decentralized waste management for 23 million inhabitants facing chronic water stress, providing nutrient-rich biofertilizer (optimal C:N 15-18:1). The study promotes energy security, water conservation, and circular economy principles, with scaling potential across 1,262 municipalities in Brazil's semi-arid polygon, aligning with SDGs.

Keywords: Anaerobic co-digestion, Biogas production, Biofertilizer, Water conservation, Semi-arid regions.

DEVELOPMENT AND EVALUATION OF A PROTOTYPE FOR THE REMOVAL OF CARBON DIOXIDE (CO₂) AND HYDROGEN SULFIDE (H₂S) FROM BIOGAS USING MICROALGAE

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This study describes the development and evaluation of a pilot-scale prototype, operated continuously, designed to integrate microalgae cultivation with biogas purification. The system was built and tested at the Center for Research in Sustainable Energy and Technologies (CPETS/Univates) aiming to simultaneously remove CO₂ and H₂S, contaminants that limit the energetic application of biogas. Microalgal cultivation was found to be feasible, with growth observed after an initial adaptation period. The results indicated high efficiency and stability in H₂S removal, with an average efficiency of $98.9 \pm 1.3\%$, maintaining residual concentrations below 30 ppm in the treated biogas. CO₂ removal was moderate and variable, averaging $41.3 \pm 13.6\%$, influenced by factors such as pH, alkalinity, and aeration regime, but sufficient to promote an increase in CH₄ content, which reached up to 82.5%. The system demonstrated robustness under environmental and thermal fluctuations, preserving operational stability. Thus, the developed and tested prototype confirmed its technical feasibility and represents a promising platform for future studies and large-scale applications.

Keywords: Bioenergy. Biogas. Biogas purification. Microalgae. Photobioreactor.

EFFECT OF MICROALGAE SUPPLEMENTATION ON THE BIOENERGY POTENTIAL OF INDUSTRIAL SLUDGE

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Anaerobic digestion of industrial waste represents a promising strategy for energy recovery through the production of biogas, a renewable energy source that also contributes to the management of organic waste. The addition of biomass as co-substrates has proven to be potentially effective in optimizing the process. In this context, can microalgal biomass be potentially effective in optimizing the process? This study aimed to evaluate the biogas and methane yields resulting from the anaerobic digestion of industrial sludge, with and without the supplementation of 7% microalgae. The experiments were conducted at the Research Center for Energy and Sustainable Technologies (CPETS) of the University of Vale do Taquari, located in Lajeado, Rio Grande do Sul, Brazil. An automated system was used to monitor the volume of biogas produced. The substrate-to-inoculum ratio was established based on the physicochemical characterization of the samples (TS and VS), in accordance with the technical standard VDI 4630 (2006). The average biogas yields were $183.53 \pm 14.90 \text{ m}^3 \cdot \text{t}^{-1}$ for industrial sludge (IS) and $230.83 \pm 17.14 \text{ m}^3 \cdot \text{t}^{-1}$ for sludge supplemented with microalgae (IS+MA). For methane, the yields were $132.50 \pm 7.09 \text{ m}^3 \cdot \text{t}^{-1}$ (IS) and $160.45 \pm 9.28 \text{ m}^3 \cdot \text{t}^{-1}$ (IS+MA). The results show increases of 25.79% in biogas production and 21.09% in methane generation with the addition of microalgae, highlighting its potential as a complementary strategy in the bioenergy conversion of industrial waste.

Keywords: Biogas; Anaerobic digestion; Sustainable solutions.

EVALUATION OF ELECTROOXIDATION AS A PRETREATMENT FOR LIGNIN EXTRACTED FROM SUGARCANE BAGASSE FOR APPLICATION IN ANAEROBIC DIGESTION.

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This study evaluated electrooxidation (EO) as a pretreatment strategy for lignin extracted from sugarcane bagasse, aiming at its application in anaerobic digestion for energy recovery. Lignin, a major structural component of lignocellulosic biomass, exhibits low biodegradability, hindering its biological conversion. EO was applied at varying current densities (20 to 60 mA cm⁻²) to promote depolymerization of lignin and enhance its microbial accessibility under anaerobic conditions. Results indicated that EO effectively solubilized lignin and released low-molecular-weight phenolic compounds and organic acids, improving its bioavailability for methanogenic consortia. BMP assays demonstrated that intermediate current densities (30–50 mA cm⁻²) provided the best balance between lignin depolymerization and microbial inhibition, leading to a significant increase in methane production compared to untreated lignin. Notably, the assay at 60 mA cm⁻² (L60) achieved the highest cumulative methane yield (343 mL), even surpassing the control reactor without lignin addition. Analysis of intermediate compounds confirmed the presence of potentially inhibitory molecules, such as vanillin and gallic acid; however, their concentrations remained below critical thresholds. These findings suggest that EO is a promising and scalable technique to improve lignin biodegradability, enabling its integration into bioenergy conversion processes. The application of EO can support the sustainable valorization of agro-industrial residues and enhance circular economy practices in the sugarcane industry.

Keywords: Biomethane; Phenolic compounds, Recalcitrant biomass, Biodegradability enhancement, Renewable energy.

EXPLORATORY DATA-DRIVEN ANALYSIS OF BLACKWATER-CATTLE MANURE CO-DIGESTION: KINETIC MODELING AND UNCERTAINTY QUANTIFICATION AT BENCH SCALE

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This study presents a comprehensive data-driven analysis of blackwater-assisted anaerobic digestion of cattle manure, focusing on process optimization and uncertainty quantification for semi-arid applications. Using statistical modeling and uncertainty analysis of experimental data from bench-scale reactors (350 mL), we evaluated the effects of blackwater dilution ratios (25%, 50%, 75%, and 100% v/v) on biogas production kinetics, digestate quality, and system performance. Modified Gompertz kinetic modeling revealed a favorable biogas yield of $1,582 \pm 373$ mL/g VS at 25% blackwater concentration, though with extended lag phase (17.0 ± 3.0 days) attributed to ammonia inhibition mechanisms. Monte Carlo simulations quantified parameter uncertainties, showing coefficient of variation ranging from 15-24% for kinetic parameters and identifying 15% underperformance risk for high-yield treatments. Multi-objective analysis suggested BW50 (50% blackwater) as optimal compromise considering biogas quality (Wobbe Index: 33.62 ± 1.86 MJ/m³), process stability (lag phase: 11.5 ± 1.6 days), and digestate safety. Heavy metal analysis revealed systematic nickel accumulation exceeding WHO agricultural guidelines (0.070 mg/L) at concentrations $\geq 75\%$ blackwater, with strong negative correlation to volatile solids reduction ($R^2 = 0.82$). The developed framework provides mechanistic insights for process control in decentralized anaerobic digestion systems, though validation at pilot and field scales remains essential before practical implementation.

Keywords: Anaerobic co-digestion; Process optimization; Kinetic modeling; Uncertainty analysis; Blackwater treatment; Biogas production

MEMBRANES VERSUS MEA IN LANDFILL BIOGAS CO₂ CAPTURE: A TECHNO-ECONOMIC AND ENVIRONMENTAL ASSESSMENT

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The pursuit of carbon-capture technologies that are both efficient and economically viable has gained traction across academic, scientific, and industrial sectors. Landfill biogas constitutes a valuable renewable resource; however, its high CO₂ content (exceeding 40%) limits direct energy utilization and market integration. This study provides a rigorous techno-economic and environmental evaluation of CO₂ capture from landfill biogas, comparing two prominent technologies: amine absorption (monoethanolamine, MEA) and separation by membrane. Simulation models were developed in Aspen HYSYS v.14, employing realistic conditions typical of Brazilian landfills and validated against the specialized literature, demonstrate that both systems achieve CO₂ removal efficiencies above 99%. Nonetheless, membrane-based configurations, despite their higher initial capital investment, exhibit lower operational costs and, environmentally speaking, consume less water and emit less CO₂ via boiler use for steam generation. These findings highlight the strategic positioning of membrane technologies for decentralized carbon-capture solutions in emerging economies, particularly for integrating biomethane production and gas-to-energy applications, alongside with informing public policy formulation and investment planning in low-carbon infrastructure aligned with the circular economy.

Keywords: Landfill biogas; Carbon capture; separation by membrane; MEA absorption; CCS

PERFORMANCE OF THE MICROALGA *Chlorella sorokiniana* IN CARBON DIOXIDE (CO₂) BIOFIXATION FOR BIOGAS PURIFICATION UNDER DIFFERENT AERATION PERIODS

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Anaerobic digestion of residual biomass represents an efficient strategy for managing organic waste, generating biogas as a coproduct of energetic interest. However, the presence of carbon dioxide (CO₂) compromises biogas quality, requiring purification steps for its valorization. Among the promising technologies, the use of microalgae in photosynthetic biofixation systems has emerged as a sustainable approach, offering low operational costs and the possibility of biomass reuse. This study aimed to evaluate the efficiency of the microalga *Chlorella sorokiniana* in removing CO₂ from biogas under different aeration periods, using an absorption column coupled to a photobioreactor. The experiment was conducted over 523 hours, with a total of 23,815 L of biogas processed in a continuous operation system, with real-time automated monitoring of raw and treated gas composition. The results demonstrated different removal efficiencies, with the T4 period (continuous aeration) showing the highest average CO₂ removal efficiency compared to the other periods. Additionally, microalgal biomass growth was observed throughout the study. The findings indicate that *Chlorella sorokiniana* holds potential as a biological method for biogas purification, and that future perspectives include operational adjustments and the valorization of microalgal biomass, contributing to the development of biotechnological solutions.

Keywords: CO₂ removal. Microalgae. Photobioreactor. Biological gas treatment. Bioenergy.

SIMULATION AND OPTIMIZATION OF A PSA PROCESS FOR BIOGAS UPGRADING: EFFECTS OF OPERATING CONDITIONS

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Biogas upgrading is a key step in the valorization of biogas, enabling the separation of methane from other components. The resulting biomethane is a renewable fuel with high energy value and applications equivalent to natural gas, supporting large-scale utilization. Pressure Swing Adsorption (PSA) is well-established technique for biogas upgrading into biomethane, achieving high purity and recovery rates under well-defined operating conditions. This study investigated the influence of operational parameters on methane purity and recovery in a PSA process operated under a four-step Skarstrom cycle (feed, equalization, desorption and equalization. The evaluated parameters were feed time (400-1000 s), equalization time (20-40 s), volumetric flow rate (500-700 SmL/min) and pressure adsorption (1-5 bar). The process employed two adsorption columns, each filled with 0.5 m of zeolite 13X as the adsorbent material, and feed composition 60:40 mol% (CH₄/CO₂). Using software gPROMS Process, all simulations were conducted using a dynamic model, which incorporated mass balances for the gas and solid phases, energy balances for the gas, solid, and column wall, a momentum balance for the gas phase, an equation of state, and an adsorption equilibrium isotherm. The results indicate operational conditions yielding methane purities of 90–100% and recoveries of 43–82%. According to ANP Resolution No. 8, which limits CO₂ to a maximum of 3% for binary mixtures, the Pareto Front identified an optimal point with 97.56% purity and 55.38% recovery, obtained with 580 s feed time, 20 s equalization, 500 SmL/min flow rate, and 4 bar adsorption pressure.

Keywords: Biogas; Biomethane; Pressure Swing Adsorption; Mathematical Modeling; Process Simulation.

SYNERGISTIC EFFECTS OF DAIRY CATTLE MANURE AND FOOD WASTE CO-DIGESTION: INSIGHTS INTO METHANE YIELD, GAS PRODUCTIVITY, AND PROCESS STABILITY

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The aggravating environmental outlook, with concerns such as greenhouse gas emissions and waste mismanagement, calls for the development of sustainable production systems. Anaerobic digestion (AD) has emerged as a versatile biotechnology, converting organic residues into renewable biogas and nutrient-rich digestate. This study compared the performance of anaerobic mono-digestion of dairy cattle manure (DCM) with the co-digestion of DCM and food waste (FW), focusing on methane yields, volumetric biogas production, and process stability. The assays were conducted in 250 mL Duran reactors under mesophilic conditions (35 °C), employing two DCM types, sewage sludge-derived inocula, and physically pre-treated FW. In mono-digestion, inoculum-to-substrate (I:S) ratios of 1:9, 3:7, 0:1, and 1:0 (v/v) were evaluated. The most favorable condition (I :S= 0:1) achieved a specific methane yield of 248.5 mL CH₄/g VS added after 45 days. For co-digestion, I:S ratios of 1:1 and 1:2 (VS basis) were combined with DCM:FW ratios of 1:1, 1:2, 1:3, and 0:1. The best performance was obtained at DCM:FW = 1:1 with I:S = 1:1, reaching 290.0 mL CH₄/g VS added and 227.05 mL of biogas. These results highlight that co-digestion provided a moderate improvement in methane yield per unit of VS, but a substantial increase in volumetric biogas productivity, reflecting nutritional and kinetic synergies. The integration of FW with DCM thus enhances reactor-scale gas output and stability, confirming co-digestion as an effective strategy for advancing circular economy and climate mitigation efforts.

Keywords: Anaerobic co-digestion, Manure, food waste, pretreatment, Biogas production, Inoculum-to-substrate ratio.

THERMODYNAMIC MODELING OF SYNGAS PRODUCTION FROM BIOGAS VIA COUPLED DRY AND STEAM REFORMING REACTORS

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The increasing emission of greenhouse gases and the high global energy demand have driven interest in the production of fuels from renewable sources. Biogas obtained through the anaerobic digestion of various biomass sources emerges as a key asset in achieving a clean energy matrix, serving as a raw material to syngas production, which subsequently enables the synthesis of methanol, hydrogen, hydrocarbons, and ammonia through technological routes within the scope of Power-To-X (PtX). This work aims to evaluate the conversion of the major components of biogas - CH₄ (60–80%) in balance with CO₂ (20–40%) - into syngas through the sequential coupling of dry reforming and steam reforming of biogas. Reactor equilibrium compositions were determined by minimizing Gibbs free energy, while non-idealities were incorporated through species fugacity coefficients calculated with the Peng–Robinson equation of state, accounting for pressure, temperature, and composition effects. The operational conditions investigated included feed composition, temperature of each reactor and steam-to-carbon ratio. The thermodynamic modeling of reforming reactors chemical equilibrium allowed the identification of operational conditions that resulted in high conversions of the major biogas components, achieving values above 80% for CH₄ and 40% for CO₂, with the production of hydrogen-rich syngas ($H_2/CO \geq 2.0$) and absence of coke formation in the steam reforming reactor.

Keywords: Thermodynamic analysis, syngas, biogas, dry reforming, steam reforming.

UNRAVELING THE INDEPENDENT EFFECTS OF MILD ALKALINE PRETREATMENT AND BICARBONATE BUFFERING ON METHANE YIELD FROM SPENT COFFEE GROUNDS

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This study investigates the impact of alkaline pre-treatment (APT) with sodium hydroxide (NaOH) and buffer supplementation with sodium bicarbonate (NaHCO₃) on methane yield (MY) during anaerobic digestion (AD) of industrial spent coffee grounds (SCG), also providing the first microbial taxonomic analysis under these conditions. NaOH pretreatment was applied at concentrations of 1–8% (m/m, NaOH-to-SCG TS), and its effectiveness was compared to buffering with 2.6 g L⁻¹ NaHCO₃ (~0.7 g Na⁺ L⁻¹). A mild 1% NaOH dose increased MY by 42.5% (from 179.4 to 255.6 mL CH₄ g⁻¹ TS), while bicarbonate addition alone improved MY by 63.8% (to 293.7 mL CH₄ g⁻¹ TS). However, combining NaOH pre-treatment with NaHCO₃ proved detrimental at ≥2% NaOH due to residual sodium accumulation, which surpassed microbial tolerance (~0.8 g Na⁺ L⁻¹), inhibiting biodegradation and reducing methane output. Interestingly, 1% NaOH with NaHCO₃ led to the highest MY (301.1 ± 6.5 mL CH₄ g⁻¹ TS), but with negligible improvement over NaHCO₃ alone, suggesting non-additive effects. MY kinetics ($k \approx 0.50$ mL CH₄ g⁻¹ TS d⁻¹) remained largely unaffected. Agitation had no statistical impact on MY, confirming mass transfer was not a limiting factor. Microbial analysis revealed NaHCO₃ enriched cellulolytic and acetoclastic genera (e.g., *Acetivibrio*, *Methanosaeta*), whereas unbuffered systems favored hydrogenotrophic methanogens (e.g., *Hydrogenispora*, *Methanolinea*) and aromatic compound degraders (e.g., *Syntrophorhabdus*). These findings emphasize that mild alkali pre-treatment or bicarbonate buffering can independently enhance SCG conversion, but their combined use requires careful sodium management to avoid microbial inhibition.

Keywords: Coffee residues, Alkaline Pre-treatment, Sodium Hydroxide, Sodium Bicarbonate, Delignification, Taxonomic analyses

WASTE-TO-ENERGY: UNLOCKING THE POTENTIAL OF RESIDUAL BIOMASS FROM PITAYA PRUNING FOR SUSTAINABLE BIOGAS GENERATION

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The guarantee of universal access to reliable, sustainable, and affordable energy has been established as the United Nations Sustainable Development Goal (SDG) 7 to be achieved by 2030. There is a growing interest in solutions that enable the conversion of organic waste into renewable energy. The biodigestion of plant cuttings for energy production is a solution for treating this organic waste and for the growing energy demand. *Selenicereus undatus* (Haw.) D.R.Hunt, or pitaya, is a tropical plant adapted to arid regions with a lifespan of 20 years; its fruit production is annual, with high added value and a high formation of branches that can reach 30-50 per year. Its pruning stimulates plant development and disease control. Its use as a bioenergy renewable source could be a solution for the increasing energy demand in arid areas. Thus, the study aims to evaluate the production of biogas resulting from the pitaya pruning residual biomass digestion after physical pre-treatment (drying and grinding). After the pre-treatment, the biomass was characterized and used to feed the small-scale batch biodigesters, which consist of 100 mL glass reactors at 37 °C, following the methodology adapted from the Biochemical Methane Potential (BMP). The biodigestion of residual biomass from pitaya pruning operated for 22 days and achieved a biogas yield 27,92 mLg⁻¹volatile solid under a 1:1 feedstock-to-inoculum ratio in a 37°C incubating temperature. The generated waste from its pruning can be applied in energy production, promoting a circular bioeconomy and improving global energy resilience.

Keywords: waste biodigestion, residual biomass, bioenergy

WHOLE-CELL PRETREATMENT OF LIPID WASTES: STRATEGIES TO ENHANCE THE METHANE PRODUCTION

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Lipid waste is a potential producer of methane; however, it requires a pre-treatment step before being subjected to anaerobic digestion. This work is studied strategies for methane production from the codigestion of lipid wastes, such as cheese whey (CW), waste cooking oil (WCO), and dairy wastewater (DW), employing pretreatment with whole-cell containing mycelium-bound lipase. The whole-cell of filamentous fungi *Aspergillus oryzae* URM 5638 was produced using CW and WCO as nutrients for the submerged cultivation. To evaluate the thermal and microbiological effects on the whole-cell production, the culture medium was tested with and without previous sterilization. Then, the entire cultivation product (whole cells and broth) was subjected to anaerobic digestion (AD) with 50 mL of DW and 15mL of the anaerobic sludge (AS). The reactions were incubated at 30°C under orbital shaking at 130rpm for 48h. The volume of methane was measured indirectly by the volume displacement of a NaOH concentrated solution. The previous sterilization in the cultivation step proved to be crucial, as higher values of methane (392.67 ± 35.73 mL) were obtained under this condition, compared to without sterilization (116 ± 32.04 mL). However, in both conditions, there was a slight reduction in the COD value ($<10\%$), due to the pH final of about 4.0, which indicates the acidification of the substrate. When the codigestion without whole-cell pretreatment was carried out employing the same volumes of lipid wastes, no methane was produced. Thus, the results indicate that whole-cell pretreatment is efficient at enhancing methane production from lipid wastes.

Keywords: lipid waste, whole-cell, codigestion, methane

The image features a background of charcoal pieces. A large, semi-transparent green circle is centered over the image. Within this green circle, there are two smaller, overlapping circular cutouts. The cutout on the right shows a close-up of charcoal with a greenish tint, while the cutout on the left shows a more natural, dark charcoal texture. The word "Charcoal" is written in a bold, white, sans-serif font across the center of the green circle.

Charcoal

MACAUBA BIOCHAR PRODUCTION FROM ENDOCARP THERMAL LIQUEFACTION USING ANHYDROUS AND HYDROUS ETHANOL

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Biochar is a porous carbon-rich solid obtained, in most cases, as a co-product in the thermal conversion of biomass. The biomass used as a precursor and the thermal conversion process are the main factors determining its surface complexity and physical-chemical characteristics. Residual lignocellulosic biomass has garnered significant interest for the production of biochar, as it is abundant and cost-effective. In this study, we investigated the production of biochar from the thermal liquefaction of Macauba endocarp using anhydrous ethanol (A.Et) and hydrous ethanol (H.Et) as solvents at a biomass/solvent ratio of 1:10. The reaction took place at 300°C for 30 min and 200 rpm agitation in a 600 mL Parr reactor. The biochar yield was 36.3% with a higher calorific value (PCS) of 27 MJ/kg for H.Et and 42.7% and 26.6 MJ/kg for A.Et, respectively. The presence of water in the solvent favors thermal degradation, increasing the conversion into liquid and gaseous products and thus decreasing the biochar yield. Regarding the fixed carbon content, biochars with 52.3% for liquefaction with H.Et and 47.6% for A.Et were obtained. The biochar had low ash content, less than 2% in both cases, and high volatile content, 42.9% for H.Et and 48.2% for A.Et. Elemental analysis showed an H/C and O/C ratio of 0.81 and 0.29 for A.Et and 0.76 and 0.27 for H.Et, which means that hydrous ethanol yielded a less oxygenated and more aromatic biochar, confirming the positive effect of water in the biomass depolymerization.

Keywords: Biochar, Macauba, Endocarp, Liquefaction, Ethanol

OPTIMIZATION OF BIOCHAR PRODUCTION FROM AGRO-INDUSTRIAL WASTES FOR POLLUTANT ADSORPTION

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The growing demand for efficient and sustainable methods to remove contaminants from wastewater and polluting gases has driven the study of biochars as adsorbent materials. This study aimed to produce biochars from agro-industrial wastes through slow pyrolysis to evaluate their adsorption potential for ammonia. Methylene blue (MB) was used as a marker for the indirect evaluation due to its positive charge in solution and similar adsorption behavior in porous matrices. A Box-Behnken experimental design was applied to optimize the parameters: pyrolysis temperature (350 °C, 450 °C, 550 °C), residence time (0, 30, 60 minutes), and biomass (poultry litter, soybean residues, and their blend), resulting in 15 samples. Adsorption tests were carried out using 50 mg·L⁻¹ of MB in 0.5% acetic acid, under agitation for 30 minutes. The samples showed MB removal efficiencies ranging from 54.79% to 99.47%. Sample 9 (50% soybean and 50% poultry litter blend; 450 °C; and 30 minutes of residence time) achieved the highest average, with 99.47 ± 0.42%. In contrast, sample 7 (soybean residues, 350 °C, 30 minutes) showed the lowest performance and the highest variability (54.79 ± 15.78%), suggesting low stability in contaminant removal. The central points showed an average adsorption of 98.97 ± 0.57%, indicating stable and reproducible performance. The results highlighted the potential of the obtained biochars as adsorbents, confirming that efficiency depends on the pyrolysis conditions and the importance of optimizing these parameters to maximize performance. The study contributes to the development of sustainable solutions, promoting better control of pollutant gas emissions and the reuse of organic waste.

Keywords: Biochar, Agro-industrial waste, Box-Behnken design, Biomass, Adsorption

POTENTIAL OF SUGARCANE BIOCHAR FOR ELECTROCHEMICAL ENERGY STORAGE AND CONVERSION

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Lignin derived from sugarcane residues, such as bagasse (BS) and straw (ST), is an abundant yet underutilized resource in biorefinery. Commonly burned for process heat, lignin can instead be upgraded into high-value carbon materials with applications in energy storage, catalysis, and water purification. Converting sugarcane lignin into functional biochars presents opportunities to expand biorefinery product portfolios, enhance economic returns, and support sustainable operations, particularly in applications such as lithium batteries and electrocatalysis. This study examines the structural, chemical, and electrochemical properties of biochars derived from BS and ST lignin, with a focus on their electrocatalytic activity toward the oxygen reduction reaction (ORR) and oxygen evolution reaction (OER) in alkaline media. Lignin was extracted via kraft pulping and pyrolyzed at 550°C, 700°C, and 1000°C. Biochars were characterized using SEM-EDX, XRD, Raman spectroscopy, and N₂ adsorption. Electrochemical performance was assessed in 1 M KOH using cyclic voltammetry and chronoamperometry. ST lignin contained more nitrogen and silicates, while BS lignin was richer in sulfur. ST-derived biochars exhibited higher surface areas and greater graphitization than BS biochars. All samples showed electrocatalytic activity toward ORR, but none toward OER. ST biochars achieved higher ORR currents yet suffered corrosion under high anodic potentials, whereas BS biochars demonstrated lower activity but better anodic stability. ST lignin-derived biochars are promising for energy storage and conversion devices that rely on ORR, but should be used cautiously in applications requiring OER, such as water electrolyzers and metal-air batteries. BS biochars exhibit higher anodic stability but lower electrocatalytic activity.

Keywords: sugarcane, lignin, oxygen reduction reaction, oxygen evolution reaction, alkaline

REDUCTION OF COBALT SPECIES ON BIOCHAR FROM CORN HUSK WASTE FOR NaBH_4 HYDROLYSIS

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Biochars have emerged as promising platforms for sustainable catalyst development. In this study, cobalt-modified biochar derived from corn straw was synthesized via pre- and post-pyrolysis modification. Comprehensive characterization (SEM, TEM, EDS, XRD, XPS, and FTIR) revealed that the synthesis route and pyrolysis temperature strongly influenced particle size, crystallinity, and phase distribution, with pre-pyrolysis impregnation at 400 °C (BP400) producing a highly dispersed amorphous $\text{CoO}/\text{Co}_3\text{O}_4$ phase. BP400 exhibited the highest catalytic performance for NaBH_4 hydrolysis, achieving a hydrogen generation rate of $1416.5 \text{ mL g}^{-1} \text{ min}^{-1}$ at 25 °C and an activation energy of $45.13 \text{ kJ mol}^{-1}$, outperforming several conventional carbon-supported catalysts. Importantly, this catalyst retained ~50% of its initial activity after four reuse cycles under alkaline conditions, with deactivation mainly attributed to the precipitation of borate and sodium residues on the surface. These results establish agricultural waste-derived biochar as an efficient, low-cost, and magnetically recoverable support for cobalt-based catalysts, offering a sustainable pathway for hydrogen production while advancing biomass valorization and the United Nations Sustainable Development Goals.

Keywords: Green catalyst; hydrogen; biochar; sodium borohydride; hydrolysis

REUSE OF EGGSHELLS IN BIOCHAR TECHNOLOGY – A BIBLIOMETRIC OVERVIEW

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Introduction: According to Brazilian Institute of Geography and Statistics, Brazil produced approximately 5 billion dozen eggs in 2023, ranking it as the sixth-largest producer in the world, according to Food and Agriculture Organization of the United Nations. This production generates a large amount of waste, eggshells, composed mainly of calcium carbonate, which can be used to produce biochar. **Objective:** The objective of this research was to identify the articles that use eggshells to produce biochar, analyze the main applications of this material, and the most influential countries and institutions in this field. **Methodology:** Publications were gotten from the Web of Science database by searching for the keywords "biochar*" and "eggshell*". Bibliographic data from the 112 papers were exported and processed using VOSviewer software, analyzing them by co-authorship and co-occurrence, through graphs representing correlation networks and tables identifying the number of publications. **Results and discussion:** Keywords analysis shows that biochar was primarily used to remove chemical elements through adsorption in water, wastewater, or soil. The most common were phosphorus, due to worsening eutrophication, and the heavy metals lead and cadmium, bioaccumulators that affect health. The most influential country is China, with 61 papers, followed by India, South Korea, the USA, and Egypt. Brazil ranks 12th with 3 papers. Of the 14 institutions with the most articles, eleven are Asian, seven of which are Chinese. **Conclusion:** Therefore, reusing eggshells to develop biochar generates added value and scientific and technological knowledge in the treatment of contaminated environmental areas, contributing to the achievement of the Sustainable Development Goals.

Keywords: Adsorption; removal; phosphorus; lead; cadmium

SULFAMETHOXAZOLE REMOVAL BY ADSORPTION USING BIOCHAR OBTAINED FROM COCONUT RESIDUES AND *Terminalia catappa*

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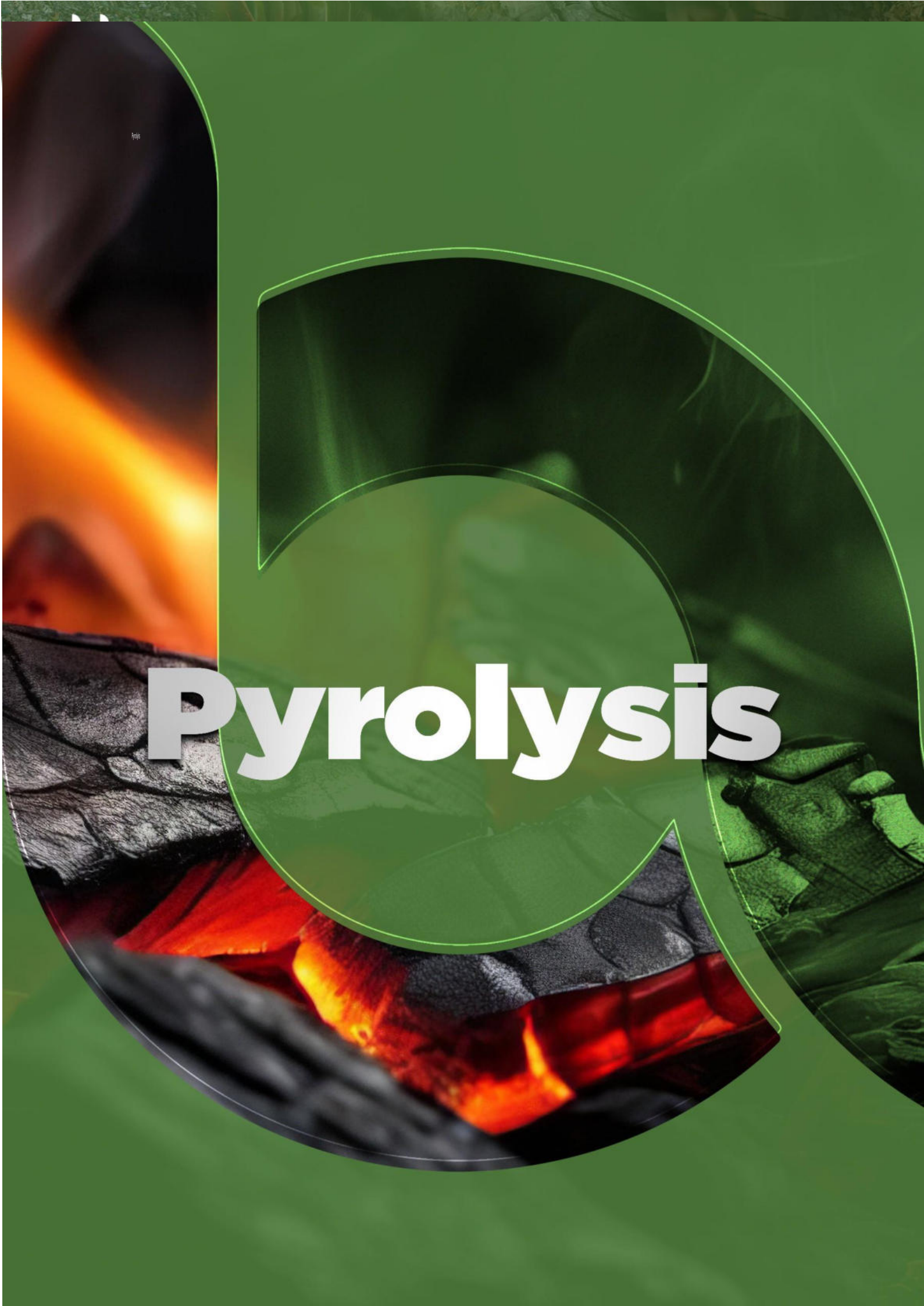
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The disposal of emerging pollutants into water bodies has been an important environmental challenge. For instance, the inappropriate disposal of sulfamethoxazole (SMX) has gained attention as a threat to marine and human life. Therefore, the development of effective, low-cost, and sustainable adsorbents has been encouraged in order to remove SMX from water bodies. This work focused on investigating the SMX adsorption capacity of biochar produced from three different biomasses: mesocarp (B1) and endocarp (B2) of *Cocos nucifera*, and *Terminalia catappa* (B3). Pyrolysis was performed in a cylindrical electric furnace of 827 cm³ with inert N₂ atmosphere, at different heating rates and final fixed temperatures ranging in 400-600 °C. Three fixed-bed adsorption columns (5.26 cm diameter, 15 cm height) were filled with 21.61 g, 39.28 g, and 10.39 g of B1, B2 and B3 biochars, respectively, and then saturated with CaCl₂ solution. Water samples with SMX concentrations around 29 mg/L were permeated through the columns, and the effluents were analyzed by high-performance liquid chromatography (HPLC). The SMX recoveries in the total effluent volumes were 72.91%, 54.93%, and 93.89% for B1, B2 and B3, respectively, with specific adsorption capacities of 15.5, 9.9, and 4.9 µg of SMX per gram of biochar, in the same order. These results indicate that biochar obtained by pyrolysis of coconut residuals, especially mesocarp, show potential for SMX removal from water, while the biochar from *Terminalia catappa* showed lower performance in contaminant retention.

Keywords: Adsorption; Biochar; Coconut residues; Sulfamethoxazole; *Terminalia Catappa*.

Pyrolysis

Pyrolysis



BIOCHAR PHYSICAL DEGRADATION: LONG-TERM EFFECTS AS SOIL AMENDMENTS

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This study investigated the hypothesis that biochars derived from sewage sludge (SS) and wheat straw pellets (WSP) withstand long-term environmental aging in drought-prone areas while maintaining their functionality as sustainable soil amendments. This is especially urgent given the global need to reduce fertiliser dependence, enhance soil health and sequester carbon in the face of climate instability. Biochars were produced at pyrolysis temperatures of 400, 550, 600 and 700°C, and subjected to wet-dry cycling – a method that simulates natural weathering processes such as rainfall and temperature fluctuations. The results revealed that biochar performance after aging is strongly influenced by biomass type and pyrolysis conditions. SS biochars are more prone to carbon loss and oxidative transformations; however, they show great potential as biofertilisers due to their elevated nitrogen content, organic matter availability, and reactive surface characteristics. Meanwhile, WSP biochars show greater promise for carbon sequestration and improved soil water-holding capacity, owing to their higher resistance to degradation and increased porosity. These findings emphasise the importance of considering both chemical stability and physical structure when selecting biochar for soil management. A deeper understanding of these mechanisms can optimise feedstock use and boost industrial efficiency, leading to fertilisation and irrigation savings, increased carbon credit income, and broader environmental and climate resilience benefits.

Keywords: Biochar aging, Abiotic processes, Water holding capacity, Sustainable agriculture, Carbon stability, Circular economy.

WASTES FOR THE PRODUCTION OF BIO-OILS RICH IN PHENOLIC COMPOUNDS

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Research into alternative and sustainable sources of chemicals and fuels has been growing in recent decades, driven by the need to reduce dependence on fossil resources and mitigate the environmental impacts associated with their use. In this context, agro-industrial waste has emerged as a promising biomass source for the production of high-value-added products, such as bio-oils rich in phenolic compounds. This study aims to characterize and evaluate the seeds of acerola (ACE), grape (UVA), guava (GOI), and passion fruit (MAR), investigating their properties and potential for conversion into bio-oils rich in phenolic compounds. The biomass samples were characterized through elemental analysis (CHNO), thermogravimetry (TG), ash content, moisture, total extractives, and oil content. The samples showed low ash content (1.00 to 2.71%) and moisture (1.55 to 6.61%). Thermogravimetric analysis elucidated the lignocellulosic composition of the samples, a relevant parameter for understanding the thermal degradation of their constituents. Using GC-MS, the bio-oils were characterized, demonstrating the potential for using these biomasses in the production of phenolic resins. The predominant classes differed according to the compositions: higher percentages of phenols were found in the bio-oil from ACE, and carboxylic acids were more prevalent in the others, due to the oil content.

Keywords: Agro-industrial residue; biomass; characterization; bio-oil

COMPARATIVE STUDY BETWEEN CONVENTIONAL AND RECYCLED CARBON BLACK AFTER LEACHING

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This study conducts a comparative analysis of conventional carbon black and recycled carbon black following leaching processes. Traditionally used as a reinforcing agent in rubber and plastic products, carbon black is produced through the incomplete combustion of petroleum derivatives. However, environmental concerns and the demand for sustainable practices have driven interest in recycled alternatives. The research focuses on recycled carbon black derived from pyrolyzed tire waste, subjected to leaching to remove impurities and enhance properties. Acidic leaching primarily removes metallic contaminants, while alkaline leaching reduces ash content. Parameters such as surface area, structure, mechanical properties in rubber compounds, and pigmentation in thermoplastic compounds will be evaluated. Previous studies indicate that leaching significantly enhances the quality of recycled carbon black, aligning its characteristics more closely with those of conventional carbon black. Increased surface area and reduced impurities contribute to improved tensile strength and abrasion resistance in rubber applications, as well as enhanced pigmentation in thermoplastics due to reduced intrinsic ash content from pyrolysis. This study highlights the potential of recycled carbon black as a viable and environmentally friendly alternative in industrial applications, promoting circular economy practices and reducing reliance on non-renewable resources.

Keywords: ashes, tires, pyrolysis, waste tires, carbon black

COMPOSITIONAL CHARACTERIZATION OF PYROLYSIS BIO-OILS AS FEEDSTOCK FOR GREEN DIESEL AND SAF: A REVIEW OF PRODUCT COMPOUNDS AND FUTURE PERSPECTIVES FOR EMERGING ECONOMIES

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The global energy transition demands sustainable solutions for the transportation sector, with green diesel and sustainable aviation fuel (SAF) standing out as promising alternatives to fossil fuels. Among the technological pathways, the pyrolysis of biomass, residues, and vegetable oils has gained attention due to its ability to convert organic materials into bio-oils rich in hydrocarbons. However, the technical and economic feasibility of using these bio-oils as feedstocks for advanced fuels strongly depends on their chemical composition to ensure compliance with the quality standards required for commercialization. Bio-oils derived from different sources and pyrolysis conditions exhibit complex and heterogeneous compositions, containing aromatic and aliphatic hydrocarbons as well as oxygenated compounds, phenolics, carboxylic acids, and aldehydes. Many of these components are unstable, corrosive, or incompatible with the quality requirements for green diesel and SAF, making selective upgrading or refining processes necessary. Therefore, it is essential to understand which components are present in these pyrolysis products and how feedstock, catalysts, and reaction conditions influence their composition and the proportion of compounds of interest. In this context, the present critical literature review systematizes this knowledge to support ongoing research in the field and outline future perspectives for the production of drop-in fuels through pyrolysis. The review highlights an increasing focus on non-food feedstocks, particularly lignocellulosic and residual sources. Another point to emphasize is the growing role of emerging countries in renewable fuel research.

Keywords: Green Diesel; SAF; Compounds; Bio-Oils; Pyrolysis

COUPLED EFFECT OF PYROLYSIS TEMPERATURE AND HNO_3 PRETREATMENT ON SUGARCANE BAGASSE FAST PYROLYSIS FOR LEVOGLUCOSAN PRODUCTION

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This work aimed to evaluate the potential of HNO_3 (0.1 wt.%) in the pretreatment of sugarcane bagasse as a strategy to intensify levoglucosan production, before subjecting it to fast pyrolysis under different temperature conditions. The experiments were conducted in a pyroprobe reactor coupled to a GC/MS at temperatures ranging from 350 to 600°C, with 50°C intervals. Thus, in addition to the impact of nitric acid on levoglucosan yield, the formation profile of other pyrolytic derivatives during the thermochemical conversion of biomass is reported. The best results regarding levoglucosan yield were obtained when pyrolysis was performed at 450°C, resulting in approximately twice the amount of levoglucosan obtained from sugarcane bagasse after treating the biomass with acid compared to the control (untreated biomass), while the profiles of the other pyrolytic derivatives identified showed different and lower behaviors after acid washing of the biomass. The observed effect may be due not only to the removal of alkali and alkaline earth metals, whose catalytic activity influences the pyrolytic pathways, but also to the probable partial removal of lignin and/or hemicellulose fractions by the acid washing. On the other hand, despite the observed increase in levoglucosan formation, the results obtained with HNO_3 at 0.1% by biomass weight do not seem to be a good alternative for the intensification of the target compound, when compared with other acids used in washing/passivation procedures of sugarcane bagasse under similar experimental conditions.

Keywords: Sugarcane bagasse; biomass acid pretreatment; fast pyrolysis; levoglucosan

ENERGY ASSESSMENT OF ORANGE BAGASSE IN FAST PYROLYSIS FOR BIO-OIL PRODUCTION

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Energy recovery from citrus residues, particularly orange bagasse, represents a strategic alternative for diversifying the energy matrix and mitigating environmental liabilities in Brazil. This study aimed to evaluate the technical feasibility of orange bagasse as feedstock for fast pyrolysis, in comparison with other agro-industrial biomasses. Proximate and ultimate analysis data from the scientific literature were compiled and organized on a dry basis, then normalized to ensure comparability. Based on chemical composition, higher (HHV) and lower heating values (LHV) were estimated using the Van Loo and Koppejan equation. Historical series of orange production (2003–2023), obtained from USDA, were used to project residue availability scenarios and bio-oil energy potentials up to 2035. The results indicated that orange bagasse presents LHV values ranging from 11.08 to 18.36 MJ/kg, showing performance comparable to woody biomasses such as alder wood (18.41 MJ/kg) and sugarcane bagasse (16.21 MJ/kg). Energy projections revealed high sensitivity to process yield and bio-oil LHV: in 2025/26, scenarios ranged from 736,289 TOE (35.53%; 14.77 MJ/kg) to 1,702,875 TOE (54.9%; 18.95 MJ/kg).

Keywords: Orange bagasse, Pyrolysis, Bio-oil, Ultimate Analysis, Energy potential

ENERGY POTENTIAL OF AÇAÍ SEED (*Euterpe* sp.) BIOCHAR OBTAINED BY TORREFACTION AND CONVENTIONAL PYROLYSIS

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The decarbonization of the Brazilian energy matrix is driving the utilization of agricultural residues as renewable feedstocks. Among these residues, açaí seed, an abundant by-product of the food supply chain, still lacks valorization routes that combine energy efficiency and industrial feasibility. This study evaluated the potential of açaí seed biochar obtained by torrefaction (200–320 °C) and conventional pyrolysis (350–700 °C). Samples of 300 g (dry basis) were processed in a fixed-bed reactor heated in a muffle furnace, with a heating rate of 100 °C/h, a residence time of 30 min, and an inert atmosphere maintained by the process gases. A progressive increase in fixed carbon was observed, reaching 84% at 450 °C. Under mild torrefaction (200 °C), the higher heating value (HHV) increased by up to 24% (24.1 MJ/kg) compared to the raw biomass. In this condition, the gravimetric yield of biochar remained high (72%), revealing a favorable balance between mass and energy. At 500 °C, the biochar exhibited a maximum HHV of 32–33 MJ/kg and a volumetric energy density above 14.9 GJ/m³, indicating potential application as a metallurgical reductant or high-value solid fuel.

Keywords: Lignocellulosic residues, Amazonian biomass, thermochemical conversion, circular economy, fixed carbon.

EXPLORING ALTERNATIVE AND SUSTAINABLE SOLUTIONS FOR THE DISPOSAL OF SOLID HEALTH WASTE – OBTAINING CHAR, OIL AND GAS

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This study employed a thermochemical process, specifically slow pyrolysis process, applied to solid healthcare waste (SHW), which poses significant challenges in terms of disposal. Typically, SHW is subjected to autoclaving for inerting followed by disposal in sanitary landfills. However, in this research, slow pyrolysis was utilized to transform SHW into valuable products including char, oil, and gas. The adoption of slow pyrolysis not only addresses environmental concerns associated with SHW mismanagement but also yields satisfactory outcomes. The experiments were conducted using a continuous-feed rotary kiln reactor equipped with an integrated material shredding system and conveyor belt. The process was carried out at a temperature of 450 °C, with a residence time of 40 minutes. The resulting biochars were subjected to a comprehensive characterization, including proximate analysis (moisture content, volatile matter, fixed carbon, and ash content), chlorine content, high calorific value (higher heating value), elemental analysis (CHNS), metal content determination, and Fourier Transform Infrared Spectroscopy (FTIR). The resultant oil and gas are utilized within the process itself, leading to a substantial reduction in the consumption of liquefied petroleum gas (LPG). Chemical analysis of the char, post-sieving and crushing, was conducted to elucidate its composition. Various assessments were undertaken to explore potential commercial applications of the char, including coprocessing, application in civil construction, utilization in the steel industry, incorporation into composites, utilization as fertilizers, as well as its potential in filters and catalysis. The findings underscored the promising prospects of the char derived from SHW pyrolysis.

Keywords: Pyrolysis; char; environment; applications

FAST PYROLYSIS OF SUGARCANE BAGASSE IN A FLUIDIZED BED REACTOR

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The use of fossil fuels, mainly petroleum derivatives, and the growing global concerns about greenhouse gas emissions and global warming have led to international agreements, such as the Paris Agreement, aiming to reduce environmental impacts caused by human activity. In this context, biofuels have gained prominence as a sustainable alternative, driving advances in technological development. One promising route for biofuel production is the fast pyrolysis of biomass, a thermochemical process that converts lignocellulosic materials into a liquid product known as bio-oil. This study investigates the fast pyrolysis of sugarcane bagasse, an abundant agro-industrial residue in Brazil, using a fluidized bed reactor at 500 °C. The process achieved a total liquid yield of 62.2 wt%, with 6.5 wt% solids and 24 wt% non-condensable gases. The bio-oil, the main product, was characterized and showed promising results: 36 wt% carbon, 5.87 wt% hydrogen, 0.2 wt% nitrogen, < 0.2 wt% sulphur, 0.11 wt% ash, and 27 wt% moisture. The higher heating value (HHV) was 18.15 MJ/kg, and the lower heating value (LHV) was 16.9 MJ/kg. These results indicate that the bio-oil has a good energy density and favourable elemental composition, with high carbon and hydrogen contents and low levels of nitrogen, sulphur, and ash—parameters that are desirable for energy applications and minimize environmental impacts. Although the moisture content is slightly high, it is within the expected range for bio-oils from pyrolysis. Overall, the study confirms the potential of sugarcane bagasse as a viable feedstock for high-yield bio-oil production, contributing to the development of renewable energy alternatives in the Brazilian context.

Keywords: Residual Biomass; Fast pyrolysis; Characterization of bio-oil

MICROWAVE PYROLYSIS OF INVASIVE PLANT SPECIES BIOMASS: ANALYSIS OF KINETIC PROPERTIES

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This study investigates the thermochemical behavior and microwave pyrolysis potential of three biomass samples: Acacia dealbata (Mimosa), Robinia pseudoacacia (Robinia), and wood waste from Brazil. Thermogravimetric analysis was performed at heating rates of 10-20 °C/min under an inert nitrogen atmosphere to evaluate thermal decomposition kinetics and thermodynamic parameters. Iso-conversional models were employed to determine activation energies, while scanning electron microscopy and energy-dispersive X-ray spectroscopy revealed morphological changes and elemental compositions post-pyrolysis, with fixed carbon content increasing significantly for all biomass samples (e.g., 83.69% for wood waste). Microwave pyrolysis at 400 °C and 800 W demonstrated efficient conversion, with reduced pyrolysis times. A mathematical model was developed to predict charcoal

production using microwaves, achieving reasonable accuracy with errors ranging from 9% to 24%. This model aims to assist industry decision-making in microwave charcoal production.

Keywords: Microwave pyrolysis, kinetic properties, invasive plants, thermo-kinetics and mathematical model.

PRODUCTION AND CHARACTERIZATION OF CHAR OBTAINED VIA PYROLYSIS OF BIOMASS AND PLASTIC RESIDUES

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Population growth has intensified the concern on rising energy demand and environmental pollution. Pyrolysis offers an alternative for waste valorization by thermally decomposing feedstocks in an inert atmosphere, producing solid, liquid, and gas fractions. However, applications depend on structure, morphology and physicochemical properties of these chars, which correlate to the material itself and pyrolysis conditions. This work produced and characterized chars from pyrolysis of four residues: tropical almond (*Terminalia catappa* L.) (S1), coconut (*Cocos nucifera* L.) endocarp (S2) and mesocarp (S3), and polyethylene terephthalate (PET) (S4). Samples were pyrolyzed in a cylindrical electric furnace (8.9 cm diameter, 13.3 cm height) at 400-600 °C. Inert conditions were ensured by purging oxygen with nitrogen (4 cm³/min) for 5 minutes before heating. The heating rate was 10 °C/min for 1 hour, followed by 15 °C/min for 30 minutes. Product yields (wt%) were: S1 – 26.8 biochar, 34.8 liquid, 38.4 gas; S2 – 53.6 biochar, 30.2 liquid, 16.2 gas; S3 – 31.4 biochar, 54.1 liquid, 14.5 gas; and S4 – 16.6 char, 83.4 gas, with no liquid fraction. X-ray diffractograms suggested different carbonaceous morphology and crystallinity degrees among chars: highly amorphous in S4, semi-crystalline disordered in S2, mixed crystalline-graphitic in S3, and well-ordered crystalline in S1 likely mineralized. Results indicate that feedstock type and pyrolysis parameters such as temperature, heating rate and residence time strongly impacted char morphology, crystallinity, porosity and surface area. In particular, the greater surface area, fewer crystallinity and amorphous chars, the better for applications in environmental remediation and circular bioeconomy.

Keywords: Char, pyrolysis, waste valorization, X-ray, diffraction

PRODUCTION OF BIOCHAR FROM PHYTOPLANKTON BIOMASS FOR BIOREMEDIATION

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Phytoplankton is naturally present in bodies of water as the main primary producer and basis of food chains in aquatic ecosystems, being essential for marine ecological and biogeochemical processes. However, during the eutrophication process, accelerated growth of this biomass occurs, caused mainly by excess nutrients (phosphorus and nitrogen), which can have environmental, health, social, and economic impacts, especially in the case of cyanobacteria that release toxins that cause neurological, gastrointestinal, and dermatological problems in humans and animals. The objective is to capture phytoplankton biomass in eutrophic lakes and subsequently use it as an alternative for biochar production. The project will be conducted by collecting phytoplankton biomass at different depths of a lake. Proposing to reduce the moisture content of phytoplankton biomass and the proliferation of fungi, two drying methods will be tested, in an oven and in the open air, with the aim of comparing the best results obtained, based on drying curves. Next, biochar will be produced through pyrolysis at different temperatures, seeking to identify the best yield. Finally, the biochar obtained will be characterized by physical-chemical analyses, including pH, carbon, nitrogen, and phosphorus content; apparent density, porosity, etc. As a result, it is expected that the application of biochar will enable bioremediation as a way to recover degraded aquatic ecosystems themselves, promoting the retention of excess nutrients in the water. Therefore, pyrolyzed biomass in the form of biochar represents an alternative for mitigating the impacts of eutrophication, in addition to enabling the potential for valorization of residual biomass.

Keywords: Phytoplankton; Eutrophication; Biochar; Bioremediation

PRODUCTION OF SUSTAINABLE AVIATION FUEL-RANGE HYDROCARBONS VIA THERMAL CRACKING OF CUMARU OIL USING RED MUD AS A SELECTIVE CATALYST

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Red mud, a byproduct of bauxite refining, was evaluated as a heterogeneous catalyst in the thermal cracking of cumaru oil (*Dipteryx odorata*), a biomass native to the Amazon. This study aimed to investigate the catalytic performance of red mud in reducing oxygenated compounds and promoting hydrocarbon formation under mild conditions, without requiring hydrodeoxygenation. Cumaru oil was characterized by GC-MS, revealing carboxylic acid esters and coumarin. Thermal cracking reactions were conducted in a heating system with a flask coupled to a condenser, with temperature control of both sample and vapor phases, ranging from 250 °C to 380 °C, with and without 0.5% (w/w) red mud. Products were analyzed by GC-MS and FTIR to determine chemical composition and functional group transformations. The non-catalyzed reaction yielded a high acid value (172.1 mg KOH/g) and carboxylic acids, confirmed by FTIR and GC-MS. In contrast, the catalyzed reaction reduced the acid value to 4.76 mg KOH/g and favored the formation of C₉–C₁₇ hydrocarbons, including alkanes and terminal alkenes. FTIR confirmed the suppression of oxygenated functional groups. These results indicate that red mud promotes decarboxylation and decarbonylation pathways in the thermal cracking of Cumaru Oil, enabling selective hydrocarbon formation in the sustainable aviation fuel (SAF) range. The catalyzed sample showed strong compositional similarity to commercial JET-A fuel, reinforcing the potential of red mud as a sustainable, low-cost catalyst for biofuel production.

Keywords: Catalysis, Aviation, Thermal cracking, SAF, Red mud, Biomass

PYROLYSIS OF CUPUAÇU SEED BIOMASS: THERMAL BEHAVIOR, CATALYTIC EFFECTS, AND BIO-OIL COMPOSITION

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This study investigates the chemical and thermal characteristics of cupuaçu seed biomass and its potential for bio-oil production via pyrolysis at 600 °C. Elemental analysis revealed a high carbon content (59.12%) with low oxygen-to-carbon ($O/C = 0.33$) and hydrogen-to-carbon ($H/C = 2.01$) ratios, indicating favorable energy potential and a tendency toward the formation of less oxygenated compounds. Thermogravimetric analysis (TGA) identified five distinct degradation stages, highlighting significant hemicellulose decomposition (47.7%) and a notable contribution from natural oils (17.05%). The resulting bio-oil exhibited a hybrid chemical profile dominated by carboxylic acids (75.3%), hydrocarbons (9.98%), and nitrogenated compounds (7.42%). The high acid content is linked to the degradation of hemicellulosic and cellulosic fractions, while hydrocarbons derive from thermal cracking of the biomass's extractive oils. Trace metals such as potassium, phosphorus, magnesium, calcium, and iron were identified as natural catalysts, potentially enhancing deoxygenation and cracking reactions during pyrolysis. The findings underscore the need for refining strategies to improve bio-oil stability and suitability for energy applications. Overall, cupuaçu seed biomass presents a promising feedstock for producing chemically diverse bio-oil, with potential applications in advanced biofuels and integrated biorefineries.

Keywords: cupuaçu seed biomass; catalytic metals; bio-oil composition; pyrolysis; renewable biofuels

THERMODEGRADATION MECHANISMS USING SLOW PYROLYSIS OF LIGNOCELLULOSIC BIOMASS, DOMESTICS AND INDUSTRIAL WASTE MATERIALS WITH FORMATION OF OIL, CHAR AND GAS.

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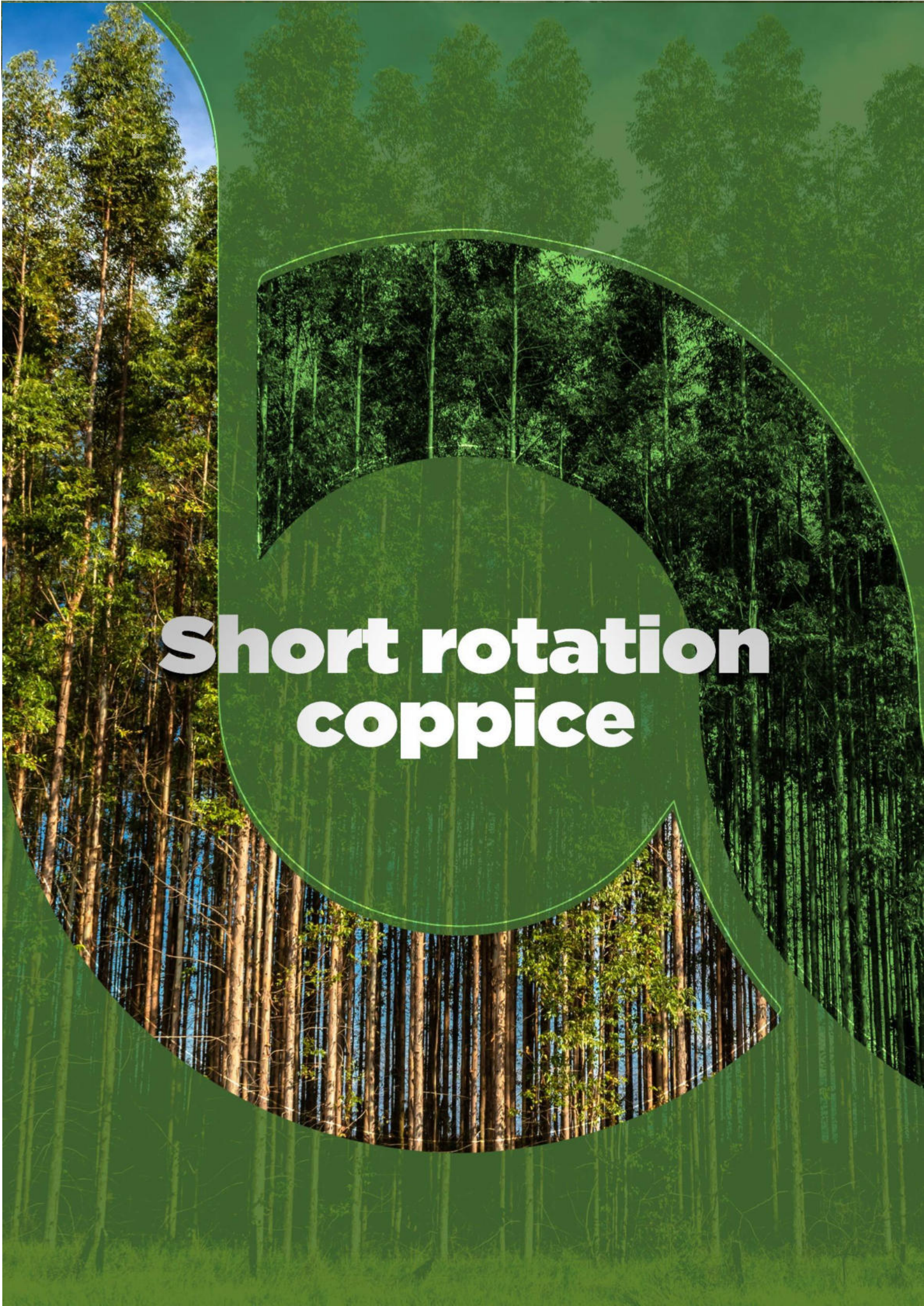
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This paper describes two groups of raw materials, Group I – Lignocellulosics Biomasses (LB) that include agricultural, forest and aquatic biomasses. Group II – Industrial and Domestic Wastes (IDW), constituted by Plastics (P); Industrial Solid Blends (ISB); Urban Solid Waste (USW); Health Solid Waste (HSW); Oily Sludge (OS); Sludge from Treatment Station (STS); Drilling Mud (DM) and Miscellaneous (M), studied upon slow pyrolysis conditions by Romeiro's research group. These materials were submitted to slow pyrolysis at the temperature of 400 - 450°C, under a N₂ atmosphere during two hours. The products obtained were oil, char, gas and an aqueous fraction, characterized using several analytical methods to establish some of their chemical and physicochemical properties. This work focused on the pyrolysis yields of different residues and the study of products mechanisms formation of oil, char and gas.

Keywords: Slow pyrolysis; oil; char; biomass; domestic and industrial wastes

The background is a photograph of a dense forest of tall, thin trees, likely spruce or fir, with green foliage. A semi-transparent green overlay covers the entire image. Two large, irregular circular cutouts are present: one in the upper right and one in the lower right, revealing the original forest image underneath. The text 'Short rotation coppice' is centered in the middle of the image, overlaid on the green background.

Short rotation coppice

BIOCHAR AND SLAG FERTILIZER APPLICATION ON THE GROWTH AND BIOMASS YIELD OF WILLOW

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The increasing utilization of renewable woody biomass energy has resulted in an increase in the adoption of gasification combined heat and power (CHP) systems. However, the disposal of biochar, a byproduct generated during this process, has emerged as a significant issue. Furthermore, in the steel industry, the high-value utilization of slag generated during steelmaking remains a challenge. Although both these materials contain nutrients such as calcium and potassium and have the potential for circular utilization, their use is limited. Therefore, this study was conducted to demonstrate the effectiveness of CHP-derived biochar and steel slag as fertilizers for willow cultivation through fertilization experiments conducted in an experimental field under extensive management. Results showed that application of 10 Mg ha⁻¹ of biochar or 2 Mg ha⁻¹ of biochar combined with 5 Mg ha⁻¹ of slag fertilizer increased soil pH and improved willow tree height growth compared with the control. Moreover, plots in which soil pH reached ≥ 5.5 due to the application of biochar or slag fertilizer showed yields of 11–12 Mg ha⁻¹ year⁻¹ simply converted to hectares, 7.3–8.3 Mg ha⁻¹ year⁻¹ converted to 15,000 trees per hectare. However, tree height growth showed no significant difference between the control plot and the plot with 2 Mg ha⁻¹ biochar application. Overall, this study suggests that appropriate application of biochar and slag fertilizer promotes soil pH improvement and contributes to increased willow yield. Hence, CHP-derived biochar and steel slag demonstrate potential as effective fertilizers for willow cultivation.

Keywords: CHP, biochar, steel slag, willow, pH

A collage of images related to solid biofuels, including wood logs, green biomass, and wood pellets, set against a green background with a large circular graphic element.

Solid biofuel

AN INVESTIGATION INTO THE CO-DENSIFICATION PROCESS FOR BRIQUETTE PRODUCTION USING BLENDS OF RAW AND TORREFIED EUCALYPTUS SAWDUST

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This study evaluates the effects of incorporating torrefied eucalyptus sawdust on briquette densification, mechanical strength, and combustion. Briquettes were produced with torrefied fractions of 25% and 50% at 200, 250, and 300 °C. ANOVA shows significant effects of torrefaction temperature and torrefied fraction and a significant temperature–fraction interaction. Quadratic models fit the compressive-strength data with adjusted R^2 of 0.61 for the 25% series and 0.92 for the 50% series. All briquettes achieve apparent bulk densities between 1188.09 and 1289.09 kg·m⁻³, while the control is approximately 1150 kg·m⁻³, which confirms effective compaction. Density gains are more consistent at 25% addition than at 50%. Compressive strength increases with severity up to an optimum and then decreases as temperature approaches 300 °C. For the 50% series, strength peaks near 220–240 °C and declines at 300 °C. Burn time above 150 °C increases with both torrefaction severity and torrefied fraction. The 50ET300 condition shows the longest burn and the highest combustion index but requires a larger ethanol ignition aid to initiate. Moderate torrefaction at 250 °C combined with a 50% torrefied fraction provides the best balance between mechanical durability and stable high-temperature combustion

Keywords: Eucalyptus torrefield, co-densification, binder

ANALYSIS AND PRODUCTION OF BRIQUETTE BLENDS FROM BIOMASS: (ALGAE + COFFEE WASTE) AND PLASTIC.

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The growing demand for energy in sectors such as transportation, industry, domestic activities etc, has intensified environmental impacts from daily waste disposal, highlighting the need for sustainable solutions. The purpose of this research is to produce briquettes using commonly discarded and abundant materials, such as polypropylene plastic, coffee waste, and algae (*Cosmarium sp.*) as an alternative to fossil fuels. Including polypropylene in the blends increases the calorific value of the briquettes, while the addition of algae and coffee waste is intended to reduce the use of agricultural chemicals, offering an ecological benefit by redirecting pollutants into energy production. The methodology included literature review, gathering and processing of materials (drying at 100°C to 12% humidity, followed by grinding and sieving into 0, 20 and 40 mesh), and production of 11 briquette blends with varying plastic concentrations (5%, 7.5%, and 10%) at different temperatures (0°C, 60°C, and 120°C), which six briquettes were produced per blend using an automated briquetting machine. Afterwards, their volumetric expansion was analyzed up to 72 hours post-production. Elemental analyses were performed to determine moisture, volatile matter, ash content and fixed carbon quantities. Preliminary results showed that the most efficient blend included 5% plastic, due to its high combustion properties and low ash content, enhancing energy efficiency. Therefore, this study demonstrates the viability of transforming organic and synthetic waste into high-energy briquettes offering a promising alternative to non-renewable fuels, especially in regions with agricultural waste excess and limited access to clean energy.

Keywords: Biomass; Briquettes; Renewable Energy; Coffee Waste Biofuel; Algae Biofuel.

BIOCALC: A NOVEL LIFE CYCLE-BASED TOOL FOR QUANTIFYING THE CARBON CREDITS OF SOLID BIOFUELS IN BRAZIL

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The increasing global demand for low-carbon energy sources has intensified interest in solid biofuels, such as pellets, particularly in regions with abundant biomass availability like Latin America. However, methodological and regulatory challenges persist in assessing their carbon footprint and integrating them into carbon credit schemes. This study presents BioCalc, a novel computational tool adapted from the Brazilian RenovaCalc model to quantify the carbon intensity of solid biofuels under a Life Cycle Assessment (LCA) framework. The tool incorporates harmonized emission factors, land use change modeling, and cradle-to-grave system boundaries to enable robust assessments. Three biomass sources—peanut shell, Pinus, and Eucalyptus—were analyzed across domestic, export, and mixed market scenarios. BioCalc calculated carbon intensity and potential decarbonization credits (CBIOs) using three LCA approaches: standard attributional LCA, Circular Footprint Formula (CFF), and zero-burden assumption. Results revealed substantial emission reductions—up to 97% compared to fossil fuels—and highlighted methodological sensitivities in credit quantification, with CFF yielding the highest economic potential. National production forecasts were evaluated, projecting up to USD 103.9 million in revenues under specific conditions. This research provides a policy-aligned, science-based pathway for integrating solid biofuels into regulated and voluntary carbon markets. It strengthens the case for regulatory updates to include densified biomass fuels in Brazil's decarbonization strategies and offers a replicable model for advancing circular bioeconomy principles in the global energy transition.

Keywords: Life Cycle Assessment, Carbon Intensity, RenovaBio, Decarbonization Policies, Pellets

BRIQUETTES FROM PHYTOREMEDIATING GRASSES: AN ENERGY SOLUTION FOR AREAS CONTAMINATED BY CADMIUM

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Areas degraded by mining face serious environmental challenges, primarily due to contamination by heavy metals such as cadmium (Cd). Phytoremediation using extractor plants is an effective recovery method. However, the contaminated biomass still represents a technical and environmental obstacle. In this context, briquetting emerges as a sustainable strategy, converting this contaminated waste into solid biofuels with potential for domestic and industrial use, especially when combined with forestry residues. This study evaluated the potential of biomass from the grass *Megathyrsus maximus* cv. Mombaça, grown in Cd-contaminated soil, with and without the addition of *Eucalyptus* spp. for briquette production. The contaminated biomass originated from a phytoremediation experiment conducted in microcosms with 100 dm³ of Entisol, artificially contaminated (8.0 mg Cd dm⁻³), plus a control, at UFVJM. The grass was grown for 210 days, processed, and compacted (20 g) into briquettes using a hydraulic press, with and without a 50% mix of eucalyptus residues sourced from a forestry company. Five treatments were evaluated: pure eucalyptus (T1), uncontaminated biomass (T2), uncontaminated biomass + eucalyptus (T3), contaminated biomass (T4), and contaminated biomass + eucalyptus (T5). Chemical and energetic characterization of the biomass and the physical and energetic properties of the briquettes were evaluated. All treatments demonstrated energetic viability, regardless of contamination. The addition of eucalyptus contributed to the dilution of the metal and an improvement in the energetic quality of the briquettes. The briquetting of phytoremediating biomass proves to be a promising solution for the recovery of degraded areas, combined with clean energy generation.

Keywords: degraded areas; briquetting; contaminated biomass; bioenergy; phytoremediation.

CHARACTERIZATION AND EVALUATION OF THE ENERGY POTENTIAL OF ORANGE BAGASSE

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Climate change, fossil fuel scarcity, and the growing energy demand reinforce the urgency of strategic alternatives for energy conversion. In this context, the citrus sector, particularly orange juice processing industries, offers substantial potential for bioenergy recovery. Global orange processing (17.14 million metric tons), led by Brazil, Mexico, and the United States, generates large volumes of residues (peel, pulp, and seeds) that are often underutilized. This study aimed to characterize the chemical and thermophysical properties of these residues and assessed their energy availability. The results revealed attractive fuel properties, with lower heating value ($LHV_{db} = 14.92 \text{ MJ} \cdot \text{kg}^{-1}$), ultimate and proximate compositions comparable to those of sugarcane bagasse, a biomass widely employed in Brazilian sugar-energy facilities. However, a significant ash content (>6%) suggests potential risks of corrosion and fouling in thermal systems. Despite the high theoretical energy potential, the natural moisture content (>80%) represents a critical challenge, requiring reduction to enable efficient combustion. To address this challenge, scenarios combining preliminary mechanical pressing with subsequent drying in rotary dryers were assessed in terms of net energy availability. Even under conservative assumptions, these approaches not only met the thermal demand of the juice concentration stage but also generated surplus energy for additional uses, such as biomass drying for animal feed production. Overall, the valorizing of citrus residues as solid biofuel emerges as a promising strategy to enhance energy self-sufficiency in the sector, reduce dependence on external fuels, mitigate environmental liabilities, and lower operational costs.

Keywords: orange waste, laboratory analyses, proximate analysis, ultimate analysis, heating value, energy recovery

EFFECT OF BARK BLENDING WITH WOOD PARTS ON ASH FUSION CHARACTERISTICS AND INHIBITION OF SLAG DERIVED FROM K–CA CARBONATE MELTS UNDER GASIFICATION CONDITIONS

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In response to Japan's 2050 carbon neutrality target and the increasing demand for decentralised renewable energy, small-scale fixed-bed gasification systems using woody biomass are gaining attention. Japanese cedar (*Cryptomeria japonica*), abundant in domestic forests, is a key biomass source; however, slag formation during gasification, primarily caused by low ash fusion temperatures and potassium-rich ash, limits operational stability. This study investigates the influence of blending different anatomical parts—heartwood, sapwood, and bark—on ash fusion temperatures and slag behaviour. Ash fusion tests, thermogravimetric/differential thermal analysis, X-ray diffraction, X-ray fluorescence, and thermodynamic equilibrium calculations were conducted under a CO₂ atmosphere. Heartwood ash exhibited low hemisphere temperatures and foaming, linked to CO₂ release from the decarbonation of K₂CO₃ and CaCO₃. In contrast, bark blending increased CaO/K₂O ratios and substantially raised hemisphere temperatures. When the Ca/(Ca + K₂) molar ratio exceeded 83%, hemisphere temperatures rose above 1420 °C, suppressing slag formation. X-ray diffraction and thermodynamic analyses revealed that the presence and transformation of K–Ca carbonates—specifically fairchildite, bütschliite, K₂CO₃, and CaCO₃—played a critical role in governing ash melting behaviour. These findings provide a practical approach for controlling slag via biomass blending, improving the performance and reliability of gasifiers. They also suggest new utilisation strategies for woody residues such as bark as slag formation inhibitors, contributing to a resilient and sustainable bioenergy system.

Keywords: bark, sapwood and heartwood, biomass ash, ash melting, K₂CO₃–CaCO₃, forming phenomenon, gasifier.

EFFECT OF OXIDATIVE DELIGNIFICATION AFTER ACID PRETREATMENT WITH LIQUID FRACTION RECYCLING ON THE RELEASE OF FERMENTABLE SUGARS

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Sugarcane bagasse is a promising lignocellulosic biomass for the production of fermentable sugars, but its high recalcitrance limits enzymatic accessibility. Combined pretreatment strategies can overcome these barriers. This study aimed to evaluate oxidative delignification with hydrogen peroxide after acid pretreatment to enhance sugar release. To reduce costs, the liquid fraction from the acid pretreatment was reused and its efficiency was analyzed. The pretreatment with 1% v/v H₂SO₄ was carried out in five cycles, in triplicate, using 10% bagasse (25 g) in 225 mL of solution under autoclaving at 121 °C for 1 h. After each cycle, the solid was separated, washed to neutral pH, and dried, while the liquid fractions were characterized by high-performance liquid chromatography. The resulting biomass underwent oxidative delignification with 7.5% v/v H₂O₂ at pH 11.5, 50 °C for 1 h, followed by enzymatic hydrolysis with cellulase (10 FPU/g) in 50 mM citrate buffer at 50 °C and 150 rpm for 48 h. The results indicated that the combined process significantly increased the availability of reducing sugars compared to acid pretreatment alone. The synergistic effect observed demonstrates that integrating multiple cycles of acid hydrolysis with alkaline oxidation is a promising strategy to maximize sugarcane bagasse conversion into fermentable sugars, supporting advances in the production of biofuels and bioproducts.

Keywords: Sugarcane Bagasse; Oxidative Delignification; Acid Hydrolysis.

EFFECT OF PRETREATMENT ON THE COMBUSTION KINETICS OF SUGARCANE BAGASSE: COMPARISON OF INERT AND OXIDATIVE TORREFACTION

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Torrefied biomass typically exhibits enhanced combustion performance; however, there is a lack of studies directly comparing the combustion kinetics of torrefied biomass under inert and oxidative atmospheres. To address this gap, the present study provides a comparative evaluation of the thermal, chemical, and kinetic behavior of raw and torrefied sugarcane bagasse at torrefaction temperatures of 200, 225, 250, and 300 °C, with particular emphasis on combustion kinetics. The biomass samples were characterized, subjected to torrefaction, and subsequently analyzed through thermogravimetric (TG) techniques. Within the temperature range of 200 to 250 °C, torrefied sugarcane bagasse showed similar physicochemical characteristics and combustion behavior in both atmospheres. However, the combustion indices of torrefied samples in oxidative atmosphere were slightly lower than those of the samples treated under inert conditions. These findings suggest that, within the temperature range of 200 to 250 °C, oxidative torrefaction provides an optimal balance between mass yield, energy yield, and higher heating value (HHV). This condition represents a promising operational window for the pre-treatment of sugarcane bagasse, with potential applications in industrial processes that utilize hot flue gases from other processes.

Keywords: Combustion index, Biomass pretreatment, Kinetic Analysis, Dry torrefaction, Combustion reactivity, Comparative assessment, Thermal decomposition

EFFECT OF SULFURIC ACID IN THE HYDROTHERMAL CARBONIZATION PROCESS OF SEWAGE SLUDGE

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Hydrothermal carbonization (HTC) is a promising thermochemical route for the treatment and valorization of wet biomass, such as sewage sludge (SS), which has a composition rich in organic materials and nutrients with potential for agricultural use, converting it into hydrochar (HC) and process water (PW). The challenges of waste management are related to the increase in the production of sewage sludge, with landfills and incineration as the most common disposal or management technologies, where both alternatives present drawbacks regarding pollutants and the high moisture content of the biomass. This study aimed to carry out the hydrothermal carbonization of SS and evaluate the effect of adding 1% (m/m) sulfuric acid (H₂SO₄) in the HTC process. The sewage sludge was collected from an anaerobic sewage treatment plant located in Toledo-PR. The experiments were conducted at 200 °C for 3 h, with a solid content of 10%, in a 0.5-L reactor at autogenous pressure. The evaluated responses included the yield of hydrochar, proximate analysis (moisture, volatiles, fixed carbon, and ash), calorific value (HHV), nutrient extraction efficiency, and FTIR for evaluating chemical and structural modifications. The addition of sulfuric acid resulted in an increase in HC yield (from 59.6% to 63.0%), enhancing the carbon retention in the solid phase, besides additional benefits such as ease of dewatering due to the higher hydrophobicity of the HC. Overall, HTC with acid addition improved the process, promoting greater carbon densification and nutrient recovery, proving to be a viable and sustainable strategy for sewage sludge management.

Keywords: Waste management; hydrothermal processes; nutrient recovery; biomass conversion; circular economy.

EFFECT OF TORREFACTION ATMOSPHERE ON THE COMBUSTION PERFORMANCE OF SUGARCANE BAGASSE BRIQUETTES

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Torrefaction has gained significant attention as an effective thermal pretreatment technique to improve the physicochemical properties of biomass. Torrefied biomass generally has a better combustion performance. Most studies on lignocellulosic biomass combustion rely on thermogravimetric analysis under idealized conditions with small sample masses, while few investigate bench-scale combustion and the performance of torrefied briquettes under different torrefaction atmospheres. The present study aims to analyze and compare the combustion behavior of sugarcane bagasse briquettes torrefied under inert and oxidative atmosphere. Biomass was initially characterized and subsequently subjected to torrefaction at 200, 250 and 300 °C. Briquetting was conducted under consistent pressure, time, and temperature conditions. Bench-scale combustion tests were then performed on both raw and torrefied samples, followed by the evaluation of combustion indices to compare their performance. Torrefied Sugarcane bagasse at temperatures between 200 and 250 °C yield a torrefied material with improved physicochemical properties for combustion processes, with the highest combustion index observed at 250 °C under a partially oxidative atmosphere, highlighting a notable advantage over the more costly inert torrefaction. The torrefaction temperature directly influences the physicochemical properties of the material, which in turn affects the briquetting pretreatment. Together, these factors determine the overall combustion performance.

Keywords: Bench-Scale, Inert torrefaction, oxidative torrefaction, Biomass, Combustion Index

ENERGETIC CHARACTERIZATION AND HEATING VALUE OF TERNARY BLENDS OF SYNTHETIC FABRIC, SUGARCANE BAGASSE, AND EUCALYPTUS

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The improper disposal of textile waste, driven by fast fashion, represents a severe environmental problem, highlighted by the accumulation of tons of clothes in Chile's Atacama Desert. In this context, the energy recovery from this waste emerges as a necessity for a sustainable solid biofuel. This study aimed to analyze the energy potential of synthetic fabric waste, sugarcane bagasse, and eucalyptus wood, both individually and in blends, for future use in briquette composition. Proximate analysis (% ash, volatiles, and fixed carbon) was performed on the pure components and four mixtures, and the Higher Heating Value (HHV) was determined by empirical correlation. According to the results, eucalyptus showed the highest average HHV among the pure components, at 21.35 MJ/kg. Among the blends, Mixture 3 (50% eucalyptus, 30% fabric, and 20% bagasse) was the most effective, with an HHV of 19.98 MJ/kg, while Mixture 4 (50% bagasse, 30% fabric, and 20% eucalyptus) registered the lowest value at 19.26 MJ/kg. Notably, Mixture 2 stood out as the most balanced, as despite having the highest proportion of fabric (80% fabric, 10% bagasse, and 10% eucalyptus), it maintained a high HHV of 19.86 MJ/kg. The analysis demonstrated that it is feasible to incorporate up to 80% fabric in a blend without significant energy loss. It is concluded that blending textile waste and agricultural biomass is a promising strategy for resource valorization, validating a high potential for diversifying the energy matrix.

Keywords: Biomass; Proximate Analysis; Textile Waste; Agricultural Residues

EUCALYPTUS BARK AND RDF BLENDS: ASSESSING ENERGY, ASH, EMISSIONS, AND COMPONENT CONTRIBUTIONS

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Eucalyptus bark, a low-energy biomass, offers potential for energy enhancement when blended with high-calorific-value industrial wastes such as Refuse-Derived Fuel (RDF). However, RDF is highly heterogeneous, which complicates material characterization, and contains elements such as chlorine that can affect combustion, causing boiler corrosion and toxic gas emissions. This project aims to investigate mixtures of eucalyptus bark and RDF in different proportions, as well as the contribution of major RDF components. The study will chemically characterize the blends and their individual materials, and evaluate the calorific value, ash content, and emissions during combustion. The findings will provide insights into optimal mixture ratios, the role of individual RDF components, and support strategies for the efficient and environmentally responsible use of biomass in industrial combustion systems.

Keywords: biomass, solid biofuel, bioenergy

EXTRUDED BRIQUETTES OF RICE HUSK AND COFFEE HUSK BIOCHAR: EFFECT OF BINDER CONTENT ON PHYSICO-MECHANICAL AND ENERGY PROPERTIES

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The thermochemical valorization of agro-industrial residues is a relevant strategy for Brazil's energy transition and circular economy. This study evaluated the production and performance of extruded briquettes from rice-husk and coffee-husk biochars, using wheat flour as a binder at 0, 4, 8, and 12 wt%. Biochars were produced in batch kilns and characterized by proximate analysis and higher heating value (HHV). Carbonization of rice husk increased fixed carbon by 30%, but its high ash content (46%) lowered HHV to 14 MJ kg⁻¹. Coffee-husk biochar showed 51% fixed carbon, 10% ash, and HHV of 24 MJ kg⁻¹. Binder-free briquettes exhibited poor cohesion in both materials. Adding binder enhanced bulk density, energy density, and mechanical strength, with optimum results at 8 wt%. At this level, coffee-husk briquettes reached 0.85 g cm⁻³, 350 kPa, and low friability (2.8%). Rice-husk briquettes reached 0.77 g cm⁻³ and high compressive strength (1.31 MPa), but did not meet ISO durability (friability 15%), indicating the need for process adjustments. Although 12 wt% binder improved density, it increased friability and fungal susceptibility, limiting storage and logistics. The results demonstrate that briquetting rice- and coffee-husk biochars is a promising route to produce densified solid fuels, with 8 wt% binder offering the best property balance. However, the high ash content of rice husk requires further optimization to meet domestic fuel standards. This study provides formulation and processing guidelines to expand the solid-biofuels portfolio from agricultural residues, reinforcing their role in emission mitigation and local value creation. **Keywords:** durability; residues; circular economy; energy densification

Keywords: Biochar; rice husk; coffee husk; binder; energy densification.

GREEN-RFD: A SOLUTION FOR TEXTILE WASTE DISPOSAL IN THE ATACAMA DESERT

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The production of briquettes from textile waste and cassava rhizome presents an efficient energy densification strategy, converting challenging waste into useful, sustainable energy. Our findings show that combining these materials overcomes individual limitations, such as the high volumetric expansion and low impact resistance seen in pure textile waste briquettes. The cassava rhizome's starch acts as a natural binder, significantly reducing these issues. This starch promoted enhanced dimensional stability, increased fixed carbon content, and improved mechanical strength in the briquettes, all without compromising their calorific value. Through experimental assessment of various formulations, the 25% textile waste and 75% cassava rhizome blend demonstrated optimal overall performance. This blend exhibited high calorific value, low volumetric expansion, excellent durability, impact resistance, and high energy density. Furthermore, its volatile, ash, and fixed carbon contents align with industrial standards. Although the maximum energy density (13.14 MJ/m³) of the 25% textile/75% cepa briquettes is lower than conventional fossil fuels like diesel and gasoline, these briquettes offer an efficient, sustainable alternative for energy and industrial uses. They notably contribute to effective waste management and reduced environmental emissions. Applying this study to the textile waste problem in the Atacama Desert, a rudimentary economic model projects an energy output of 1900.5 TJ. Additionally, the economic value achievable from utilizing the 25% textile/75% Cepa blend is estimated at US\$49,000,000.00

Keywords: Energy densification; Briquetting; Textile waste; Cassava rhizome, economic analysis.

HYDROGEN-RICH SYNGAS PRODUCTION FROM SUGARCANE RESIDUES VIA THERMAL REFORMING

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Biomass gasification is a promising low-carbon emission energy pathway due to the carbon-neutral potential of its feedstock. However, concerns regarding the "tank or table" dilemma and agricultural waste management have increased interest in second- and third-generation biofuels. Syngas produced by gasification typically has low hydrogen content and contains undesirable compounds like tars, which condense at lower temperatures and cause operational issues like clogging or catalyst deactivation. Therefore, an upgrading step is necessary to meet the requirements of subsequent processes. This study aims to evaluate sugarcane bagasse and straw – by-products of Brazil's sugar and ethanol industry – and thermal reforming, a process that remains not much studied. Baseline gasification tests for tar and syngas characterization and combined gasification–thermal reforming experiments were carried out using a newly designed reformer reactor. Each biomass, after being dried and milled, was pelletized to increase the rheology of the material in the feeding system. The amount of gasifying agents were determined based on equivalence ratio and steam-to-biomass ratio values found in the literature., while reforming temperature was selected from prior studies conducted at the same conditions. Thermal reforming simulations of the gas produced from each biomass gasification were performed in Aspen Plus using Peng-Robinson thermodynamic model and an RGibbs reactor to complement and support the experimental work. Raw syngas from straw showed higher concentrations of light hydrocarbons and 1.3 vol.% more hydrogen (dry basis) than bagasse syngas. These findings support thermal reforming as a pathway for valorising sugarcane residues into a cleaner and hydrogen-rich syngas.

Keywords: Thermal reforming, hydrogen-rich syngas, sugarcane residues

LIGNOCELLULOSIC RESIDUE FROM 2G ETHANOL AS AN EFFECTIVE BINDER FOR ENHANCING THE QUALITY OF PINE SAWDUST BRIQUETTES

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This study investigated how binder type and concentration influence the performance of pine sawdust briquettes. Two binders were assessed, cassava starch and a lignocellulosic residue from second-generation ethanol production. Briquettes were formed at 127 MPa with 0 to 20 % binder by mass and were characterized for proximate and ultimate composition, higher heating value, apparent density, compressive strength, 72-hour longitudinal expansion, and moisture uptake. Analysis of variance showed a significant effect of binder concentration on mechanical performance. Compressive strength followed a quadratic pattern with minima at about 8 % cassava starch and 4 % lignocellulosic residue, decreasing at low concentrations and recovering at higher concentrations. Apparent density increased steadily with concentration. Relative to the briquette without binder, density increased from 869 to 1061 kg m⁻³ at 20 % lignocellulosic residue and volumetric energy density rose from 17.55 to 21.77 GJ m⁻³. The lignocellulosic residue increased the higher heating value relative to the briquette without binder and reduced short-term longitudinal expansion compared with cassava starch at matched concentrations. Taken together, the results indicate that 10 to 20 % lignocellulosic residue by mass delivers the best overall balance of densification, mechanical strength, dimensional stability, and energy quality for producing high-quality solid biofuel.

Keywords: Pine sawdust, binder, lignocellulosic residue, ethanol 2G, cassava starch

MECHANICAL STRENGTH IMPROVEMENT OF AMAZONIAN AÇAÍ SEED BRIQUETTES THROUGH STATISTICAL MODELING AND OPTIMIZATION

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The energetic valorization of Amazonian açaí seed waste into compacted fuels, such as briquettes, requires the optimization of their mechanical strength to ensure efficiency in transport, storage, and handling. This study aimed to model and optimize the production parameters of açaí seed (*Euterpe oleracea* Mart.) briquettes to enhance their mechanical resistance. Briquettes were produced from ground seeds (< 0.5 mm) with 12% moisture content at temperatures ranging from 120-160 °C and pressures of 15-25 MPa. Diametral compression strength of 45 briquettes was measured using a universal testing machine (EMIC-DL 30000N). Linear regression models proved inadequate due to heteroscedasticity and lack of fit, even after Box-Cox transformation. In contrast, a Generalized Linear Model (GLM) performed robustly (adjusted $R^2 = 0.8308$), with statistically significant coefficients that confirming the influence of process variables on strength. The GLM indicated optimal conditions of 184.75 °C and 15.44 MPa, with a predicted strength of 3931.89 KPa. However, the significant lack of fit suggests that the model did not fully capture the complexity of the system. The presence of low compressive strength values at the minimum temperature tested (an average of 265.33 KPa for treatments at 120 °C) likely influenced the model to project an optimal temperature beyond the experimental range. The GLM is the most suitable approach for optimizing and investigating the impact of production parameters on briquettes. Future studies should expand the temperature range to validate the predicted optimum and refine the mechanical performance of açaí seed briquettes as a sustainable biofuel.

Keywords: *Euterpe oleracea*, Amazon, Compressive Strength, Biomass Valorization, Solid Biofuel

OXIDATIVE TORREFACTION OF EUCALYPTUS WOODCHIPS WITH HEMATITE AS A SOLID HEAT CARRIER

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In recent years, the growing demand for energy has increased the prominence of renewable sources, with biomass recognized as the fourth major contributor. In Brazil, eucalyptus wood chips generated from industrial processing represent a particularly important biomass resource. These chips are mainly used as fuel across several industries; however, like other biomass feedstocks, they present drawbacks such as low calorific value and high moisture content. These limitations can be mitigated through torrefaction. Among the approaches described in the literature, oxidative dry torrefaction has drawn attention. A specific variant involves immersing the biomass in a bed of inert mineral, though this method remains under investigation. One limitation of using mineral materials in this context is their low thermal conductivity, which may negatively impact the process. To address this issue, this study proposes the use of a metal-based inert medium. Specifically, hematite-assisted oxidative torrefaction of eucalyptus chips is evaluated, with variations in the temperature range and bed height systematically investigated. The findings indicate that the mass yield of torrefied biomass decreases with increasing temperature but increases with greater hematite bed height. Overall, hematite-assisted oxidative torrefaction enhances the high heating value, reduces moisture content, and improves hydrophobicity of eucalyptus chips.

Keywords: Biomass; Mineral layer; Oxidative torrefaction; Eucalyptus Woodchips

OXIDATIVE TORREFACTION OF EUCALYPTUS WOODCHIPS USING A SILICA SAND LAYER FOR BIOENERGY ENHANCEMENT

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Due to the growing demand for energy, renewable sources have gained increasing relevance. Among them, biomass is considered the fourth major energy source. In Brazil, eucalyptus woodchips represent a significant biomass residue from industrial processes and are widely used as fuel. However, like other types of biomasses, eucalyptus chips present limitations such as high moisture content and low high heating value. This study investigates silica sand-assisted oxidative torrefaction as a low-cost strategy to upgrade eucalyptus woodchips. The aim is to evaluate the effect of temperature (200–300 °C), residence time (30 and 60 minutes), and mineral layer height (3, 6, and 12 cm) on the energy properties of eucalyptus woodchips. Results show that mass yield decreases with increasing temperature and time, while the enhancement factor increases under the same conditions. Torrefaction at 300 °C with a 3 cm sand layer and 60 minutes residence time achieved the highest enhancement factor and improved higher heating value. The height of the sand layer affects both oxygen diffusion and heat transfer, influencing torrefaction severity and product properties. Thermogravimetric and elemental analyses confirm the progressive decomposition of hemicellulose and cellulose, leading to carbon enrichment in the final product. Overall, silica sand-assisted oxidative torrefaction significantly enhanced the fuel characteristics of eucalyptus woodchips, offering a promising method for industrial biomass upgrading.

Keywords: Biomass; Torrefaction; Mineral layer; Eucalyptus woodchips.

PARAMETRIC STUDIES ON THE TORREFACTION OF URBAN TREE PRUNING BIOMASS FOR BIOENERGY RECOVERY: IMPLEMENTING A COMBINED MIXTURE-PROCESS EXPERIMENTAL DESIGN APPROACH

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Urban tree pruning residues represent an abundant yet underutilized biomass resource. This study aims to investigate the torrefaction behavior of urban tree pruning biomass, considering variations in the proportions of branches, leaves, and moisture, as well as process parameters such as temperature, heating rate, and residence time. A mixture-process design was employed to evaluate response variables, including mass yield, energy yield, index of torrefaction, fuel ratio, and energy density. The results indicate that both biomass composition and torrefaction parameters significantly influence the responses. Temperature was the most influential factor affecting torrefaction severity, while the effects of residence time and heating rate became more prominent at higher temperatures. For a sample composed of 69.2% branches, 17% leaves, and 13.8% moisture, assessment targeting high index of torrefaction and energy yield results in a temperature of 260 °C, a heating rate of 3 °C/min, and a residence time of 60 min, achieving a higher heating value of 20.8 MJ/kg and an energy yield of 91.2%. It was also observed that as I_{torr} increased, energy density improved, and geometric mean diameter decreased. These findings contribute to the valorization of urban tree pruning biomass by identifying suitable torrefaction conditions based on the feedstock composition, thereby enabling the process to adapt to the inherent variability of urban pruning residues.

Keywords: Biomass blends, Branch, Leaf, Thermochemical pretreatment, Torrefaction severity

POULTRY LITTER VALORIZATION BY HYDROTHERMAL CARBONIZATION FOCUSING ON HYDROCHAR PRODUCTION AND ENERGY POTENTIAL

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Poultry litter is one of the main residues generated by Brazilian poultry farming, an industry in which Brazil stands out as the world's largest exporter of chicken meat and ranks third globally in terms of production volume. Recent changes in production practices, such as the increased number of flocks raised on the same bedding and the use of lime as a sanitizing agent have altered the characteristics of this waste, demand effective, safe and sustainable management technologies. Hydrothermal carbonization (HTC) is a thermochemical process that converts biomasses under aqueous subcritical conditions (160–250°C, under autogenous pressure). Recently, HTC emerged as a promising technology for converting wet biomass into hydrochar, a carbon-rich material with potential applications in energy, agriculture and environmental sectors. In this context, this study aims to evaluate the application of HTC for the valorization of poultry litter, focusing on hydrochar production and the assessment of its energy content and nutrient potential. Experiments were carried out in a 0.5 L high-pressure batch reactor at 200 °C (with a heating rate of 7.5 °C/min) for 3 h, without agitation, 10% of solids content and 50% reactor volume filling. The study evaluates the yields of the reaction products (hydrochar and process water) and their physicochemical properties, energy content, and nutrient composition. Characterization techniques were applied to the solid and liquid fraction, namely, proximate analysis, TGA-DTG, HHV, elemental analysis (TXRF), and FTIR. The results indicate the HTC as a viable and sustainable route for poultry farming residues valorization, aligned with bioeconomy principles.

Keywords: HTC; biomass conversion; chicken manure; biocoal; biofertilizers.

PREDICTION OF WET BASIS MOISTURE CONTENT OF BIOMASS DURING DRYING USING ARTIFICIAL NEURAL NETWORKS

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This study employs a Multilayer Perceptron (MLP) to predict the moisture content of biomass wood chips during convective drying with heated air, using 4,333 experimental samples including mass, moisture, temperature, air velocity, time, and water removal rates. The dataset underwent a thorough preprocessing stage, including outlier removal, normalization, and verification of consistency across all experimental measurements, ensuring high-quality inputs for training the network. After data cleaning and normalization, 90% of the samples were used for training, and 5% for validation and testing, respectively. The network architecture consisted of 11 input neurons, 15 hidden neurons with the hyperbolic tangent activation function, and 1 output neuron with a linear function. The selection of the network topology was guided by preliminary sensitivity analyses to optimize predictive accuracy while avoiding overfitting. Training was performed using backpropagation in MATLAB. The model achieved a mean squared error (MSE) of approximately 0.0963 and a Pearson correlation coefficient greater than 0.9 in all phases, indicating that the network effectively captured the complex nonlinear relationships between the drying parameters and moisture content. The robustness of the model was further confirmed by consistent performance across both validation and independent test datasets, demonstrating high accuracy and robustness, with strong potential for industrial application in biomass drying process optimization.

Keywords: Biomass, artificial neural networks, drying, wet basis moisture content

PROPOSAL FOR PORE FILLING TO INCREASE THE ENERGY PROPERTIES OF ANY TYPE OF SOLID BIOMASS

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The main objective of this work is to propose an alternative method to increase the energy properties of briquettes made from any type of wood. The method basically consists of filling the pores of the briquettes with carbonaceous solids. The biomass used as a test for this purpose was the *Anadenanthera macrocarpa* (Benth). Particles of this material were compacted at pressures up to 300 MPa without the use of binders or heat treatment. Subsequently, the briquettes obtained were immersed in an aqueous solution enriched with 63% carbonaceous solids until their porous microstructures were saturated and finally subjected to heat treatment. The briquettes produced were characterized by measuring compacted, bulk, and energy densities, porosity, immediate analysis, and determination of the upper and lower calorific values. Complete briquettes were obtained with energy density values up to 11969 MJ/m³. In terms of energy, briquettes made from any wood, produced under the same conditions, are also expected to show a considerable increase in their energy density. Additionally, spark interest in: a) its use in energy generation in boilers; b) add value to solid biomass waste; c) reducing the large amount of these materials discarded as waste in the areas where they are produced; d) creation of an alternative for reducing deforestation in several areas of the country, such as in the Center-West, particularly in the state of Mato Grosso, where the implementation of new forest plantations is very difficult. Keywords: Energy density; Briquettes; Carbonaceous Solids; Binders; Porosity

Keywords: keywords: Energy density; Briquettes; Carbonaceous Solids; Binders; Porosity.

SOLID FUEL FROM BIOMASS BLENDS AND PLASTIC AS BINDER

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The economic development of a country is strongly linked to its energy consumption, as this reflects the level of industrialization. Since the Industrial Revolution, the global economy has largely relied on fossil energy sources such as oil and coal, which are major contributors to pollution, climate change, and global warming. As a result, the search for alternative energy sources has become necessary, and the use of renewable energy has grown in recent years. This research project analyzes the production of briquettes made from a mix of coffee grounds, wood pieces, and municipal solid waste (MSW), using plastic as a binder. The goal is to evaluate whether this combination improves the fuel quality and structural integrity of the briquettes, considering both technical and environmental aspects. The project involved a proximate analysis of the biomass, along with the determination of the Higher Heating Value (HHV) of the materials. After that, the biomass underwent an energy densification process to form the briquettes, followed by resistance and durability tests. The results showed that the blends had an average heating value of 18.07 MJ/kg, volatile matter content of 80.64%, ash content of 3.15%, and fixed carbon content of 16.25%. These results indicate that the blends have favorable chemical properties for energy generation and for use as solid fuel. Therefore, the energy densification of these residues offers an effective and sustainable alternative for adding value to these materials, resulting in a fuel with high energy potential.

Keywords: Bioenergy; Biomass; Densification; Waste

STUDY OF THE FUSIBILITY OF SOLID BIOFUELS ASHES

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Energy generation from renewable resources has grown in recent years due to the need to reduce the use of petroleum derivatives for economic and environmental reasons. Solid biofuels have proven to be an alternative for both electricity production and the transportation sector. To efficiently utilize these materials in their various applications, their characteristics must be understood. This study aims to map the melting temperature of ash in biomass samples. The methodology applied was based on the physical-chemical analysis of sugarcane bagasse and wood chips samples, using standardized methods. These materials were selected because they are the most widely used as a sustainable energy source. Ash is a solid residue formed in boilers during the combustion of materials and must have suitable properties, such as a melting temperature compatible with the process. The melting characteristics of ash are directly related to its chemical composition, since the presence of certain elements can impact the melting behavior of materials. A lack of information on this parameter can result in problems such as incrustations and unexpected interruptions in generation unit operations. Despite the importance of this topic, there is still a lack of scientific literature on the fusibility of ash from solid biofuels.

Keywords: Boiler ash; Biomass; Fusibility; Biofuels

SYSTEMATIC ANALYSIS OF BABASSU COCONUT SHELL COMBUSTION USING TG, FTIR, ACTIVATION ENERGY, AND PREDICTION OF GAS EMISSIONS

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In this study, the thermal behavior of babassu coconut shell (BCS) combustion was analyzed by systematizing data obtained from thermogravimetric analysis, FTIR spectroscopy, molar ratios (H/C and O/C), and prediction of the combustion gases. The isoconversional methods of Friedman, Ozawa–Flynn–Wall (OFW) and Kissinger–Akahira–Sunose (KAS) were utilized to evaluate the kinetics in the conversion range 0.1 - 0.9. The molar ratio of H/C was ~ 1.3 -1.8, and O/C ~ 0.45 -0.9. The FTIR spectra showed functional groups compatible with lignocellulosic biomass. The average activation energies were 152 kJ mol⁻¹ (Friedman), 180 kJ mol⁻¹ (KAS), and 190 kJ mol⁻¹ (OFW). The percentage of combustion gases was 21.05% for CO₂, 0.012% for NO, and 0% for SO₂. The results of E and the prediction of emitted gases agree with other lignocellulosic biomasses. The findings substantiate the viability of BCS for utilization in combustion processes.

Keywords: Babassu coconut shell; activation energy; isoconversional methods; gas emissions; FTIR

TEMPERATURE EFFECT ON HYDROCHAR YIELD FROM SEWAGE SLUDGE VIA HYDROTHERMAL CARBONIZATION

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The amount of sewage sludge (SS) generated worldwide has been increasing along with population growth, making it necessary to treat it properly to protect the environment and human health. SS is a wet biomass that usually needs drying steps for its management. However, hydrothermal carbonization (HTC) is a thermochemical treatment that uses heat and pressure in the presence of water to produce a solid, carbon-rich product called hydrochar (HC), along with process water (PW). These products can be used to generate energy as biocoal, serve as a soil conditioner, agricultural fertilizer, among other applications. This study aims to evaluate the influence of the reaction temperature on the hydrochar yield from SS and to analyze its properties. The sewage sludge was collected from an anaerobic sewage treatment plant located in Toledo-PR, and it was used as HTC feedstock. The experiments were conducted in a 0.5-L high-pressure reactor, under operating conditions of 10% of total solids, at three different temperatures (160°C, 180°C and 200°C) and autogenous pressure for 3h. Hydrochar (HC) and process water (PW) were separated by vacuum filtration. The yields were calculated taking into account all mass losses in the reactor components. Among the tested conditions, the yield obtained at 160°C was the highest, resulting in 79.8%, compared to 59.9% at 180 °C and 59.6% at 200 °C. Overall, the results show that the HTC can be a promising technology for wet waste management, such as sewage sludge, for its valorization into valuable products, namely, energy and fertilizers.

Keywords: Wet biomass; HTC; biocoal; biomass conversion; circular economy.

TECHNO-ECONOMIC AND LIFE CYCLE ANALYSIS OF HYDROGEN PRODUCTION FROM EUCALYPTUS GASIFICATION IN MINAS GERAIS, BRAZIL

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This study assesses the feasibility of hydrogen production via eucalyptus biomass gasification in Minas Gerais, Brazil, through an integrated techno-economic analysis and Life Cycle Assessment (LCA). The ReCiPe Midpoint (H) method was applied to evaluate nine environmental impact categories, with Global Warming Potential (GWP) emerging as the most critical, highlighting the relevance of greenhouse gas (GHG) mitigation. The techno-economic results identified feedstock cost (1135 USD/ton H₂) as the primary economic driver, followed by transportation (713 USD/ton H₂) and capital expenditure (619 USD/ton H₂). Economic viability is highly sensitive to hydrogen selling prices: a price of 5000 USD/ton H₂ yields a payback period of three years, while 3000 USD/ton H₂ extends it to 15 years, significantly affecting investment attractiveness. LCA results indicate that hydrogen produced via biomass gasification emits approximately 1610 kg CO₂-eq/ton H₂—an 85% reduction compared to steam methane reforming (10400–13900 kg CO₂-eq/ton H₂). This reduction is primarily attributed to biogenic carbon uptake during eucalyptus growth. However, impact categories such as Human Non-Carcinogenic Toxicity (HNCT), Terrestrial Ecotoxicity (TEC), and Fossil Resource Scarcity (FRS) showed elevated contributions from biomass cultivation, feedstock transport, and steam generation. These findings underscore the importance of adopting more sustainable agricultural practices and decarbonized process inputs. Overall, the study reinforces the potential of renewable hydrogen from lignocellulosic biomass as a key contributor to GHG emission reduction and the broader clean energy transition.

Keywords: Renewable energy, Sustainability, Emissions, Life cycle assessment, Economic feasibility

WATER LEACHING AS A PRETREATMENT TO IMPROVE THE THERMOCHEMICAL PROCESSMENT BEHAVIOR OF ELEPHANT GRASS AND EMPTY FRUIT BENCH

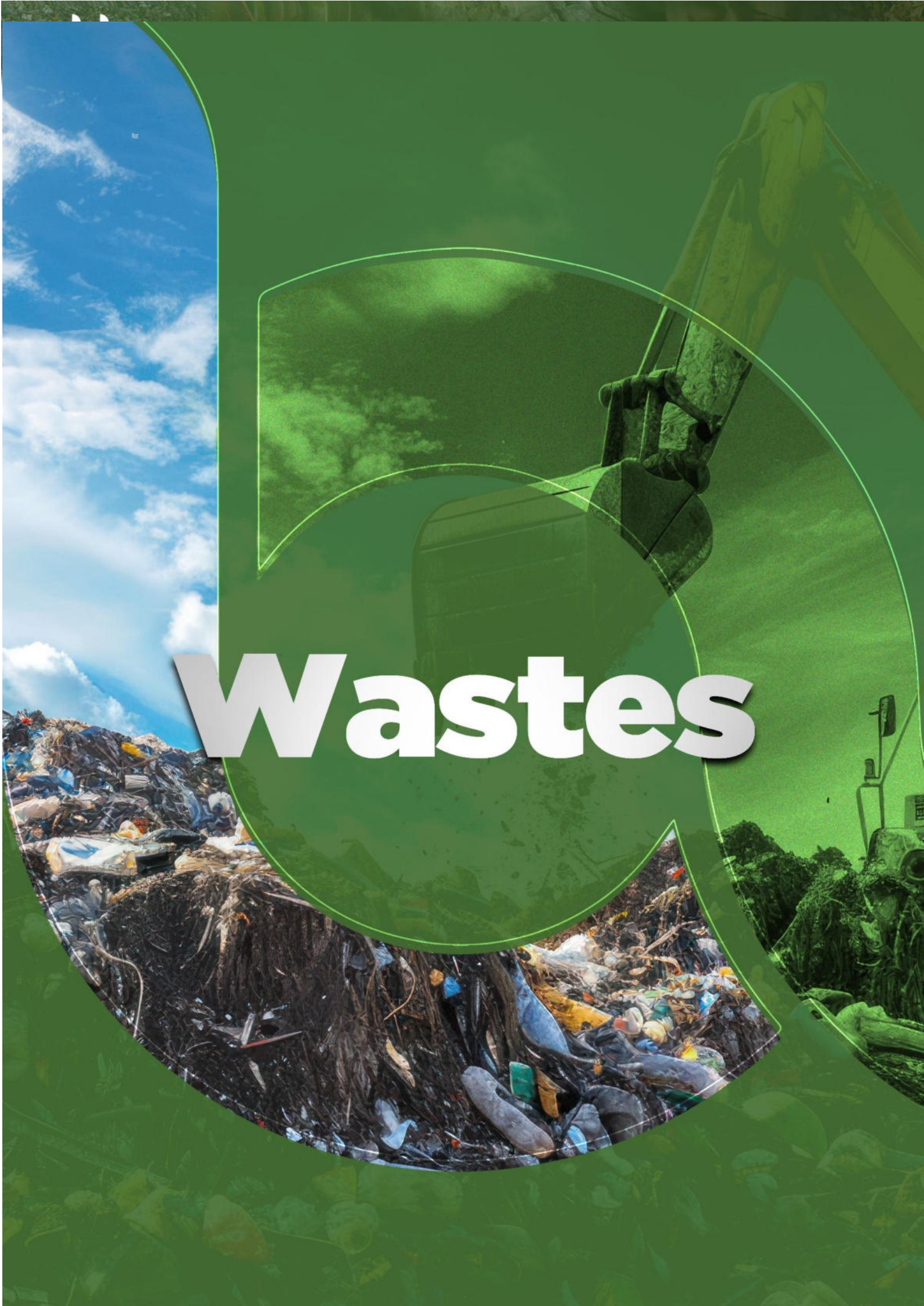
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Elephant grass (EG) and palm empty fruit bunch fiber (EFB) are promising biomass sources for bioenergy production. Nevertheless, their elevated concentrations of chlorine, alkaline ash, and other inorganic contaminants hinder their direct use in combustion systems, due to risks of slagging, fouling, and increased emissions. This study aimed to evaluate water leaching as an effective pretreatment method to lower the inorganic ash content in EG and EFB, improving their thermochemical conversion performance. A factorial design was implemented to investigate the influence of particle size, leaching time, and water-to-biomass ratio on ash removal, with EG serving as the reference feedstock. Among the variables tested, particle size had the greatest impact, with ash content reduced by up to 41% in milled samples (

Keywords: biomass pre-treatment; water leaching; particle size; ash removal



Wastes

ACID HYDROLYSIS OPTIMIZATION AND ETHANOL PRODUCTION FROM RUBBER TREE SEEDS

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Ethanol is a biofuel produced from the fermentation of reducing sugars (RS) from biomass, a renewable feedstock, capable of substituting gasoline in internal combustion engines. Moreover, ethanol production from residual feedstocks is highly advantageous. In this context, the rubber tree (*Hevea brasiliensis*) is cultivated across the world for the extraction of latex, simultaneously producing large quantities of seeds that are rich in oil, which may be extracted through mechanic pressing and used to produce biodiesel, and carbohydrates. These seeds, however, do not possess large scale applications currently. As such, this work aimed to analyze the ethanol production from pressed rubber tree seeds (PRTS). For this, the PRTS composition was analyzed and the acid hydrolysis of PRTS with sulfuric (H₂SO₄), hydrochloric (HCl) and phosphoric (H₃PO₄) acids was optimized, yielding 353.14 ± 3.35 g RS/kg PRTS and generating 4.819 mg of furfural and hydroxymethylfurfural fermentation inhibitors/g PRTS. Finally, fermentation tests using the RS obtained with the hydrolysis of PRTS were carried out, using *Saccharomyces cerevisiae* yeast. The highest obtained ethanol yield was of 50.11 ± 2.04 mL/kg of PRTS, only 35.94 ± 1.47 % of the theoretical yield. The main reason for this low yield was the high concentration of salts created due to the neutralization of the acids used in the acid hydrolysis, which may be solved by increasing the hydrolysates' dilution. Despite this, ethanol was still produced and, as such, it is possible to affirm that the production of ethanol from PRTS is possible.

Keywords: Biofuel; Second generation ethanol; Acid hydrolysis; Residue; Optimization; Rubber tree seed.

ANAEROBIC MONO AND CO-DIGESTION OF FOOD AND GARDEN WASTE: EFFECTS OF PARTICLE SIZE, INOCULUM RATIO, AND THERMAL PRETREATMENT ON BIOGAS PERFORMANCE

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The increasing volume of municipal solid waste (MSW) in urban areas presents both environmental and operational challenges. This study investigated the potential for biogas production generated at a higher education institution (HEI), using food waste (FW) and garden waste (GW) as substrates. Physical (grinding to 4 mm and 6 mm) and thermal (autoclaving GW at 120 °C for 30 min) pretreatments were applied to improve biodegradability. Mono- and co-digestion of the residues were evaluated under varying inoculum-to-substrate (I:S) ratios (1:1, 1:2, and 1:3), in batch reactors operated at 35 °C for 40 days. Methane content was estimated using the ADM1-R3 model implemented in the SuperPro Designer simulation software, along with the OBA platform. FW mono-digestion yielded the highest methane production, especially at moderate I:S ratios and bigger particle sizes. Methane yield was more sensitive to particle size than volume, with 6 mm particles generally outperforming 4 mm at I:S ratios of 1:1 and 1:2. Thermal pretreatment significantly enhanced methane yield at an I:S ratio of 1:3, with increases of 55.7% and 84.4% for 4 mm and 6 mm particles, respectively; however, this effect was not observed at lower I:S ratios. The final methane content in the biogas ranged from 56% to 65%. These findings underscore the relevance of tailored pretreatment strategies, particularly thermal disruption of lignocellulosic biomass—in improving anaerobic co-digestion efficiency and supporting decentralized energy generation from institutional organic waste.

Keywords: Anaerobic co-digestion, Food waste, Garden waste, pretreatment, Biogas production, Inoculum-to-substrate ratio

APPLICATION OF RICE HUSK ASH: COMPOSITION AND POTENTIAL

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Rice husk is an abundant biomass, and the utilization of its combustion ashes can add value and reduce environmental impacts. This study characterized fly ashes derived from rice husk combustion in a fixed-bed boiler to assess their reuse potential. Analyses included particle size distribution, moisture content, bulk density, chemical composition (EDS), proximate analysis, higher heating value (HHV), FTIR, and pH. The ashes exhibited fine and homogeneous particles, low moisture content (2.06%), and low bulk density (274,5 kg/m³), indicating good physical stability. Chemically, they showed high ash content (81,5%) and significant levels of phosphorus (7.5%) and silica (29,1%), suggesting potential for use as an alternative fertilizer or soil amendment. The pH values were acidic (4.05), unlike most biomass ashes, attributed to the high presence of acidic oxides such as silica and phosphates, and low concentrations of alkaline cations (Ca, Mg). FTIR analysis confirmed the presence of phosphate and silicate groups, while XRD revealed KH₂PO₄ as the predominant phase, explaining the acidic character. Rice husk ashes stand out due to their high nutrient content and acidity, showing promise for agricultural use, especially as a renewable source of phosphorus, contributing to sustainability and circular economy initiatives.

Keywords: Acidic biomass ash, Soil amendment, Silica-rich ash, Phosphorus content

ASH CHARACTERIZATION AND ENERGY RECOVERY POTENTIAL

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The growing demand for energy has highlighted the need for more sustainable and diversified sources. In this context, biomass emerges as a strategic alternative, but its combustion generates ash that is often discarded without being used. Considering that some ash may have significant fixed carbon content and calorific value, as a result of an inefficient boiler, investigating its potential for energy recovery is relevant. The objective of this work is to physically and chemically characterize ash from the combustion of different biomasses in boilers, evaluating its reuse as a secondary fuel. The methodology involves the collection of bottom and fly ash, followed by laboratory analyses of moisture, bulk density, particle size, ash content, volatiles, and fixed carbon, in addition to the determination of the gross calorific value and morphological characterization by SEM/EDS. The results are expected to reveal significant differences between ash types depending on the source biomass, allowing us to identify those with the greatest potential for energy recovery. Samples with higher fixed carbon content and higher calorific value can be reused in combustion processes, reducing primary biomass consumption. Granulometric analysis should indicate the influence of particle size on combustion efficiency, while density and moisture parameters will help understand the physical behavior of the ash. Microstructural and chemical analyses will provide detailed information on the mineral elements present, contributing to a more comprehensive assessment of the residue. In this way, we hope to propose strategies for recovering energy from ash, promoting environmental and economic gains.

Keywords: Biomass; FCB Ash; Energy recovery; Physicochemical characterization; Sustainability.

BIOCHAR FROM AGRICULTURAL WASTE GASIFICATION: CHARACTERIZATION AND POTENTIAL FOR NUTRIENT RECOVERY AND SOIL ENHANCEMENT

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Gasification is a thermochemical process that converts biomass into syngas and biochar under limited oxygen conditions. It offers a sustainable treatment alternative for agricultural residues such as tomato plant waste (TPW), which are often, polluting, landfilled or inadequately managed. Unlike biochar derived from dry pyrolysis, gasification-based biochar has been less studied for soil amendment applications. This study evaluated biochar produced from five TPW-to-wood chip feedstock ratios, using both laboratory- and pilot-scale gasification systems. Efficient operation was maintained with feedstocks containing up to 40% TPW; higher ratios led to operational failure due to filter clogging within 30 minutes. The resulting biochar exhibited nutrient concentrations of phosphorus (0.72%), potassium (7.64%), magnesium (3.14%), calcium (0.26%), nitrogen (28.66%), and carbon (15.18%), while heavy metal contents remained below regulatory thresholds. The biochar was hydrophobic, suggesting potential to improve water retention in coarse-textured soils, such as sand. These characteristics highlight its agronomic value and environmental safety for use in arid and semi-arid agricultural systems. Overall, the findings emphasize the dual benefits of gasification for renewable energy generation and production of value-added soil amendments. This aligns with circular economy principles and offers a sustainable strategy for agricultural waste valorization. Further field-scale studies are warranted to evaluate the long-term effects on soil health and crop productivity.

Keywords: agriculture residues treatment, biochar, syngas, sustainable desert agriculture

CITRUS WASTE VALORIZATION THROUGH SUPERCRITICAL CO₂ EXTRACTION OF LIMONENE

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The present study presents a novel experimental and economical approach to citrus waste valorization based on the extraction of limonene from orange, lemon, lime and tangerine peels using supercritical CO₂, with focus on Brazilian varieties of citrus fruits. Samples of citrus fruit wastes were pre-processed by drying at 60°C for 24 hours and submitted to extraction using CO₂ at 150 bar and 35°C for 30 minutes. The results of the extractions were used to estimate the cost of manufacture of limonene, which ranged from US\$ 50 to US\$ 530 /kg of extract, depending on the variety of citrus fruit. The use of energy recovery in the CO₂ cycle would increase the economic feasibility of this strategy, with 10% lower manufacture costs for the extracts.

Keywords: Waste; Citrus; Orange; Lemon; Limonene; Supercritical Extraction

COMPUTATIONAL FLUID DYNAMICS (CFD) OF A HYDROTHERMAL CARBONIZATION BATCH REACTOR

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Hydrothermal carbonization (HTC) is a thermochemical process that converts biomass under aqueous environment at subcritical conditions (160–250°C) under autogenous pressure (10–50 bar), which has been recently emerging as a promising thermochemical route for waste management through the circular economy and valorization of wet biomasses into energy and high-value products. Computer-aided engineering (CAE) and computational fluid dynamics (CFD) are powerful tools for engineering design, optimization, and scale-up of processes, since they allow a complex understanding of the behavior of phenomena with little or no experimentation. Particularly, for HTC, this is relevant since the reactor operates at high-pressure and temperature conditions, making it difficult to collect experimental and operational data. In this context, this work aims to develop a CAE/CFD model to simulate and optimize a batch reactor used in the hydrothermal carbonization (HTC) process. For this, a 3-D transient simulation was performed in Ansys Workbench/Fluent 2025 R1 from a 1-L high-pressure stirred reactor (Parr 4520), which was drawn using Ansys SpaceClaim software and simulated, aiming to investigate the fluid dynamics and heat transfer of the HTC process. The operational conditions of the HTC process were heating rate of ca. 2 °C/min, reaction temperature of 200°C for 2.5 h and stirring speed of 200 rpm. As responses, pressure, momentum, temperature and velocity profiles, as well as vector streamlines, were obtained. Ultimately, the goal is to obtain data to support the understanding of fluid dynamics and heat transfer and to optimize the reactor's operational parameters to improve the reaction performance.

Keywords: Computer-aided engineering; heat transfer; HTC; process simulation; reactor design

CONSOLIDATED BIOPROCESSING OF EUCALYPTUS CHIPS KRAFT PULP USING A MULTIPLE HYDROLYTIC ENZYME PRODUCER *Saccharomyces Cerevisiae*

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The consolidated bioprocessing (CBP) of biomass comprehends the enzyme production, biomass hydrolysis, and fermentation simultaneously in a single reactor, being a potential technology for the valorization of lignocellulosic wastes, such as eucalyptus chips. The complexity of biomass hydrolysis makes understanding the influence of process parameters on CBP performance a key factor for its scale-up in biorefineries. Process operation at high solids loading is important to achieve high product titers, however the low water availability and enzyme adsorption in lignin makes it challenging. In this sense, the present work investigated the CBP of eucalyptus pulp at different solids loadings (0.4-10%wt.) and different moisture contents (5-60%) using the recombinant *Saccharomyces cerevisiae* AC14, which secretes seven hydrolytic enzymes. Strategies to increase biomass hydrolysis conversion and ethanol production were evaluated by adding soybean protein as a lignin blocker and supplementing the medium with commercial enzymes. Ethanol production of 11.5 g/L with a productivity of 0.96 g/L/h were observed in only 12h at 10%wt. solids loading and 60% of moisture without enzyme addition. However, the best results were obtained when exogenous enzyme was added (27.8 g/L, 1.7 g/L/h) highlighting the importance of the development of efficient enzyme-producing microorganisms and the optimization of CBP conditions to maximize enzyme production to achieve higher biomass conversion.

Keywords: Consolidated bioprocess, eucalyptus crips, kraft pulp, recombinant *Saccharomyces cerevisiae*, enzymatic hydrolysis, ethanol 2G

DARK FERMENTATIVE BIOHYDROGEN PRODUCTION BY *Clostridium butyricum* USING CASHEW APPLE BAGASSE HYDROLYSATE: EFFECT OF GLUCOSE AND GLYCEROL MODULATION

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The increasing demand for sustainable energy sources has led to growing interest in biohydrogen as a clean and renewable alternative to fossil fuels. Biotechnological production is widely used, however optimizing process parameters remains essential, whether through favorable modulation of the biochemical route toward enhanced biofuel production. Therefore, this study explores the potential of cashew apple bagasse as a lignocellulosic feedstock for biohydrogen production through dark fermentation. The influence of supplementing the fermentation medium with glucose and glycerol, a valuable byproduct of the biodiesel industry, was evaluated. Enzymatic cashew apple bagasse hydrolysate was obtained after sequential acid-alkali pretreatment followed by enzymatic hydrolysis using cellulase from *Trichoderma reesei* ATCC 26921 and β -glucosidase NS 50010. Batch fermentations were performed in shaker at 35 °C, pH 7.0, 150 rpm for 72 h using *Clostridium butyricum*, and hydrolysate as culture medium under varying glucose concentrations (10 or 20 g/L) with glycerol supplementation (1 or 5 g/L). The highest hydrogen production was achieved with 20 g/L glucose and 5 g/L glycerol, yielding $2,604.0 \pm 336.3$ mL/L of hydrogen, equivalent to 4.3 ± 0.6 mol H₂/mol glucose and 2,294.3 L of H₂ per 1,000 kg of bagasse. Additionally, value-added byproducts such as butyric, acetic, lactic, and formic acids were generated, with applications in food, pharmaceutical, and chemical industries. These findings highlight the feasibility of integrating biohydrogen production into agro-industrial systems, as it can be used to operate irrigation robots, offering a sustainable route for waste valorization and supporting circular economy and the United Nations Sustainable Development Goals.

Keywords: cashew apple bagasse; enzymatic hydrolysate; dark fermentation; glycerol supplementation; biohydrogen.

DEFATTED SPENT COFFEE GROUNDS-DERIVED ACTIVATED BIOCHAR FOR FREE FATTY ACID REMOVAL FROM WASTE COOKING OIL TOWARD SUSTAINABLE BIODIESEL PRODUCTION.

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Waste cooking oil (WCO) is a strategic feedstock for biofuels (biodiesel and sustainable aviation fuel). However, due to the high free fatty acids (FFA) WCO content ($\geq 2\text{mgKOH/g}$), the purification/esterification process is necessary prior to transesterification. This study produced activated biochar from spent coffee grounds (SCG) to FFA removal from WCO (soybean oil). SCG was pretreated via Soxhlet extraction with hydrated ethanol for oil extraction, yielding defatted spent coffee grounds (DSCG), that was impregnated with ZnCl_2 , H_3PO_4 , or KOH followed by activation at 600°C under N_2 flow. Activated biochars were characterized by SEM, BET, TG/DTG, and Iodine Number (IN). Samples with surface area $\geq 400\text{ m}^2/\text{g}$ and $\text{IN} \geq 600\text{ mg I}_2/\text{g}$ were tested for FFA adsorption in lab-degraded soybean oil (SODC4, 4 mgKOH/g) and further analyzed by FT-IR, XPS, and point of zero charge (PZC). ZnCl_2 -activated biochar (1:1 ratio, ABZ1-1) exhibited the best performance: $616\text{ m}^2/\text{g}$ surface area, $797\text{ mg I}_2/\text{g}$ IN, and 80% FFA removal at 20% m/m biochar to oil. Kinetics followed pseudo-second-order model ($R^2=0.992$), and isotherms fitted Langmuir model ($R^2=0.995$) with q_m of 19 mgKOH/g , indicating a chemisorption monolayer adsorption. Commercial activated carbon (CA-Sigma) showed lower effectiveness. In an adsorption with WCO from a local restaurant ($\sim 4\text{ mgKOH/g}$), BBZDZnCl₂ 1-1 achieved 33% FFA removal, though insufficient for base catalyst biodiesel production. This work found that ZnCl_2 -activated DSCG biochar is a viable alternative for WCO pretreatment with lower FFA content. Further studies should evaluate upscaling parameters (temperature, agitation, adsorption method) and adsorption of others WCO contaminants.

Keywords: coffee grounds, biochar, cooking oil, free fat acids, biomass, biodiesel.

DEVELOPMENT OF AN ORGANIC-MINERAL BIOFERTILIZER FROM ENRICHED SEWAGE SLUDGE WITH FLY ASHES

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Fly ashes are residuals from the combustion of biomass, mainly in the power generating industries, known for their high pH value. Also, the sewage sludge results of the water and common thrash treatment from the cities and towns, known for the big presence of organic matter in their composition. The present study discusses about the enrichment of sewage sludge with fly ashes, in order to neutralize the pH of the sewage sludge, making it a potential alternative for industrial fertilizers. The material characterization, through the proximate analysis: moisture, volatile matter, ashes and fixed carbon. With the pH values, they compound the main properties analyzed. Besides that, the compost with sewage sludge and ashes were realized according to different portions, being 90/10, 70/30 and 50/50, for both of the residuals. The tests were realized with radish seeds, with a full spectrum LED lamp, with a 12 h light/12 h dark cycle. The expected results are the neutralization of the pH of the compost, its effectiveness as a biofertilizer, making it usable as a complete renewable resource to the agricultural industry and the optimization of the mixture, achieving the best utilization of both residues. Finally, the utilization of sewage sludge enriched with fly-ashes shows great potential, since both the residues are commonly produced in large scale, and it can substitute completely or partially the utilization of industrial fertilizers.

Keywords: Residues; pH; Neutralize; Portions; Renewable.

EFFECT OF BIOMASS PARTICLE SIZE ON BREWERS' SPENT GRAIN PRETREATMENT FOR SIMULTANEOUS ISOMERIZATION AND FERMENTATION

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The production of bioethanol from lignocellulosic by-products, such as brewers' spent grain (BSG), is seen as a pivotal strategy in the global energy transition. However, the main sugar released after biomass pretreatment (xylose) is not assimilated by the yeast *Saccharomyces cerevisiae*. This limitation can be overcome by the use of exogenous enzyme xylose isomerase to isomerize xylose to xylulose together with the yeast through SIF (Simultaneous Isomerization and Fermentation). The optimization of biomass pretreatment is a critical step in biomass processing and can be significantly affected by particle size due to limitations in mass transfer. In this context, the present work evaluated the influence of BSG particle in the release of fermentable sugars during the pretreatment step aiming to BSG valorization through SIF process. In addition, the detoxification of BSG hydrolysate through two different methods was evaluated: liquid-liquid extraction using oleic acid and the adsorption in 2% activated charcoal. The use of larger BSG particles led to a higher sugar concentration and less inhibitor production. Adsorption and liquid-liquid extraction were both effective strategies for the removal of fermentation inhibitors, resulting in improved process performance. The presence of inhibitors in the hydrolysate significantly influenced the SIF process, with a decrease in sugars assimilation rate from 3.9 to 2.0 g/L/h when using crude hydrolysate. The best fermentation performance was obtained using BSG hydrolysate detoxified with activated charcoal (0.46 g/g, 0.62 g/L/h). These results contribute to the development of a process for the valorization of BSG in the concept of biorefinery.

Keywords: biomass pretreatment, liquid-liquid extraction, adsorption, 2G ethanol, phenolic compounds

EFFECT OF KILN DRYING WITH LOAD ON CORRECTION OF WARP OF LUMBER – A LUMBER PRODUCTION TECHNOLOGY WITH MINIMAL WASTE

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When logs are sawn along the pith to produce structural lumber, residual stresses within the log are released, causing lumber to warp. This is often a serious problem for lumber-without-pith. This not only reduces lumber yield, but also requires correction sawing to remove the warp, resulting in increased waste and costs. Therefore, it is important to develop a technology that can produce structural lumber without the need for correction sawing, while simultaneously minimizing waste. Based on this background, this study focused on producing straight lumber by performing a series of kiln drying under load. Using lumber- without-pith and lumber-with-pith sawn from large diameter logs of Japanese cedar as materials, two types of kiln-drying schedule were tested. One was the high temperature drying (HT-drying) with 8 hours steaming at 90°C followed by 16 hours drying at 120/90°C (DB/WB), followed by 11 days drying at 80~90/60°C (DB/WB), while the other was the low-vacuum-medium-temperature drying (LVMT-drying) with 12 hours steaming at 80°C followed by 10 days, 40 kPa, 80~90/55~65°C (DB/WB)), both with load (650kgf/m²) to the stacked green lumber to address these questions. It was confirmed that residual stresses were eliminated, and lumber warps were corrected by the optimal schedules of kiln-dryings, and the HT-drying was found to be relatively effective than the LVMT-drying. This technology produces straight lumber without the need for corrective sawing, while minimizing waste and costs, and is expected to improve the sustainability of forestry.

Keywords: sawmill waste, forest product, plantation, cost reduction, sustainable forestry

EFFECT OF IMPROVEMENTS IN SELECTIVE COLLECTION RATES ON LANDFILL GAS GENERATION: A CASE STUDY FOR URBAN SOLID WASTE IN THE MUNICIPALITY OF SANTO ANDRÉ/SP

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This study aimed to evaluate the energy recovery of municipal solid waste (MSW), through the capture of biogas in landfills, as a relevant strategy to generate electricity, in addition to reducing greenhouse gas emissions (GHG). The municipal solid waste (MSW) of Santo André, a municipality located in the Metropolitan Region of São Paulo, with 748,919 inhabitants and daily generation of 640.02 tons of MSW, was evaluated. The municipality has a selective door-to-door collection, serving all neighborhoods, with recycling rates of around 5%. Three scenarios were analyzed, considering different recycling rates and national targets for 2040. From secondary data on the gravimetric composition and the average rate of waste generation, for each scenario a mass balance was carried out to determine the quantity and composition of waste destined for landfills and the generation of biomethane. The study found that energy recovered from landfill gas could supply electricity to up to 6,100 city residents. However, this estimate may not be precise, as the IPCC Model is generic and does not account for local MSW generation or specific properties. The increase in recycling rates has resulted in a decrease in the theoretical global estimate of biogas, as predicted by the IPCC model (2006), which uses the total organic carbon of the different fractions of solid waste to calculate biogas production.

Keywords: Energy recovery, Landfill gas, Urban Solid Waste, Selective Collection, biogas.

ENERGETIC CHARACTERIZATION OF COMPOSITES FORMULATED WITH REFUSE-DERIVED FUEL (RDF) AND BAUXITE RESIDUE

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Refuse Derived Fuel (RDF) is a solid fuel obtained from municipal and industrial waste, while bauxite residue (RB) is a by-product of aluminum production. Both are generated in large quantities, demanding sustainable alternatives for their use. This study analyzed the calorific value of composites produced with different contents of RDF and BR. The formulations included: RDF 100%, RDF 90% + RB 10%, RDF 80% + RB 20%, RDF 70% + RB 30%, RDF 60% + RB 40%, and RDF 50% + RB 50%. Energy characterization was conducted by determining the gross calorific value (GCV) in a calorimetric bomb. Samples were quartered to minimize heterogeneity, resulting in six replicates. Statistical analysis was performed using Analysis of Variance. The results showed that the composite with RDF 90% + RB 10% had the highest calorific value, while RDF 50% + RB 50% presented the lowest. The formulations with RDF 80% + RB 20% and RDF 70% + RB 30% did not differ significantly. These variations may be related to siliceous components present in the raw materials, which reduce the calorific value. Despite this reduction, the controlled incorporation of RB into RDF produced energetically viable composites, especially compared with other solid wastes commonly used for energy purposes. Moderate addition of RB proved capable of influencing the energy efficiency of composites while enabling the recovery of industrial waste. Therefore, this study reinforces the potential of combining RDF and RB for sustainable energy generation, promoting waste valorization and reducing environmental impacts linked to their disposal.

Keywords: Refuse Derived Fuel; Bauxite Residue; Gross Calorific Power; Composites; Waste; Waste-to-Energy.

ENERGY RECOVERY OF SOLID AGRO-INDUSTRIAL WASTE: BYPRODUCT IN THE FORM OF BRIQUETTES

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The generation of solid waste and the associated negative environmental and socioeconomic impacts are increasing. Agro-industrial waste generated in the production and processing stages of agricultural and forestry products constitutes an important part of the total solid waste generated in countries with large agroforestry production, such as Brazil. The energy contained in solid agro-industrial wastes can be recovered through various technologies. The recovery or energy use of this waste in the form of high added value biofuels (i.e. briquettes) appears as a promising alternative for disposing the large amount of solid waste generated by agro-industry. Therefore, this study aims to propose the energy recovery of solid waste generated in agro-industry as an energy byproduct in the form of briquettes. Three solid wastes generated by agro-industry were defined: (i) Wood sawdust; (ii) Tomato bagasse; and (iii) Corn bagasse. These wastes were chosen due to the large quantities generated by agro-industry in Brazil. They were evaluated as they are generated in the production process (*in natura*) and after briquettes production. The use of tomato and corn wastes *in natura* in 100% composition was not considered satisfactory for energy generation, especially due to the high moisture content. The addition of small wood sawdust fractions to the corn and tomato wastes *in natura* improves their energy characteristics. Drying the wastes and subsequent briquetting significantly improved their energy characteristics, and therefore constitute the indicated technological route for the energy recovery of tomato bagasse, corn bagasse and wood sawdust.

Keywords: Biomass; valorization; biofuels; residue

ETHYL ESTERS PRODUCTION VIA DIRECT TRANSESTERIFICATION OF BIOMASS OLEAGINOUS FUNGI CULTIVATED IN AGRO-STARCHY WASTEWATERS

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The production of biodiesel from microbial lipids obtained from filamentous fungi is distinguished by the capacity to employ diverse substrates for microbial cultivation, thereby fostering the reuse of agro-industrial residues and supporting the development of versatile processes within agribusiness. Such residues are generated in substantial amounts worldwide during food processing and industrialization. For instance, the global starch sector is primarily supplied by five raw materials: corn, wheat, rice, potatoes, and cassava. Accordingly, the present study aimed to investigate the application of starchy raw materials as culture mediums for the growth of *Mucor circinelloides* and to produce biodiesel via direct transesterification of the resulting oleaginous biomass. Wastewater derived from corn, wheat, rice, potatoes, and cassava was employed as the carbon source. Fermentations were conducted in a bioreactor at 26 °C for 120 h, supplemented with solid residues generated during the brewing process of beer as a growth factor. The oleaginous biomass was subjected to direct transesterification using aluminum oxide-supported heteropolyacid catalyzed ethanol. The starch substrates were efficiently assimilated by the microorganism, yielding elevated biomass concentrations (10.5–16.2 g L⁻¹). The lipid fraction was predominantly composed of palmitic (21.7–22.9%) and oleic acids (25.4–25.9%). Direct transesterification reactions reached mean ester yields of 95.5% g g⁻¹, with minimal monoacylglycerol and diacylglycerol content. Overall, the findings demonstrate that biodiesel production through direct transesterification of *M. circinelloides* biomass cultivated in starchy wastewater streams constitutes a promising and sustainable alternative for renewable energy generation.

Keywords: Lipid, Biodiesel, starch, waste water, fungus

EVALUATION OF THE CHEMICAL PRECIPITATION PROCESS FOR THE RECOVERY OF NUTRIENTS FROM SWINE MANURE DIGESTATE

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The swine production in Brazil generates large volumes of organic waste, which still pose an environmental challenge. Anaerobic digestion, widely adopted to treat these wastes, produces biogas and digestate, the latter being a nutrient-rich byproduct. However, its direct application to soil without technical criteria can cause nutritional imbalances and contamination of water bodies. In this context, the aim of this work was to investigate the feasibility of nutrient recovery from digestate through chemical precipitation forming struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$), or magnesium ammonium phosphate (MAP) a commercial fertilizer. Physicochemical analyses (pH, moisture, total solids), FTIR spectroscopy, and TXRF were performed to quantify the elements present in the digestate. For comparison, precipitation was also carried out with raw manure, prior to the anaerobic digestion process. The precipitation was conducted by adding magnesium chloride (MgCl_2) and adjusting the pH to 9. Results indicated precipitate formation in both samples, with lower yield (1,92 g/L) in the digestate compared to raw manure (17,94 g/L), due to the reduction of organic matter during digestion. Despite this, the precipitated products showed significant nutrient potential. Thus, this approach presents a viable alternative for the utilization of swine waste as agricultural fertilizer. Furthermore, it reinforces the importance of nutrient recovery as a strategic tool for food security, reduction of dependence on imported fertilizers, and promotion of a circular economy.

Keywords: Digestate; nutrient recovery; struvite; swine manure; chemical precipitation.

FROM POLLUTANT TO RESOURCE: TEXTILE WASTE-TO-ENERGY AS A CIRCULAR ECONOMY MODEL FOR BRAZIL

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The relentless growth of the global textile industry, driven by the fast fashion model and ever-growing consumerism, generates increasing volumes of post-consumer and industrial textile waste. Primarily composed of non-degradable polyester, this waste is typically landfilled or incinerated without energy recovery, resulting in significant environmental and economic burdens. Without intervention, this trend will continue to strain urban waste management systems. This study maps the current scenario of textile waste generation and its contribution to pollution, with a focus on mismanaged streams. It then investigates the potential of directing this waste toward energy recovery as a sustainable alternative within a circular economy model. A systematic bibliographic review is being conducted to compare the industrial cases that have successfully implemented textile-to-energy solutions. The methodology identifies operational processes, plant capacities, and best practices in real case studies, providing robust, data-driven processes and waste management solutions. Expected research outcomes include a comprehensive overview of the success of waste-to-energy cases, exploring how textile waste can be transformed into renewable energy while demonstrating scalability and sustainability. The discussion will highlight actionable lessons for other regions, including Brazil, where large-scale textile waste remains largely unmanaged, presenting a major opportunity for a circular approach. In conclusion, this research focuses on demonstrating that planned energy recovery of textile waste provides both environmental and economic benefits. It transforms a persistent and resistant pollutant into a valuable resource, providing practical models that can inform sustainable industrial practices and accelerate the transition toward a more circular and resilient textile sector.

Keywords: Circular Economy; Waste-to-Energy (WtE); Textile Waste Management; Sustainable Development; Fast Fashion

FROM WASTE TO WARMTH: A REVIEW ON INSULATING MATERIALS FROM INDUSTRIAL, AGRICULTURAL, AND FOREST RESIDUES

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The review explores the thermal and hygroscopic behavior of various waste-derived materials and their environmental impacts, with a particular focus on their potential to enhance thermal comfort in building. We discuss a wide range of residues, primarily from agricultural, forest and industrial sources, highlighting their technical performance, environmental advantages, and limitations when used as building insulation materials. Key contributions of this review include: A comprehensive assessment of recent developments in the use of waste materials for thermal insulation in the construction sector. A critical discussion on the benefits, drawbacks, and life cycle consideration associated with these materials. Insights into how waste-based insulation products can compete with conventional materials in terms of thermal performance and cost-effectiveness. Identification of research gaps and future opportunities in the field are presented.

Keywords: biomass; agricultural waste; industrial waste; forest waste; bio-based waste material; thermal insulation; hygroscopic property

HETEROPOLYACID-CATALYZED HYDROLYSIS OF BREWERS' SPENT GRAIN FOR BIOFUEL PRODUCTION

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The annual volume of agro-industrial waste continues to grow in tandem with technological advancements and production increases, particularly within the brewing industry. In response, new biomass processing alternatives are continually being developed with a focus on sustainability, specifically for brewers' spent grain (BSG). Heterogeneous catalysts emerge as a green and sustainable option, adding value to this co-product within a biorefinery framework causing less environmental harm. This study investigates the hydrolysis of BSG using a thermally stable heteropolyacid catalyst. Under optimized conditions, a maximum glucose yield of 88.34% was achieved, while other conditions yielded significant conversions of 53.49% and 46.31%. These results highlight the substantial potential of the hydrolysate for producing biofuels and cereal alcohols via fermentation. Furthermore, this approach offers a new pathway for the industrial management of brewing residues, effectively promoting circular economy strategies.

Keywords: biomass; agro-industry; waste; hydrolysis; heteropolyacid-catalysis; biofuels.

HYDROGEN PRODUCTION VIA BIOMASS ENTRAINED-FLOW GASIFICATION IN A TWO-STAGE REACTOR USING ASPENPLUS

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The growing demand for hydrogen in the energy and industrial sectors has prompted the search for alternative and renewable production routes. Biomass gasification has emerged as a promising pathway for hydrogen generation and warrants further investigation. In this study, a process model for hydrogen production from energy cane bagasse gasification in a two-stage entrained-flow reactor was developed using Aspen Plus V10. A parametric analysis assessed the impact of equivalence ratio (0.35–0.46) and water/feed ratio (0.30–0.40) on gasifier temperature, syngas composition, hydrogen yield, and cold gas efficiency (CGE). At $ER = 0.46$ and $water/feed = 0.30$, typical operating temperatures of an E-Gas™ type gasifier—approximately 1504 °C in the first stage and 997 °C in the second—were reached, yielding 78.0 kg H₂ per ton of dry biomass. Overall, the two-stage entrained-flow gasifier produced hydrogen yields comparable to other gasification technologies, with the added benefit of simplified downstream gas cleaning due to low tar content. However, the requirement for high-purity oxygen may limit practical implementation.

Keywords: Hydrogen, entrained-flow gasification, biomass, Aspen Plus

LACTIC ACID PRODUCTION BY LACTIC ACID BACTERIA IN A SEMI-DEFINED MEDIUM FROM HEMICELLULOSIC HYDROLYSATE OF SPENT COFFEE GROUNDS

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The growing demand for sustainability has boosted interest in utilizing agro-industrial residues for bioproduct production. Spent coffee grounds (SCG), produced in large volumes (in 2017, Brazil generated approximately 838 thousand tons), are a low-cost residue rich in hemicellulose, offering substantial biotechnological potential. Lactic acid (LA), highly valued in food, cosmetics, and bioplastics industries, stands out due to its diverse applications and economic significance. Hence, employing SCG as a substrate for LA production represents an environmentally friendly strategy, enhancing waste valorization and supporting sustainable biotechnological advancements. This study evaluated LA production efficiency by LA bacteria in semi-defined media prepared from SCG hemicellulosic hydrolysate. *Lactocaseibacillus paracasei* Shirota and *Bifidobacterium animalis lactis* were cultured in defined synthetic media containing galactose (12g/L), mannose (40g/L), peptone (10g/L), meat extract (10g/L), yeast extract (5g/L), and cysteine (0.5g/L). Fermentations were conducted in triplicate in 15 mL Falcon tubes (9 mL) at 37°C for 60 hours, under static conditions and agitation at 100 rpm. Periodic sampling monitored cell growth (spectrophotometry), sugar consumption, and LA production (HPLC). *L. paracasei* consistently exhibited superior LA production compared to *B. animalis*, especially under agitation (100 rpm), achieving 25.27 g/L LA (YP/S=1.90g/g; QP=0.42g/L.h), approximately 1.3-fold higher than static conditions. *B. animalis* showed no significant difference between conditions, reaching a maximum of 4.14g/L LA (YP/S=0.37g/g; QP=0.06g/L.h). Moderate agitation significantly enhanced LA production efficiency by *L. paracasei*, suggesting its suitability for optimized industrial-scale processes. These findings reinforce the potential of SCG as a sustainable substrate.

Keywords: Biorefinery; fermentation; low-cost substrate; sustainability; waste valorization.

MANAGEMENT TOOL FOR ESTIMATING THE ENERGY POTENTIAL OF MUNICIPAL SOLID WASTE (MSW) THROUGH THERMOCHEMICAL PROCESSES

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The efficient management of municipal solid waste (MSW) requires qualified professionals and digital tools that assist decision-makers in selecting the most suitable technological pathway for waste utilization and to determine the amount of energy to be generated through the application of a specific technological route. Many available tools necessitate expertise in programming software or qualified environmental professionals. A simple tool can support municipal managers in decision-making, enabling more municipalities to achieve more efficient utilization of MSW through thermochemical and biochemical pathways, thereby reducing the volume of waste sent to landfills and dumps. This contributes to diversifying the energy matrix, reducing greenhouse gas emissions, and minimizing the risk of soil and water body contamination. The objective of the present study was to develop an easy-to-use and intuitive tool using Microsoft Excel to assist municipal managers in estimating the amount of energy to be generated through the application of mass burning of mixed MSW based on the gravimetric data of their municipal solid waste. The results demonstrated that the tool has a simple, easily applicable, and comprehensible layout, capable of estimating the daily and annual energy generated through mass burning according to different percentages of combustible and/or organic categories present in municipal solid waste (MSW). Moreover, the tool can be applied and adapted to any municipality, respecting the specific characteristics and particularities of each local context.

Keywords: Municipal Solid Waste; Management toll; Thermochemical process; Energy Recovery, mass burning

MECHANISMS OF HYDRATION INHIBITION AND MITIGATION IN CEMENTITIOUS COMPOSITES CONTAINING BIOMASS ASH AND EUCALYPTUS PARTICLES

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The compatibility between lignocellulosic materials and Portland cement is a critical factor affecting the performance of wood-cement composites, with hydration inhibition being a major technological challenge. This study examines the hydration interactions within composites composed of three different types of Portland cement—CPII-E, CPII-F, and CPV-ARI—according to Brazilian standards. The composites also include Eucalyptus wood particles of two sizes (9 mesh and 35 mesh) and residual biomass ash as a 20% partial replacement for cement. Hydration kinetics were monitored over 24 hours using a custom thermocouple-based data acquisition system designed for semi-adiabatic calorimetry. The Inhibition Index (II) was calculated to assess compatibility. Chemical characterization of the ash through EDS analysis revealed significant amounts of Silicon and Calcium, indicating supplementary cementitious activity. The results indicated that the high-early-strength cement (CPV-ARI) generated the most vigorous exothermic reaction and the lowest Inhibition Indices, with an average of 18.8%, confirming its superior compatibility. Notably, the inclusion of biomass ash consistently lowered the Inhibition Index across all formulations, achieving a minimum value of 14.49% with CPV-ARI. The study concludes that the selection of cement is the most important factor in reducing inhibition, and biomass ash acts as a beneficial compatibilizing agent, likely through a combination of dilution and the surface adsorption of inhibitory wood extractives.

Keywords: Wood-cement composite; Hydration inhibition; Cement kinetics; Biomass ash; Compatibility; Lignocellulosic.

OBTAINING BIOPRODUCT FROM SUGARCANE BIOREFINERY EFFLUENT

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Brazil is the world's largest producer of sugarcane ethanol, whose production generates large quantities of byproducts, including vinasse, an effluent much more polluting than domestic sewage. Vinasse is used in the fertigation of sugarcane fields to recover nutrients and water. However, this practice can contribute to greenhouse gas emissions and risks of soil and groundwater contamination. Although it has the potential to produce biomethane, vinasse biogas contains sulfur, the reduced form of which is corrosive to engines. The production of struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) is emerging as a sustainable alternative to vinasse, as it reduces the organic load of the effluent and adds value to the ethanol chain, generating a monoammonium phosphate fertilizer with low water solubility. Among the available production routes, the biological method stands out for its environmental advantages over the physicochemical method. This study aims to evaluate the growth of struvite-biomineralizing bacteria in synthetic media that simulate the composition of sugarcane industry effluents, using aerobic reactors. Batch tests will be conducted for 10 days at 30°C and 150 rpm, with monitoring of electrical conductivity, pH, and microbiological analyses. The resulting crystals will be characterized by scanning electron microscopy, energy-dispersive X-ray spectroscopy, and X-ray diffraction. The research aims to propose a more valuable use for vinasse, applying biotechnology to generate a phosphate fertilizer, a scarce resource of great interest for agricultural production, also meeting the UN Sustainable Development Goals (SDGs).

Keywords: Biostruvite; Vinasse; Biotechnology

OLEAGINOUS LICHENS AS A PLATFORM FOR MICROBIAL LIPID PRODUCTION WITH HIGH C18 FATTY ACID CONTENT

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The cultivation of lichen consortia represents a promising strategy for sustainable lipid production. This study aimed to evaluate the cocultivation of the microalgae *Scenedesmus obliquus* and the filamentous fungus *Mucor circinelloides* in sugarcane molasses for biomass and lipid generation. The consortium was cultivated under controlled conditions, where the fungal mycelium acted as a biosupport to promote algal growth and lipid accumulation. The coculture produced 1190 mg/L of biomass with a lipid content of 27%. The lipid profile showed predominance of C18 fatty acids, totaling 10.9% of the extract. Oleic acid (C18:1) represented 22.5% of the fatty acids, linoleic acid (C18:2) 15.9%, and α-linolenic acid (C18:3) 25.5%. The high proportion of polyunsaturated fatty acids enhances the nutritional value of the extract, with relevance for nutraceutical applications. Moreover, the efficiency of lipid accumulation highlights the role of fungal mycelium in supporting algal metabolism. The cocultivation of *S. obliquus* and *M. circinelloides* in sugarcane molasses offers a sustainable pathway for lipid production. This strategy adds value to an agro-industrial byproduct, contributing to waste valorization and circular economy principles, while providing potential feedstocks for biodiesel and high-value lipid bioproducts.

Keywords: Fatty acid, lipid, molasses, microalgae, fungus

ORIGIN OF THE ABNORMAL BEHAVIOUR IN TENSION WOOD OF *Zelkova serrata* DUE TO BOILING AND DRYING TREATMENTS

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Developing highly-productive techniques of wood processing is essential for the sustainable use of forest resources including softwoods as well as hardwoods. However, some hardwoods are often difficult to process, such as warp and crack during lumber sawing, and twisting during drying. One of the causes of those issues is the presence of abnormal tissue known as tension wood fiber (TW-fiber), which seriously decreases production yields of harvested logs. This study aims to address those challenges by analyzing the properties of *Zelkova serrata* TW-fiber. Specimens (15mm longitudinal × 15mm tangential × 5mm radial) were sampled from the pith to the barks in a thick branch of *Z. serrata*, and they were subjected to boiling treatment in water at 120°C for 40 minutes, followed by fully drying. Then, dimensional changes (strain), crystallinity index, and TW-fiber development were measured. The results showed that drying strain and crystallinity index were higher in specimens with well-developed TW-fibers. However, the strain caused by boiling was influenced not only by the extent of TW-fiber development but also by the sampling position within a branch. This suggests that growth stress — an internal stress accumulated during tree growth and known to vary with distance from the pith — may contribute to boiling strain. Therefore, warp and crack caused in lumber may become more pronounced by the kiln-drying treatment at high temperature. In the future, we aim to propose methods for reducing or preventing such processing defects by combining the analysis of these behaviors with research on growth stress.

Keywords: hardwood, tension wood, growth stress, sawing

PHOTOELECTROCATALYTIC DEGRADATION OF REAL TEXTILE EFFLUENT USING A W/WO₃/BiVO₄ HETEROJUNCTION PHOTOANODE

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The growing environmental concern regarding the improper disposal of industrial effluents, particularly from the textile sector, has driven the development of advanced technologies for wastewater treatment. Among these, photoelectrocatalysis (PEC) stands out as a promising approach that combines electrochemical and photocatalytic processes to mineralize recalcitrant organic compounds. This study investigated the photoelectrocatalytic degradation of a real textile effluent using a nanostructured W/WO₃/BiVO₄ heterojunction photoanode. The electrode was synthesized through electrochemical anodization of a tungsten plate, followed by bismuth electrodeposition and subsequent conversion into BiVO₄. The research was divided into five main stages: (i) synthesis of W/WO₃ electrodes coated with BiVO₄; (ii) physicochemical and photoelectrochemical characterization of the heterojunction; (iii) optimization of operational parameters (electrolyte, applied potential, and reaction time); (iv) chemical and physicochemical analysis of the effluent before and after treatment; and (v) performance comparison with isolated WO₃ and conventional treatment methods (photolysis, photocatalysis, and electrocatalysis). Optimal degradation was achieved using raw effluent, without electrolyte addition or stirring, under an applied potential of 1.0 V vs Ag/AgCl and 8 h of treatment, reaching removals of 95.8% COD, 94.6% NPOC, and 99.1% turbidity. The W/WO₃/BiVO₄ heterojunction significantly outperformed isolated WO₃ and traditional methods due to its efficient charge separation, enhanced visible light absorption, and continuous generation of oxidative species. The integrated analysis confirmed PEC with W/WO₃/BiVO₄ as an effective and environmentally friendly strategy for the treatment of complex industrial effluents.

Keywords: Photoelectrocatalysis; industrial wastewater; semiconductors; advanced oxidation processes; organic matter degradation.

POTENTIAL FOR ENERGY RECOVERY FROM MUNICIPAL SOLID WASTE BY DIRECT COMBUSTION: EFFECT OF IMPROVING SELECTIVE COLLECTION RATES IN THE MUNICIPALITY OF ITAQUAQUECETUBA/SP

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This study assessed the impact of increased selective collection on the potential for energy recovery from municipal solid waste (MSW) using mass-burning technology. The study was applied to the municipality of Itaquaquecetuba, located in the São Paulo Metropolitan Region, Brazil. Three scenarios were analyzed: (1) current; (2) current recycling rates in municipalities in the São Paulo Metropolitan Region; and (3) national targets for 2040. Using secondary data on gravimetric composition and average waste generation rates, a mass balance was performed to determine the quantity and composition of wastes destined for Waste to Energy (WtE) plants, for each scenario. As expected, the results indicated increasing selective collection reduces the mass of MSW destined for WtE plants, influencing the heat value and decreasing the energy generated. Annual electricity production ranged from 33,000 MWh (scenario 1) to 53,000 MWh (scenario 3), sufficient to supply the consumption of 13,400 to 21,500 inhabitants, based on an average consumption of 205.5 kWh/inhab/month in São Paulo. Scenario 3 reduced energy recovery by 10.55%. Although selective waste collection partially compromises electricity generation, it extends the useful life of landfills and reinforces sustainability initiatives.

Keywords: waste to energy, incineration, MSW, recycling, waste composition

POTENTIAL USE OF BAUXITE RESIDUE AND EUCALYPTUS BARK IN THE NEUTRALIZATION OF AGRICULTURAL SOILS UNDER DIFFERENT TREATMENT TEMPERATURES

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Bauxite residue (BR) is generated in large quantities and lacks practical application on the same scale, requiring vast disposal areas that pose environmental risks. Eucalyptus bark, although it has some uses, because of the large generated volumes it is possible to increase its utilization. The objective is to identify the most efficient proportion of BR and eucalyptus bark for soil pH correction after biochar production. Three material mixtures were prepared: T1 (25% bark and 75% BR), T2 (50% bark and 50% BR), and T3 (75% bark and 25% BR). Each mixture was subjected to temperatures of 250, 350, 450, and 550°C, resulting in 12 treatments, each performed in triplicate. After the production of biochar from each sample, the pH was measured according to ABNT NBR 10004. The pH values obtained showed greater reduction potential in the T2 (from 8.53 to 7.61) and the T3 (from 8.10 to 7.10), both at a temperature of 250°C. At temperatures of 350, 450, and 550°C, there was an increase in the pH values. In the T1, no significant changes were observed. It is concluded that bauxite residue and eucalyptus bark can be used in proportions of both 50% and 75% for soil pH neutralization. Since bauxite residue is more abundant, it is preferable to use the 50% bark and 50% BR proportion in order to allocate as much of it as possible.

Keywords: Red Mud; Environmental Studies; Biomass; Biochar; pH correction.

PRETREATMENT STRATEGIES FOR SUGARCANE BAGASSE TO ENHANCE THE PERFORMANCE OF RECYCLED POLYETHYLENE BIOCOMPOSITES

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The growing demand for sustainable materials has driven interest in biocomposites that combine recycled polymers with lignocellulosic residues. This study investigated the influence of hydrothermal and organosolv (acetosolv and ethanosolv) pretreatments of sugarcane bagasse on the properties of high-density polyethylene (HDPE)-based biocomposites. Recycled HDPE was obtained from supermarket crates, washed, shredded, and homogenized using a thermokinetic mixer. Hydrothermal pretreatment was performed in distilled water (10% w/v) at 121 °C for 1 h. Acetosolv treatment was carried out in glacial acetic acid (10% w/v) at 116 °C under reflux for 1 h, while ethanosolv treatment employed an ethanol:water mixture (80:20 v/v) with 0.5% w/v HCl, under reflux at 80 °C for 1 h. After pretreatment, bagasse samples were washed to neutral pH and dried. Biocomposites were produced with 15% (w/w) bagasse reinforcement and injected at 300 °C. Mechanical analysis showed that untreated bagasse increased the Young's modulus of the recycled HDPE by 18%, while hydrothermal, acetosolv, and ethanosolv treatments led to increases of 29%, 36%, and 33%, respectively. The improved stiffness is attributed to partial removal of amorphous fractions, enhancing interfacial adhesion between matrix and reinforcement. Thermogravimetric analysis and X-ray diffraction confirmed hemicellulose removal under hydrothermal treatment and more pronounced lignin solubilization under organosolv pretreatments, resulting in increased crystallinity of the treated fibers. These findings demonstrate a dual waste-to-resource strategy by enabling lignocellulosic upgrading and polymer reuse, supporting biomass and plastic valorization through the development of functional green composites aligned with circular bioeconomy principles.

Keywords: mechanical reinforcement, circular economy, fiber surface modification, waste valorization, biorefinery integration

PRODUCTION AND TECHNICAL EVALUATION OF DENSIFIED REFUSE-DERIVED FUEL: PRE-TREATMENT, PELLETIZATION AND REDUCTION OF OPERATIONAL EMISSIONS

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Municipal solid waste generation poses a significant challenge to both environmental and energy sustainability. Refuse-derived fuel (RDF) emerges as a promising alternative to reduce landfill disposal, as it enables the recovery of its energy potential and partial substitution of fossil fuels. However, its application is still constrained by the heterogeneity of its composition, low bulk density, and the presence of contaminants such as chlorine. This project aims to overcome these barriers through an integrated densification process comprising: (i) pre-treatment by drying with controlled aeration and temperature to reduce initial waste moisture; (ii) physicochemical characterization through the analysis of calorific value, ash, chlorine, and heavy metals; and (iii) high-pressure pelletization using controlled proportions of agricultural biomass (eucalyptus bark, sugarcane bagasse) to improve calorific value and mechanical resistance. The expected outcome is a densified RDF with a calorific value between 18 and 24 MJ/kg, reduced fine particulate (PM10) emissions, and lower corrosive elements, enabling stable application in boilers and cement kilns. The densification of RDF is expected to provide a robust technical and environmental solution capable of enhancing industrial acceptance, reducing logistics costs, promoting circular economy practices, and supporting the energy transition in urban and industrial contexts.

Keywords: Renewable energy; municipal solid waste; thermal pre-treatment; alternative fuels

PRODUCTION OF COLORED COMPOUNDS BY ENZYMATIC OXIDATION OF FERULIC ACID: POTENTIAL FOR DYEING CELLULOSE-BASED MATERIALS

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Ferulic acid is a phenolic compound found in lignocellulosic wastes such as sugarcane bagasse and rice straw. Its enzymatic oxidation can produce colored compounds with potential applications in material dyeing. To evaluate the oxidation of ferulic acid by *Trametes versicolor* laccase and assess the potential use of the resulting products for dyeing cellulosic materials. The reaction involved 20 mg of ferulic acid and 16 IU of laccase (based on ABTS oxidation rate) in 50 mL of an aqueous/ethanolic solution (3:1 v/v), stirred at 200 rpm for 20 minutes, followed by nitrogen bubbling. After saturation with NaCl, products were extracted with ethyl acetate and heated for 30 minutes in aqueous and organic media, before and after extraction, respectively. Visible spectra (380–800 nm) were recorded, and dyeing tests were conducted on copy paper and cotton. Oxidation generated reddish compounds with low affinity for paper and cotton that, after heating in aqueous/ethanolic medium, turned yellowish, became clear (without turbidity), and showed higher affinity for these cellulosic materials, suggesting hydrolysis and formation of more polar products. Heating in organic medium caused no color or spectral changes, corroborating hydrolysis. Spectroscopy showed a decrease in the 520 nm band (associated to reddish) and increase in the 430 nm band (associated to yellowish) after aqueous heating. Enzymatic oxidation of ferulic acid yields hydrophobic and reddish compounds that become more polar and yellowish upon thermal hydrolysis in aqueous medium. These products have potential for dyeing cellulose-based materials.

Keywords: Dyeing, Color change, Visible spectroscopy

PRODUCTION OF SECOND-GENERATION ETHANOL FROM COFFEE FARMING RESIDUE BY FERMENTATIVE BIOPROCESSES WITH DIFFERENT WILD YEAST STRAINS

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Bioethanol is a renewable energy alternative and can be produced from biomass rich in organic matter, such as coffee straw, an abundant agro-industrial waste in Brazil. This study evaluated fermentative bioprocesses using the hydrolysate obtained in the treatment by thermochemical hydrolysis of coffee straw in batch systems with two strains of wild yeasts, to obtain second-generation ethanol. First, the molecular identification of 15 strains of wild yeasts isolated from brewery wastewater and decaying fruit was performed. From a screening of these 15 strains, it was found that *Pichia kudriavzevii* (LMP-Y 10) and *Saccharomyces cerevisiae* (LMP-Y 14) had the best ethanol production (1.64 and 1.91 g L⁻¹, respectively). From the optimization of biomass production, it was found that LMP-Y 10 presented better biomass yield at 38 °C, 20 g L⁻¹ of glucose and pH 6.0, and the LMP-Y 14, at 34 °C, 30 g L⁻¹ of glucose and pH 7.0. In the fermentation bioprocess assays in a batch system, from the hydrolyzed coffee straw pre-treated with H₂SO₄ 1% and 2%, with and without agitation, it was obtained, for both strains, better ethanol production with H₂SO₄ 2%, obtaining 0.58 g L⁻¹ with LMP-Y 10, under agitation, and 0.43 g L⁻¹ with LMP-Y 14, in static condition. These results indicate the discovery of two new wild strains with potential production of second-generation ethanol that may contribute to future research and advances in biotechnology, offering sustainable alternatives to produce bioenergy from agro-industrial waste.

Keywords: agro-industrial waste; bioenergy; biological fermentation; applied microbiology; waste-to-energy

REFUSE-DERIVED FUEL (RDF) AS AN ALTERNATIVE SOLID FUEL: POTENTIAL AND CHALLENGES FOR USE IN BIOENERGY

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Refuse-Derived Fuel (RDF) has been introduced in Brazil, particularly in cement industries, as an alternative fuel. However, some factors still pose challenges to its utilization, such as its heterogeneity and chemical composition. This study aimed to evaluate the physical, chemical, energetic, and structural properties of RDF produced in São Paulo state. Five RDF samples were obtained from a waste management company located in the Sorocaba region, SP. For characterization, the material was quartered, and the fraction intended for laboratory analyses was ground and re-quartered. The physical, chemical, structural, and fuel properties of the RDF were assessed. The results indicated that the analyzed RDF exhibits high heterogeneity, being composed of plastics, paper, textiles, rubber, composites, biomass, metals, and inorganic materials. Moisture contents varied (6.98% – 29.96%), and the bulk density was low (71 – 112 kg/m³). The energetic properties were suitable for fuel, with higher heating values of 20.89 to 27.77 MJ/kg. Moreover, the ash did not contain hazardous chemical constituents, allowing for the potential reuse of this waste in other processes and in the production of materials. Overall, it was found that RDF has potential for use in various industrial sectors; however, efforts are needed to improve understanding and standardization of the material.

Keywords: coprocessing; physicochemical properties; waste-to-energy; heterogeneity; biomasses; cement industry

SELECTIVE EXTRACTION OF BIOACTIVE COMPOUNDS FROM UNRIPE HASS AVOCADO (*Persea americana* Mill.): A SEQUENTIAL EXTRACTION METHODOLOGY USING SUPERCritical CO₂

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Avocado (*Persea americana* Mill. cv. Hass) is rich in unsaturated fatty acids and liposoluble bioactive compounds (BACs). This study employed a sequential extraction (SE) methodology using supercritical CO₂ (scCO₂) to obtain oil from two distinct biomasses unpeeled pulp (UP) and peeled pulp (PP) aiming to enrich extracts in α -tocopherol, total carotenoids, and chlorophylls *a* and *b*. Five SE-scCO₂ stages were conducted isothermally at 40 and 60 °C, applying pressures of 150, 200, 250, 300, and 320 bar. Oil recovery efficiency, BAC content, chemical composition, and thermal stability were evaluated. Extracts from the first three stages (150–250 bar) showed higher selectivity for chlorophyll recovery at both temperatures, regardless of biomass type, followed by a gradual decline in subsequent stages. Total carotenoids were consistently distributed across nearly all extracts, with the highest value obtained for UP at 40 °C and 320 bar (14.59 ± 0.13 mg/100 g). α -Tocopherol was the most abundantly recovered BAC, with optimal yields from UP in stages 2 and 3 at both temperatures. The maximum concentration (61.16 ± 0.39 mg/100 g) was achieved at 60 °C and 250 bar from UP. Overall, the SE-scCO₂ process selectively recovered nutraceutical compounds of commercial interest, particularly α -tocopherol, with concentrations exceeding previously reported values. Under the specified operational parameters, the SE-scCO₂ process proved selective toward commercially valuable nutraceutical compounds, with a marked content of α -tocopherol.

Keywords: Hass avocado, sequential extraction, supercritical CO₂, bioactive compounds. avocado peel

STABILITY AND EFFICIENCY OF AN UPFLOW ANAEROBIC SLUDGE BLANKET (UASB) REACTOR UNDER PROGRESSIVE ORGANIC LOAD OF CORN VINASSE

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The Upflow Anaerobic Sludge Blanket (UASB) reactor is an efficient process for organic load removal and has been used in the treatment of effluents from ethanol plants. This study aimed to evaluate the performance of a pilot-scale UASB reactor subjected to a gradual increase in the organic load of corn vinasse. The methodology consisted of monitoring the physicochemical properties (pH, alkalinity, BOD₅, and COD) in the reactor operated under different concentrations. According to the results obtained, the COD removal efficiencies ranged from 34% to 80%, with an average of 59.8%. Regarding BOD₅, values ranged from 38% to 84%, with an average of 63.8%. The pH values remained within the range of 6.5 to 7.1, conditions suitable for methanogenic bacteria. The ratio between partial alkalinity and intermediate alkalinity averaged 0.42; however, this ratio did not negatively affect the treatment process. Thus, the UASB reactor demonstrated high efficiency in removing BOD₅ and COD concentrations when subjected to a gradual increase in corn vinasse load

Keywords: Etanol, Flex plant, Industrial effluent and Anaerobic treatment

SUGARCANE BIOMASS WASTE FOR PRODUCTION OF BIOCHAR@NB₂O₅ NANOSTRUCTURED COMPOSITES AND ITS APPLICATION ON SUSTAINABLE ENERGY STORAGE DEVICE

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The use of agricultural biomass waste for the production of biochar has shown potential as electrode materials for supercapacitors, but improving its energy and power density is a challenge. One efficiency strategy consists of developing composites with compounds to enhance the performance of the devices. By controlling the pyrolysis temperature at 700 °C and synthesis atmosphere (N-rich environment), sugarcane bagasse biomass was converted into porous biochar powders in a single and fast one-step synthesis route. In this procedure, from the addition of niobium ammonium oxalate, it was possible to promote the in-situ production of Nb₂O₅-orthorhombic nanostructures on the carbon surface. The Scanning Electron Microscopy analysis reveals a needle-like morphology from the niobium oxide with length varying between 300 nm to 900 nm and thickness in 20-50 nm range. X-ray microtomography revealed a homogeneous distribution throughout the biochar matrix. A 3-electrode system characterization using 3M KOH electrolyte achieved a maximum capacitance of 219.5 F/g, energy density of 1.6 W.h/kg, and a power density of 113.7 W/kg. The assembled SNb2-3 symmetric coin cell displays a capacitance of 34 F/g, a high energy density of 20 W.h/kg, and a power density of 740 W/kg, at a current density of 0.5 A/g. This study presents a novel perspective for producing eco-friendly and sustainable carbon materials by reusing agroindustrial waste as electrodes for energy storage applications. Our achievements enhance the potential application of biomass-derived products in the area of high-performance supercapacitor devices.

Keywords: sugarcane biomass; one-step synthesis; biochar electrode; niobium oxide; energy storage; supercapacitor.

SUSTAINABLE URBAN DRAINAGE SYSTEMS: PERFORMANCE OF BIOCHAR MODIFIED WITH ACID AND BASE FOR THE REMOVAL OF EMERGING CONTAMINANTS

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One of the major concerns of humanity today is the increasing number of surface and groundwater contamination incidents caused by anthropogenic activities, especially in urban areas. Among the various contaminants, antibiotics stand out due to their crucial role in treating millions of people annually for a wide range of diseases. However, they end up polluting the environment because of their low metabolism rate. In this context, the present study aims to evaluate the sorption capacity of acid- and base-modified biochar, produced from coconut shell-based plant material, for the removal of the antibiotic Amoxicillin from aqueous solution. The objective is to provide a low-cost, alternative adsorbent material to be used in sustainable urban drainage systems to prevent the contamination of groundwater aquifers in urbanized watersheds. Recent studies have shown that modified biochars are highly effective in removing pharmaceutical compounds from aqueous media, although data on the sorptive capacity of antibiotics remain scarce. Batch sorption experiments (including kinetics and adsorption isotherms) and fixed-bed column studies will be conducted. By the end of the study, it is expected to gain an in-depth understanding of the sorptive potential of coconut shell-derived biochar for the removal of antibiotics from aqueous solutions.

Keywords: Sanitation; Contamination; Antibiotics; Adsorption; Biochar

SYSTEMATIC LITERATURE REVIEW OF ORANGE WASTE MANAGEMENT FROM THE ENVIRONMENTAL LIFE CYCLE PERSPECTIVE

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The citrus industry generates large volumes of biomass, particularly orange peels, which are often underutilized despite their high potential for energy and chemical valorization. This study presents a systematic literature review on orange waste management from an environmental life cycle assessment perspective (E-LCA), emphasizing technologies and practices aligned with bioenergy generation and sustainability goals. Searches in Scopus and Web of Science identified 201 articles, of which 17 met inclusion criteria after screening. The analysis, supported by IRaMuTeQ software, revealed that most studies follow ISO 14040/14044 standards, with dominant applications in energy recovery and extraction of high-value compounds. Energy valorization of orange peels demonstrated potential to reduce greenhouse gas emissions by up to 94% compared to fuel oil, though with trade-offs in aquatic toxicity and eutrophication. Chemical valorization processes, particularly acid hydrolysis, were identified as environmental hotspots, while emerging green extraction methods reduced energy and water consumption. Thermochemical processes offered varied performance, with incineration proving viable on small scales and pyrolysis facing economic and technical constraints. Sensitivity and uncertainty analyses were critical for robust environmental results. Adoption of renewable energy sources in processing stages significantly reduced impacts but faced high initial costs and infrastructural demands. This review highlights the integration of environmental life cycle assessment with innovative valorization technologies as a pathway to circular bioeconomy in citrus waste management, providing actionable insights for policymakers, industry, and researchers aiming to optimize bioenergy potential while mitigating environmental burdens.

Keywords: orange peel waste; environmental life cycle assessment (E-LCA); bioenergy

THE POTENTIAL USE OF BOTTOM ASH IN THE MAKING OF A VIABLE FLOOR TILING

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The wood chips used in industrial boilers can produce a variety of ash, one known as Bottom Ash (BA), this type of ash is thrown away and has no outcome. The objective of this research is to comprehend the viability of creating a concrete floor paver from these ashes by using it instead of rocks. It was Utilized Bottom Ash (BA) from a biomass boiler, which replaced the conventional rock aggregate. Two distinct mix designs were formulated by volume: Mix A (2 parts BA, 2 parts sand, 1 part cement, ~0.55 parts water) and Mix B (3 parts BA, 1 part cement, 0 parts sand, ~0.55 parts water). Each mixture was cast into cylindrical PVC molds (5 cm diameter × 9.75 cm height), and compacted. After a 72-hour curing period, the prototypes were demolded and their properties were assessed. The resistance to compression was tested mechanically, permeability was evaluated by measuring water passage, and pH was determined from a water-specimen slurry. The prototype that had sand in its composition developed a strong resistance and an alkaline attribute, with a pH of 11, which would difficult the proliferation of bacteria and other microorganisms, the second one that didn't use sand became a concrete that allowed the passage of water through it, while maintaining a neutral pH of 7. The properties of the different types of flooring are favorable, making them useful in different scenarios. The results demonstrate a new application for BA in the fabrication of floor pavers.

Keywords: Bottom Ash, Wastes.

THE PROCESSING METHOD DETERMINES THE BIOENERGY CONVERSION ROUTE FOR COFFEE HUSK

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Coffee husk is a promising agricultural waste for bioenergy and the promotion of sustainable development, whose suitability can vary according to the processing method. In this context, this research aimed to evaluate the bioenergetic potential of coffee husk from specialty and traditional coffee production systems. Samples were collected in Venda Nova do Imigrante and Domingos Martins (ES). Their physicochemical and energetic properties were statistically compared using Welch's t-test ($p > 0.05$). The moisture content of traditional coffee husk (11.66%) was significantly higher than that of specialty coffee husk (5.86%). Lower values are advantageous for direct combustion and thermochemical conversion. The bulk density (152.77 to 154.01 kg.m⁻³), higher heating value (19.38 to 20.01 MJ.kg⁻¹), and energy density (2.42 to 2.67 GJ.m⁻³) showed no statistical difference. However, proximate analysis revealed that specialty husk had a higher volatile content (80.71%), lower fixed carbon (17.59%), and lower ash content (1.70%) compared to traditional husk (76.17%, 19.96%, and 3.87%, respectively). Therefore, both wastes have the potential to be converted as renewable sources, contributing to energy security and the circular economy. Moisture and the proximate analysis profile are key factors in the valorization route, indicating that specialty coffee husk is more suitable for thermochemical conversions, while traditional coffee husk can be used as a densified fuel. Future research can refine technical parameters and expand these routes, strengthening the inclusion of these wastes in the bioeconomy.

Keywords: Sustainable Agriculture, Residues, Valorization pathway, Decarbonization, Energy Security

THE ORANGE POTENTIAL: TURNING CITRUS WASTE INTO ENERGY AND BIOPRODUCTS

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Among the countries in the world with high agricultural productivity, Brazil stands out as one of the countries that produces and processes the most oranges, with a production of 12.3 million tons and a processing of 9.7 million tons in the 2023/24 harvest, representing almost 27% of global orange production. Approximately 50% of the weight of the fruit corresponds to the bagasse, a residue with significant potential for use in thermal energy conversion systems. In this context, this review aimed to analyze the distribution of recent research aimed at the valorization of orange processing waste, focusing on the relationship between global productivity, the types of waste generated, their possible applications in alternative energy conversion routes, and the progress of associated research. Based on the data obtained, the analysis of scientific production revealed an evolution of publications and allowed the identification of trends and innovations related to the energy use of orange processing waste. The results point to a growing interest in the development of sustainable solutions aligned with the bioeconomy and the energy transition. In this scenario, the use of orange processing waste emerges as a promising alternative to prevent environmental impacts, contribute to decarbonization, and promote energy conversion technologies.

Keywords: Orange; Processing waste; Decarbonization; Thermal energy conversion.

TECHNO-ECONOMIC ANALYSIS OF THE INTEGRATION OF A KRAFT LIGNIN VALORIZATION UNIT VIA LIGNOBOOST TECHNOLOGY

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Lignin has emerged as a promising renewable alternative to meet the growing demand for bioenergy, biofuels, and bioproducts. This is justified by its high energy content and potential for high value-added applications. In this context, the objective of this study was to simulate and conduct an economic analysis of Kraft lignin production using the LignoBoost method in a large-scale industrial facility. To achieve this, a lignin extraction unit was integrated with an evaporator in a pulp mill with a production capacity of 1.5 Mt/year. Mass balance calculations were carried out using the WinGEMS® v5.4 simulator, and the economic analysis covered four plant configurations: (A) direct commercialization of Kraft lignin; (B) drying and pelletizing of the lignin, with commercialization of the pellets; (C) burning lignin as fuel in the lime kiln to replace fuel oil; and (D) reuse of flue gases from the lime kiln for medium acidification. Two scenarios for product pricing were evaluated in each configuration: (1) conservative; and (2) optimistic. The results showed that the extraction and commercialization of Kraft lignin from black liquor is financially feasible, requiring an initial investment of US\$ 2.8 million and annual operating costs of US\$ 89.9 million. Among the analyzed configurations, only the reuse of flue gases demonstrated a higher profitability when compared to lignin commercialization. The use of lignin in the kiln showed to be unfeasible in the conservative pricing scenario.

Keywords: Bioeconomy; Cellulose; Kraft Lignin, LignoBoost; Economic Analysis; Process Simulation.

USE OF ASH AS A SUBSTITUTE FOR CARBON BLACK IN POLYPROPYLENE PIGMENTATION

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An environmental liability resulting from the burning of biomass in boilers is the ash. Given the need to dispose of it in an environmentally correct manner and at lower costs, the development of applications for the use of this residue becomes a differentiator in the market. Given this theme, this work aims to apply the ash resulting from the burning of biomass in boilers to the production of black concentrates (masterbatch) intended for the pigmentation of polypropylene (PP). Fly ash will be collected from biomass-fueled boilers and the unburned materials present in them will be separated through sieving. After segregation, the unburned materials will be crushed until they meet the minimum particle size of 60 mesh. With the fine material obtained, it will be used as a black pigment for PP. It is expected that the use of these unburned materials will replace the use of carbon black of fossil origin and that it will increase the mechanical resistance of PP by containing mineral filler.

Keywords: Fly ash, carbon black, masterbatch, pigmentation

USE OF BAUXITE RESIDUE AND EUCALYPTUS BARK BIOCHAR AS AN ALTERNATIVE SUBSTRATE FOR *Bixa orellana* SEEDLING PRODUCTION

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Aluminum stands out for properties such as lightness, high electrical conductivity, corrosion resistance, and low melting point, characteristics that have driven its wide industrial use. However, primary aluminum production faces important environmental challenges, especially regarding the management of bauxite residue, also known as red mud. This insoluble and highly alkaline material (pH 10–12), rich in iron oxide, is generated during the clarification stage of the Bayer process and is usually deposited in tailing ponds, posing environmental risks. This study aims to propose the sustainable use of bauxite residue as a component of substrates for forest seedling production. For this purpose, biochar will be produced from the residue through co-pyrolysis with eucalyptus bark at a 1:1 mass ratio, aiming to reduce its alkalinity. Pyrolysis will be carried out at three temperatures (250, 450, and 650 °C), in triplicate, and the pH of the samples will be measured using a benchtop pH meter. The most suitable treatment will be selected to formulate substrates for the cultivation of *Bixa orellana* (Urucum) seedlings, testing different formulations: 100% red soil; 5% and 30% raw bauxite residue; and 5% and 30% biochar mixed with red soil. Seedling growth will be monitored every 15 days. It is expected that co-pyrolysis will reduce the alkalinity of the residue to near-neutral values (pH 7–9) and that its use will not hinder seedling development, thus representing an environmentally sustainable alternative aligned with the demands of the primary aluminum industry.

Keywords: Biomass; Bioenergy; Red mud, Aluminum industry; Alkalinity reduction

USE OF LOW-COST REACTIVE LAYER IN THE PREVENTION OF CONTAMINATION BY ORGANIC COMPOUNDS OF SURFACE AND GROUNDWATER.

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Water management is a global concern due to the increasing pressure on surface and groundwater resources, exacerbated by the occupation of watersheds, springs, and riverbanks. Notable contaminants include the herbicides glyphosate and 2,4-dichlorophenoxyacetic acid (2,4-D), widely used in agricultural and urban areas, with the potential to reach soil and water bodies. This study aims to evaluate the transport and retention of these herbicides in filter layers of biochar produced from coconut residues, in both activated and non-activated forms. The biochar will be obtained by pyrolysis and initially activated with quaternary ammonia. Experimental columns will be packed with the material and saturated with a CaCl_2 solution. Subsequently, a KBr solution will be applied to determine hydrodynamic parameters, followed by glyphosate and 2,4-D solutions for transport and retention analysis. The evaluations will include physicochemical characterization using bromide elution curves and herbicide detection by HPLC, and structural characterization using X-ray microtomography (micro-CT). The images will be processed and analyzed to determine morphometric parameters such as pore size, shape, distribution, continuity and connectivity. The results will be fitted to mathematical models of dispersion–convection (CDE) and dispersion–convection with two sorption sites (CDE-2S), enabling the estimation of the dispersion coefficient, retardation factor and adsorption constant.

Keywords: herbicides, biochar, filter layer, X-ray microtomography.

USE OF SAWDUST AS A PORE-FORMING AGENT IN SLIP-CAST CERAMICS

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Porous ceramics combine the intrinsic advantages of ceramics with the structural benefits of cellular materials. Their high specific surface area, thermal resistance and insulating capacity make them suitable for tissue engineering, catalyst supports and high-temperature filtration membranes. A common approach to producing porous ceramics is the sacrificial template method, in which a temporary material is incorporated into the ceramic matrix and subsequently removed during sintering, leaving behind pores in the microstructure. When solid waste is employed as the pore-forming agent, this strategy mitigates environmental impacts, reduces production costs and increases the added value of the waste. In this context, sawdust emerges as a particularly relevant sacrificial material. This study aimed to fabricate ceramic components with high porosity by employing sawdust as a pore-forming agent in alumina and applying the slip casting technique. Sawdust with controlled particle sizes was added at different concentrations (1, 2 and 3 wt.%) to a suspension composed of alumina and water. The green bodies obtained were subsequently sintered, and their physical properties were evaluated. The fired pieces exhibited good cohesion, indicating an adequate firing cycle. With increasing sawdust content, both bulk density and final dimensions decreased, while loss on ignition and water absorption increased. The sample containing 1 wt.% sawdust showed the largest volume of accessible void spaces (apparent porosity of 54%). Overall, porous alumina was successfully produced by slip casting, using sawdust as an effective pore-forming agent. The study aligns with Goal 9 by promoting innovation and contributing to the development of sustainable manufacturing practices.

Keywords: Functional materials; Porous ceramics; Biomass; Wood residue

VALORIZATION OF HYDROXYCINNAMIC ACIDS FROM CORNCOB: SYNTHESIS OF ALKYL ESTERS AND ENCAPSULATION IN ALGINATE MICROPARTICLES

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In addition to biofuel production, agricultural residues can be used as feedstock for hydroxycinnamic acids and esters with remarkable antioxidant and UV-blocking properties. However, to achieve scale-up, more efforts are needed in downstream steps and in establishing new applications. In this context, the present study investigated the recovery and application of hydroxycinnamic acids from corncobs. Alkaline extraction was implemented to release p-coumaric acid and ferulic acid, and different operating conditions were implemented. Cloud point extraction (CPE) was investigated to recover the target molecules and was integrated with esterification with aliphatic alcohols and synthesis of alginate-based microparticles. Excess hydrogen peroxide (5% v/v) implied loss of ferulic acid. The best alkaline extraction condition was 3% sodium hydroxide and 2% hydrogen peroxide, ensuring 591.7 and 584.6 mg/L of p-coumaric acid and ferulic acid, respectively. Low levels of Triton X-114 are already adequate to recover and concentrate hydroxycoumaric acids (recovery > 97%). The addition of sulfuric acid at values higher than 3.6% (v/v) ensured high conversion into alkyl esters, mainly for n-propanol and butanol as reactants. Double-fluid nozzle atomization was able to prepare alginate/coacervate phase CPE microparticles, presenting encapsulation efficiency higher than 47% for p-coumaric acid and 54% for ferulic acid. These microparticles can be used for cosmetic purposes, and their size is inversely proportional to the atomization pressure.

Keywords: esterification, p-coumaric acid, ferulic acid, aqueous two-phase system, corncob, waste valorization

VALORIZATION OF SPENT COFFEE GROUNDS VIA HEMICELLULOSIC HYDROLYSATE FERMENTATION FOR SUSTAINABLE LACTIC ACID PRODUCTION

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Lactic acid (LA) is crucial for producing biodegradable polymers, such as polylactic acid (PLA), aligning with global sustainability demands. Increasing concern regarding environmental pollution, notably microplastic contamination, has intensified the search for renewable and sustainable alternatives to petrochemical-derived plastics. Spent coffee grounds (SCG), an abundant lignocellulosic biomass generated daily from coffee consumption worldwide, presents a valuable opportunity for LA production. This study evaluated the fermentative potential of hemicellulosic hydrolysate (HH) from SCG for LA production. SCG underwent acid hydrolysis (159°C, 1.8%v/v H₂SO₄, solid-liquid ratio of 1:6, 37min) in ampoule reactors heated by a dry block system, then supplemented with meat extract, yeast extract, peptone, and cysteine. Fermentation using *Lacticaseibacillus paracasei* Shirota was conducted in 15 mL Falcon tubes (9 mL), agitated at 100 rpm for 60 hours with periodic sampling. Hydrolysates were detoxified by neutralization with CaO, adjusted to pH 2.5 with H₃PO₄, and treated with activated charcoal. Sugar consumption (SC) and LA production were analyzed by HPLC, and bacterial growth by spectrophotometry. In non-detoxified media, LA concentration reached 38.46g/L, corresponding to 58.98% SC, a yield (YP/S) of 0.91g/g, and productivity (QP) of 0.64g/L·h. Detoxified media yielded slightly lower values (36.7g/L LA, 57.62% SC, YP/S: 0.89g/g, QP: 0.61g/L·h). These results highlight the robustness of LA bacteria and their ability to efficiently ferment HH from SCG, even without detoxification. The omission of detoxification steps does not significantly impact LA production from SCG hydrolysates, presenting an economically advantageous and simplified alternative for sustainable bioproduct production.

Keywords: bacteria, biorefinery, fermentation, renewable feedstock, sustainability.

WOODCHIPS AND TOMATO PLANT WASTE AS FEEDSTOCK IN AN ONSITE PILOT GASIFICATION SYSTEM: WASTE REDUCTION, ENERGY PRODUCTION, AND NUTRIENT RECOVERY

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Agricultural waste is typically non-homogeneous and considered both an environmental and economic burden. This research assessed the feasibility of using advanced gasification technology as a sustainable solution to minimize waste while addressing environmental and economic challenges through the production of valuable by-products (biochar and syngas). Research objectives included evaluating the composition and agricultural potential of biochar, characterizing syngas composition and energy output, monitoring greenhouse gas emissions, and assessing overall system feasibility. The study was conducted using both a pilot-scale gasification system (1 ton/day capacity) and a laboratory unit. Woodchips (WC) were used as the reference feedstock, and five mixing ratios with tomato plant waste (TPW) were tested. Results showed ~95% waste volume and weight reduction, significant nutrient recovery, and renewable energy production, aligning with circular economy principles. Key findings included the impact of feedstock ratios on biochar quality, syngas characteristics and emissions, and pilot system efficiency. Biochar was rich in essential macronutrients such as Ca, Mg, K, Fe, N, and P, indicating strong potential as a soil amendment. Syngas average composition included approximately 0,8% H₂, 19,5% CH₄, 17,1% C₂H₄ and 1,3% CO, with an energy average output of $\sim 2.7 \times 10^3$ kWh/ton of substrate. Emissions from the syngas combustion were low in toxic gases. Of the tested ratios, the overall best performance was found in the feedstock mixture of 60% WC and 40% TPW. A conservative estimate suggested a return on investment within six years. It was postulated that onsite gasification may provide a sustainable solution for agricultural plant waste management.

Keywords: waste management; biomass energy; syngas; biochar



BIOMASS AND BIOENERGY CONFERENCE

RESEARCH ARTICLE

ANALYSIS OF THE SUPERIOR CALORIFIC VALUE OF *Pinus sp.* WOOD PELLETS FROM LABORATORY EXPERIMENTS

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ABSTRACT

Biomass is a renewable energy source derived from organic material, which helps reduce greenhouse gas emissions. Pellets are solid biofuels with low moisture content and high energy density. This article investigates the higher heating value (HHV) of pine wood pellets using empirical methods to quantify the HHV and identify influencing factors such as chemical composition, compaction, and moisture content. The PCS obtained was 18308 J/g for a sample with 11.1019% moisture. Compared to some authors, for samples with similar moisture contents, the PCS resulted in 19480 J/g, 19130 J/g and 18710 J/g. This discrepancy can be attributed to several factors, such as the origin and quality of the raw material, implying differences in the growing conditions of the trees, influencing the density and chemical composition of the wood. Even so, pellets maintain a relatively low moisture content, which is essential for maximizing calorific value and minimizing problems such as spoilage and smoke emission during combustion.

KEYWORDS: Biomass, Wood Pellets, Higher Heating Value.

INTRODUCTION

Biomass is a renewable form of energy, coming from organic matter of animal or plant origin. It can be converted into different types of energy, such as electricity, heat, and liquid or gaseous fuels [1]. In addition to its importance in the global energy matrix, the use of biomass contributes to the reduction of greenhouse gas emissions and promotes sustainable development.

Pellets (Figure 1) are solid biofuels that can be produced from waste from the agroforestry industry. Its low moisture content ($TU < 10\%$) allows for a high energy

density [2]. Thus, the higher calorific value (SCW) is an important factor to evaluate the energy potential of any biomass. It represents the total amount of energy released during the complete combustion of the material, including the energy of the water vapor generated. This characteristic is fundamental to determine the efficiency and viability of a biomass as an energy source.

The objective of this work is to carry out a detailed investigation on the PCS of *Pinus wood* pellets, using empirical methods. Through laboratory experiments, we sought to quantify the SCW and identify the variables that influence this value, such as the chemical composition, the degree of compaction and the moisture of the pellets.

Figure 1 - Pine Wood Pellets sp.



MATERIALS AND METHODS

The laboratory experiments of this work were carried out at the Biomass Laboratory of UNESP/Itapeva - Institute of Science and Engineering of Itapeva (ICE). All processes were guided by a technician for better performance and mentions risks of errors and accidents. The material used for this analysis was *Pinus sp.* The other data and procedures were detailed below as well as tabulated.

Materials

Pellets de *Pinus sp.*

Mars Digital Precision Scale

60 mesh and 35 mesh screens

Bertel Particle Size Analysis Sieve Shaker

Plastic sack

Marconi knife mill

Ponytail container

Greenhouse

Steel crucible

Calorimeter

Calorimeter Pump

Cotton Yarn

Methods

Biomass preparation

Initially, the pellet was naturally dried in the open air. Then, the biomass was crushed using a Marconi knife mill and collected in a container.

The material obtained was placed in a set of previously weighed sieves (Table 1) with openings of 60 and 35 mesh. This set was then taken to the Bertel Screen Shaker for Particle Size Analysis, where it remained for approximately 10 minutes. After this period, the material retained in each compartment of the sieves was weighed. The material that passed through the 35 mesh sieve and was retained in the 60 mesh sieve was again weighed and stored in a plastic bag.

Table 1: Weighing data

	Mass (g)
Base	370,78
60 mesh	332,10
35 mesh	349,60
Base + biomass	404,10
60 mesh + biomass	365,40
35 mesh + biomass	548,10

Sample preparation

On the second day of the experiment, two crucibles were used to measure the wet masses of the samples. They were prepared in duplicate to ensure experimental reliability, after measurement they were placed in an oven for 24 hours. After this period, the dry masses of the crucibles were measured (Table 2). The moisture content (TU) was then calculated using the following equation 1:

$$TU(\%) = \left[\frac{m_{umida} - m_{seca}}{m_{seca}} \times 100 \right] \quad (1)$$

Table 2 - Data obtained from the measurements

	Formula	Sample 1	Sample 2	Average
Crucible (g)	$m_{crucible}$	15,4232	8,2900	
Biomass (g)	m_{wet}	1,0035	1,015	
Crucible + dry biomass (g)	$M_{crucible + dry\ biomass}$	16,3265	9,2035	
Dry biomass (g)	m_{dry}	0,9033	0,9135	
Moisture content (%)	TU(%)	11,0927	11,1111	11,1019

Determination of the higher calorific value (PCS)

The PCS was determined from a calorimeter equipped with a calorimetric pump immersed in water. Initially, each empty crucible was weighed. Then, 1 g of sample was added to each of the crucibles.

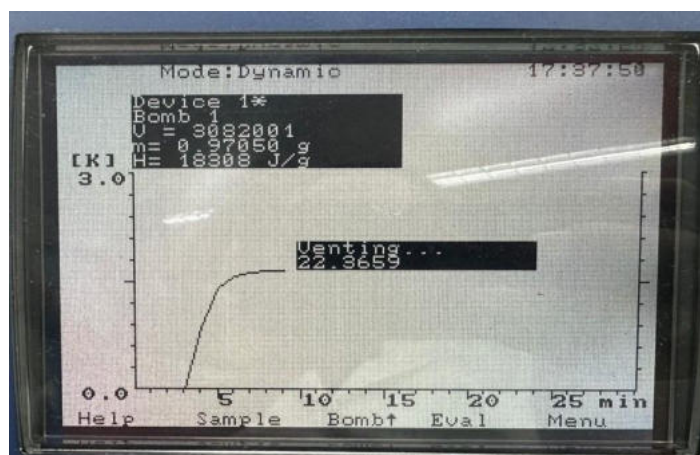
The calorimetric pump was prepared with a small sample of the material and a cotton thread in contact with a metallic wire, forming two short-circuited electrodes. This assembly was then placed on the equipment. After homogenization, the combustion of the sample began, raising the temperature and identifying the amount of energy released. The equipment deducted 50 J from the measured value, referring to the burning of the cotton thread.

The total time of the experiment was approximately 10 minutes, with 3 minutes dedicated to temperature homogenization. This is due to the need to enrich pure oxygen in the equipment, since the ambient concentration of 21% is not sufficient for proper combustion.

At the end, the pressure in the equipment reached 30 bar and the PCS result obtained was 18,308 J/g (Figure 2) considering the humidity of the sample. It is worth noting that

higher calorific value is inversely proportional to moisture content. The results obtained were compared with values reported in the literature.

Figure 2 - Combustion result



RESULTS AND DISCUSSIONS

Pinus sp. wood pellets are widely used as biofuels due to their high energy efficiency and sustainability. In the context of the analysis of the moisture content of the pellets, the data obtained of 11.1019% is in line with the results found by Camargo [3], who presented a value of 12.36%. The slight difference between the values can be attributed to variables such as storage conditions, measurement method and the specific origin of the *Pinus sp. sample*.element.

These results suggest that *Pinus sp.* pellets maintain a relatively low moisture content, which is essential for maximizing calorific value and minimizing problems such as spoilage and smoke emission during combustion.

Therefore, both the data obtained and those of Camargo [3] reinforce the feasibility of using *Pinus sp.* pellets as an efficient and sustainable biofuel option.

The data obtained in the laboratory indicate that the pellets of *Pinus sp.* have an average calorific value of 18.308 MJ/kg. This result was compared with the data available in the literature, specifically the studies by Garcia et al. [4] whose values were 19.48 MJ/kg, 19.13 MJ/kg, and 18.71 MJ/kg, which, converted to joules per gram, correspond to 19480 J/g, 19130 J/g, and 18710 J/g, respectively. When comparing the

values obtained in this study (18.308 MJ/kg) with those presented by Garcia et al. [4], we observed that there is a slight difference between the data.

The average calorific value found in this work is slightly below the values reported by these researchers. This discrepancy can be attributed to several factors, such as the origin and quality of the raw material, where the pellets analyzed by Garcia et al. [4] come from two specific regions (Paraná and Santa Catarina) and the one in this report comes from the region of Itapeva (São Paulo), which may imply differences in the growing conditions of the trees, such as soil, climate, and forest management, influencing the density and chemical composition of wood. Another factor is the processing and compaction of the pellets, since the technology and production conditions such as compaction pressure, temperature and humidity during pellet formation can vary significantly, affecting the energy density of the final products. In addition to the diameter of the pellets, where they are all 6 mm in diameter, small variations in the production process and in the characteristics of the raw material can lead to differences in calorific value.

In order to analyze the results obtained, a percentage difference was made (Equation 2), which has the function of validating experimental data, that is, comparing the experimental results with reference values taken from books or literature, which helps to validate the accuracy and reliability of the data obtained in the experiment.

$$i = \frac{V_{final} - V_{inicial}}{V_{inicial}} \times 100 \quad (2)$$

Therefore, the results obtained both in the laboratory experiments and in the literature review (Tables 3, 4 and 5) are consistent with the desired expectations, demonstrating consistency and alignment with the previously mentioned data.

Table 3 - Variation in Moisture Content between studies

Percentage Obtained	Percentage read [4]	Percentage change
11,1019	12,3600	-0,1018

Table 4 - Variation in the PCS between studies

	Percentage
Literature measurement [4]	19,48
Literature measurement [4]	19,13
Literature measurement [4]	18,71
Average	19,11

Table 5 - Percentage variation between studies

Percentage Obtained	Percentage read [4]	Percentage change
18,71	19,11	-0,02007606

CONCLUSION

In conclusion, while a slight variation has been observed, this can be attributed to external factors, as discussed earlier. It is important to note that differences in the origin and quality of the raw material, as evidenced by the study by Garcia et al. [4], can significantly impact the characteristics of the pellets analyzed.

Thus, the results obtained in this study are within the expected and contribute to all existing studies in the literature.

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CHARACTERIZATION OF RELEVANT BIOMASSES IN THE BRAZILIAN AGRICULTURAL SCENARIO

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ABSTRACT

Agricultural biomass residues represent viable and sustainable energy alternatives, contributing to the mitigation of atmospheric emissions, rural development, and the transition to a low-carbon economy. Brazil has great potential for energy use from these residues, but to achieve this, it is necessary to understand their composition. Physicochemical characterization is a critical starting point for the efficient use of biomass, as its properties directly influence technical feasibility, the selection of conversion routes, and their applicability in energy planning and optimization. Obtaining this information from the literature requires extensive literature review, and in many cases, the standard methodologies used are not clearly indicated. This study provides proximate, elemental and calorific data for six agricultural residues relevant to the Brazilian scenario – sugarcane bagasse (SCB), sugarcane straw (SCS), açai seed (AS), cottonseed (CS), green coconut husk fibre (GCHF), and rice husk (RH) – based on standardized methodologies. Analyses were performed in sextuplicate on samples as received in a biomass laboratory, with detailed methodology adopted to ensure transparency and reproducibility. The results revealed variability in composition, with carbon contents ranged from 42.75–52.63 wt.%, ash contents from 1.73–13.17 wt.% and lower heating values (LHV) from 14.90–19.37 MJ/kg (dry basis). CS sample presented a high nitrogen content (4.57 wt.%), an element associated with the formation of pollutant compounds (NO_x). By systematically adopted, this work establishes a reliable reference for both academic research and industrial application, supporting the effective integration of agricultural residues into sustainable energy systems in Brazil and beyond.

Keywords: Agro-industrial biomass; Proximate analysis; Elemental analysis; Calorific value

INTRODUCTION

The transition to renewable energy sources has intensified globally considering the urgent need to reduce greenhouse gas (GHG) emissions and mitigate the impacts of climate change. Dependence on fossil fuels compromises environmental sustainability and affects countries' energy and economic security [1].

Brazil reaffirmed its commitment to the Paris Agreement during COP29 (2024), by setting the target of reducing net GHG emissions by between 59% and 67% by 2035, compared to 2005 levels [2,3]. This target is in line with the country's progress in the energy transition. In 2023, renewable sources represented 89.2% of the electricity matrix and 49.1% of the total energy matrix, with emphasis on hydroelectric, biomass, solar and wind power [2].

Among renewable sources, residual biomass stands out as a viable and sustainable energy alternative [4], promoting environmental and socioeconomic benefits, such as mitigating the impacts of inadequate waste disposal and generating jobs in rural areas [5]. The energy use of agricultural waste also directly contributes to the achievement of the Sustainable Development Goals, especially in the areas of affordable energy, food security and combating climate change [6].

Brazil stands out among the countries with the greatest potential for energy use from agro-industrial waste, due to its territorial extension, climate diversity and broad agricultural production. Considering only the five main temporary crops – rice, sugarcane, corn, soybeans and wheat – the estimate based on production data from 2017 indicated that approximately 521 million tons of agricultural waste (dry basis) were generated, of which approximately 211 million tons (wet basis) have potential for energy use [7]. In addition to these temporary crops, waste from permanent crops and agro-industries is also significant. Among the main residual biomasses, the following stand out: açai seed (AS), cottonseed (CS), sugarcane bagasse (SCB) and straw (SCS), rice husk (RH) and green coconut husk with fibre (GCHF) – materials originating from production chains distributed throughout the five Brazilian regions.

Table 1 presents the planted area, harvested area, and production quantity for açai, cotton, sugarcane, rice, and coconut crops, based on the Municipal Agricultural

Production Survey (PAM) for the year 2023 [8]. Fig. 1 illustrates the predominant geographic distribution of these crops in the national territory.

Table 1. Planted area, harvested area and quantity produced of açai, cotton, sugarcane, rice and coconut crops in Brazil in 2023 [8].

Agricultural crop	Planted area (ha)	Harvested area (ha)	Production (t)
Sugar cane	10.081.661	10.065.599	782.585.836
Rice	1.500.926	1.482.748	10.285.663
Cotton (seed)	1.709.605	1.709.425	7.496.603
Coconut	187442	186712	1.932.282
Açaí	236.780	236.404	1.696.485

Source: Data information from [8].

Fig. 1. Regional predominance of agricultural crops of açai, cotton (seed), rice, sugarcane and coconut in the regions of Brazil [8].



Note: Generated using the Bing platform and Microsoft Excel® tools.

This agricultural base, in addition to being significant in the domestic scenario, places Brazil in a prominent position in the international context. The country is currently the largest producer, consumer, and exporter of açai [9]; in 2022, it occupied the fifth position in the world production of seed cotton [10]; and, in 2023, it was the global leader in sugarcane production, surpassing India in almost 60% of the volume produced [10]. It also stands out as the world's second largest producer of ethanol, behind only the United States - where corn is the predominant raw material, while in

Brazil production is based mainly on sugarcane [11]. In 2023, national ethanol production reached 35.4 million m³ [12]. In the case of rice, although the largest volumes are concentrated in Asia, Brazil occupied, based on 2023 data, the twelfth global position, accounting for around 1.3% of world production [10]. In 2023, Brazil was the world's fourth largest producer of coconut, although with low representation among global producers, accounting for around 4.5% of world production [10]. The main destinations for exported production were the United States, Spain and Argentina [13].

Regarding the residual biomass generated in the processing of these crops, it is estimated that the seed represents up to 85% of the açai fruit [14]; in the case of cotton, the seed corresponds to approximately 65% of the total biomass [15]; the rice husk represents approximately 20% of the grain weight [16]; the residue from the extraction of water from coconuts, also known as husk with fibre, can correspond to up to 85% of the total mass of the fruit [17]. For sugarcane, bagasse and straw residues correspond, on average, to 28% of the processed mass [18]. It is worth mentioning that sugarcane bagasse already has wide application in the cogeneration of energy in industrial plants [19] and, for other biomasses, application studies have been developed ranging from energy generation, biofuel production, animal feed, input for civil construction, among others.

The starting point for efficient energy use of biomass is the physicochemical characterization, since its properties directly influence the performance, technical feasibility and selection of conversion routes [20]. Although studies in the literature provide characterization data for different types of biomass [21-23], there is still a lack of information on the sample conditions received at the laboratory, as well as information on which standardized methodology was adopted in the execution of the analytical procedures, which makes it difficult both to compare studies and to apply these data in the planning and optimization of energy processes.

In this context, this study aims to characterize agro-industrial waste, specifically AS, CS, GCHFB, RH, SCB and SCS, providing, in addition to the results, details of the methodologies used. The determinations performed include moisture, volatile matter (VM), ash and fixed carbon (FC), elemental composition (CHNSO) and calorific value.

MATERIALS AND METHODS

Obtaining and preparing biomass

Six laboratory sample of residual biomass – AS, CS, GCHFB, RH, SCB and SCS – were supplied by partner companies. The sampling plan adopted by the companies was not provided and the preparation standards used in this work refer only to the steps applied to the general analysis sample (ISO 16559:2022 [24]). The pre-drying moisture (M_{pd}) content was determined based on ISO 18134-1:2022 [25]. The samples, as received (a.r.), were distributed on aluminium trays (27 cm x 39 cm) and dried in an air-circulating oven (Fabbe) at $(105 \pm 5) ^\circ\text{C}$ overnight. After cooling and weighing, they were subjected to additional 1 h drying cycles until constant mass achieved. Fig. 2 illustrates the raw biomasses (a.r.) and after pre-drying (p.d.). Then, the samples were milling in a Willye knife mill (Fortinox) to a particle size of 0.595 mm and sealed in plastic bags for storage [25]. Except for pre-drying moisture, the other analyses were performed in sextuplicate.

Fig. 2. Raw biomasses (AS, CS, GCHFB, RH, SCB and SCS) as received (a.r.) and after pre-drying (p.d.) at $(105 \pm 5) ^\circ\text{C}$.



Proximate analysis and heating value

The residual moisture (M_r) content was determined based on ISO 18134-3:2023 [26]. Approximately 5 g of ground biomass was weighed on six glass weighing bottle and dried in an air-circulating oven (Orion 520, Fannem) at (105 ± 5) °C overnight. After cooling and weighing, the samples were subjected to additional 1 h drying cycles until constant mass achieved and then homogenized for subsequent analyses, as shown in Fig. 3. The total moisture content (M_t) was determined according to Eq. 1.

$$M_t = M_{pd} + M_r(1 - M_{pd}/100) \quad (1)$$

Where, M_{pd} is the pre-drying moisture content of the sample (a.r.) in the laboratory and M_r is the residual moisture content determined in the milling sample.

Ash content was determined based on ASTM E1755-24 [27]. Approximately 1 g of sample was heated in a porcelain crucible in a muffle furnace (Fornitec) at 250 °C for 30 min and then at (575 ± 25) °C for at least 180 min. After cooling and weighing, the sample was reheated in 1-h cycles until constant mass achieved. VM analysis carried out according ASTM D1762-84(2021) [28]. Approximately 1 g of biomass was heated in a porcelain crucible with a lid in a muffle furnace (Forlabo) in three steps: 2 min at the outer edge (~ 300 °C), 3 min at the inner edge (~ 500 °C), and 6 min inside with the door closed at (950 ± 25) °C. The FC content, on dry basis, was calculated based to Eq. 2 described in ISO 16559:2022 [24]. The higher heating value (HHV) was determined based on ASTM D5865/D5865M-19 [29] using an automatic isoperibolic calorimeter (6400, Parr) and constant volume bomb calorimeter by combustion of 1 g of compacted sample. The lower heating value (LHV) was determined according to Eq. 3.

$$FC = 100 - (Ash + VM) \quad (2)$$

$$LHV = HHV - (0,2155 \times H) \quad (3)$$

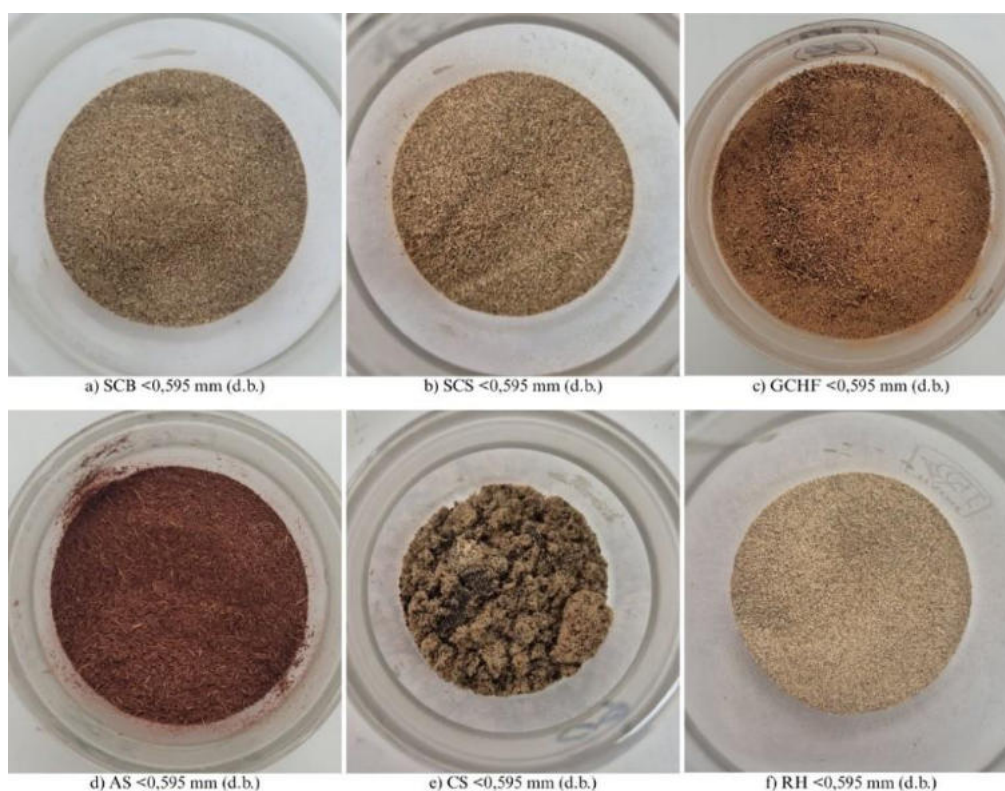
Elemental analysis

The carbon (C), hydrogen (H) and nitrogen (N) contents were determined in an elemental analyser (Flash 2000, Thermo Fischer) based on ASTM D5373-21, Method A [30] and DIN EN ISO 16948:2015 [31]. Approximately 0.003 g of sample was combusted at 950 °C under flowing oxygen (99.999%) and the resulting gases were quantified by

thermal conductivity. The total sulphur content was determined in an elemental analyser (S-144, Leco) based on ASTM D4239-18e1, Method A [32]. Approximately 0.05 g of sample was combusted at 1350 °C and the sulphur converted to SO₂ was quantified by infrared absorption spectroscopy. The oxygen content, on dry basis, was calculated by difference, according to Eq. 4 described in ASTM D3176-24 [33].

$$O = 100 - (Ash + C + H + N + S) \quad (4)$$

Fig. 3. Milling biomasses (AS, CS, GCHFB, RH, SCB and SCS) on a dry basis with particle size of 0.595 mm.



RESULTS AND DISCUSSIONS

Table 2 presents the results of the proximate analysis, elemental composition, and heating values for SCB, SCS, AS, CS, RH, and GCHF. Table 3 provides a summary of selected literature results for similar biomasses.

Table 2. Proximate and elemental analysis and heating values of SCB, SCS, AS, CS, RH, and GCHF.

Property	AS	CS	GCHF	RH	SCB	SCS
Total moisture (wt.%)	5.74	10.51	86.86	8	47.32	8.31
Residual moisture (wt.%)	3.87 ± 0.09	7.2 ± 0.13	3.63 ± 0.05	1.29 ± 0.09	4.67 ± 0.04	3.23 ± 0.06
<i>Proximate analysis – wt.% (d.b.)</i>						
Ash	1.73 ± 0.05	4.4 ± 0.06	4.97 ± 0.05	6.08 ± 0.04	6.98 ± 0.61	13.17 ± 0.53
VM	72.32 ± 0.84	78.73 ± 0.66	72.83 ± 0.65	73.72 ± 0.55	77.32 ± 0.83	70.35 ± 0.77
FC	26	17	22	20	16	16
<i>Elemental analysis – wt.% (d.b.)</i>						
C	48.67 ± 0.77	52.63 ± 0.91	47.8 ± 0.94	47.05 ± 0.64	46.85 ± 1.32	42.75 ± 0.55
H	5.72 ± 0.1	7.64 ± 0.23	5.85 ± 0.09	5.83 ± 0.09	5.88 ± 0.16	5.45 ± 0.14
N	0.67 ± 0.05	4.57 ± 0.21	0.63 ± 0.05	0.43 ± 0.05	0.2 ± 0	0.43 ± 0.05
S	<0.1	0.23 ± 0.03	<0.1	<0.1	<0.1	0.18 ± 0.01
O	43	31	41	41	40	38
<i>Heating values (MJ kg⁻¹)</i>						
HHV (d.b.)	18.87 ± 0.73	22.31 ± 0.18	19.14 ± 0.04	18.81 ± 0.06	18.19 ± 0.05	16.78 ± 0.04
LHV (d.b.)	17.64 ± 0.73	20.66 ± 0.18	17.88 ± 0.06	17.56 ± 0.07	16.93 ± 0.05	15.60 ± 0.05
HHV (w.b.)	17.10 ± 0.65	19.80 ± 0.17	2.43 ± 0.01	17.08 ± 0.06	9.14 ± 0.03	13.94 ± 0.03
LHV (w.b.)	15.76 ± 0.65	18.07 ± 0.16	0.16 ± 0.01	15.74 ± 0.06	7.30 ± 0.03	12.56 ± 0.05

Table 3. Summary of selected data from the literature for similar biomasses.

Feedstock	M	Ash	VM	FC	C	H	N	S	O	HHV	LHV	Observations	Ref.
	(wt.%)							(MJ/kg)					
AS	-	6,90	27,20	-	48,21	6,69	1,60	0,22	-	-	-	Methodology was not described.	[34]
CS	4,61	3,31	79,47	12,61	55,41	8,82	4,41	-	31,36	25,82	-	Methodology was not described.	[35]
Coconut shell	8,27	0,71	77,19	22,10	50,22	5,70	0,00	-	43,37	20,498	-	Preparation of samples - ASTM D2013-86; Proximate analysis - ASTM D3172-73(84); M - ASTM D3173-87; VM - ASTM D3175-89; Ash - ASTM D3174-89; Ultimate analysis - ASTM D3176-79(84); HHV - ASTM D2015-85 and FC and O - calculated	[36]
RH	8,47	21,24	61,81	16,95	38,50	5,20	0,45	-	34,61	14,639	-		
SCB	51,01	3,20	83,66	13,15	45,48	5,96	0,15	-	45,21	18,730	-		
RH	7,55	15,84	61,48	15,43	36,91	4,71	0,63	0,14	57,60	15,07	13,92	Ultimate analysis was conducted by GB/T 28734-2012, GB/T 28732-2012, and GB/T 30728-2014 standards. Proximate analysis followed GB/T 28731-2012 and GB/T 30727-2014 standards. Results reported on "as determined" basis (a.d.)	[37]
SCS	10,4	16,4	74,0	13,0	43,2	6,7	0,3	0,2	33,2	18,00	17,00	M - ISO-589-1981; Ash - ISO-1171-1976; VM - ISO-5623-1974; elemental analysis (CHNS) using Carlo Erba 1108; Heating value - ISO-1928-76. Results reported on dry basis (d.b.)	[38]

M: moisture content

Sample preparation and impacts on tests

Sample particle size impacts the precision and accuracy of characterization results, especially in tests that use small amounts of material, such as elemental analyses of CHN and S. This effect becomes even more relevant in materials with heterogeneous structural composition, such as biomasses with high fibre content, due to the tendency for segregation between fractions of different sizes as presented in the study by Tambani et al. [39]. Channiwala and Parikh [36] reported challenges in preparing 28 biomass and coal samples. Their study used ASTM D2013-86, a standard for preparing coal samples that recommends reducing particle size to 250 μm . However, for highly fibrous materials such as bagasse, coconut shell, and cottongin waste, it was not possible to achieve the particle size recommended by the standard, and these samples were cut to 1 mm in size. In the present study, the general analysis sample was prepared with a final particle size below 1 mm, following ISO 18134-3 [26]. Apaydin-Varol et al. [35] also highlighted the role of particle size in sample characterization, reporting the use of 0.92 mm for CS, although without specifying the standards applied in each test. As particle size can impact characterization analyses, it is important to report the procedure adopted in sample preparation and the particle size adopted.

Total moisture

The moisture content in biomass is a variable characteristic due to the influence of several factors such as plant species, climate, exposure time, storage, and transportation. It is a critical property in the evaluation of biomass for thermochemical purposes, as it exerts a strong influence on the calorific value and may even make direct combustion unfeasible. This is because there is an inverse proportionality relationship between these properties, since part of the energy generated in combustion is consumed in the evaporation of water present in the biomass [40,41].

SCB and GCHF were the biomasses that presented the highest total moisture contents, both above 40% (Table 2), typical values for these types of agricultural residues [23,36,42,43]. GCHF was the biomass that underwent the most visible

physical changes after pre-drying, as illustrated in Fig. 2. From a methodological point of view, both temperature and drying time have a significant influence on the determination of total moisture. High temperatures can induce transformations in the biomass constituents [44], while prolonged times can result in the loss of VM in addition to water [25]. Therefore, in order for the results to be comparable between different studies, it is essential that the same standardized methodology be adopted.

Apaydin-Varol et al., [35] determined the moisture content of CS (4.61 wt.%), however, the methodology is not indicated, and it is also not possible to identify whether the value refers to total or residual moisture content. Channiwala and Parikh [36], studied samples of coconut shell and SCB and obtained moisture contents of 8.27 wt.% and 51.01 wt.%, respectively, following the ASTM D3173 methodology, which is aimed at coal and coke. Since ASTM D3173 does not mention the need for pre-drying [45], it is not possible to identify whether the reported value refers to residual or total moisture. Still regarding coconut shell, the sample composition may also be a factor linked to the difference between the value obtained by the authors [36] and that reported in this article, which studied a coconut sample composed of husk and fiber. Wang X et al. [37] and Channiwala and Parikh [36], characterized rice husk samples using different methodologies, reporting moisture values of 7.55 wt.% (ASTM D3173) and 8.47 wt.% (GB/T 28731), respectively, values close to those found in this work for total moisture. For this type of biomass, the difference in methodologies did not cause significant impacts.

Ash

High ash content of the biomass favours the formation of slag and incrustations, potentially compromising the performance of combustion systems [46]. The average ash contents, on a dry basis, ranged from 1.73-13.17 wt.%, in the following decreasing order: SCS > SCB > RH > GCHF > CS > AS (Table 2). Channiwala and Parikh [36] applied ASTM D3174-89, standard method for coal and coke, which employs higher temperatures (735–765 °C) than those specified in ASTM E1755-24 [27], the standard

method for biomass. The values they reported for coconut shell and SCB were 0.71 wt.% and 3.2 wt.%, respectively, both lower than those obtained in the present study.

For biomass samples, ISO 18122:2022 [47] also describes a methodology for determining ash in solid biofuel samples, adopting an ashing temperature similar to that indicated by ASTM E1755 [27], i.e., 550 °C, and allows higher temperatures (710 and 815) °C, but does not detail in which situations these temperatures can be used. However, the burning time is different: while ASTM recommends 3 hours, ISO recommends a 2-hour burning period, which can be extended by an additional 30 minutes for samples that do not present complete incineration.

Combustion temperature is a critical parameter in ash determination, as higher temperatures may promote volatilization of inorganic elements, decomposition of carbonates forming CO₂, and further oxidation of inorganic compounds, resulting lower ash contents [21, 47]. Consequently, meaningful comparisons of ash contents across different biomasses require knowledge of the combustion temperature employed.

Among the biomasses studied, those from sugarcane presented the highest standard deviations (0.5–0.6%). For SCB, the repeatability limit established by the standard (10.4%) [27] was exceeded, indicating greater sample heterogeneity. For this type of biomass, particle size becomes an important factor, since smaller particles contribute to a more homogeneous sample by ensuring adequate incorporation of the fibrous fraction, which is mainly organic [39].

Volatile matter and fixed carbon

In combustion process, high content of VM when combined with a low FC content, favours rapid thermal conversion of biomass [43, 48]. The average VM contents, on a dry basis, varied between 70-78 wt.%, with the following decreasing order: CS > SCB > RH > GCHF > AS > SCS (Table 2). FC varied between 16-26 wt.%, with the following decreasing order: AS > GCHF > RH > CS > SCB > SCS. Regarding the methodologies for determining VM, the available standards methods are specified for different matrices and present variations in parameters such as temperature and combustion time [48],

these methodological differences can lead to variations in the results obtained. Moreira et al., [49] reported a difference of 1.94% between the results obtained for VM using the ASTM D1762 and ISO 18123 standards for a cryogenically ground for SCB sample.

Apaydin-Varol et al. [35] reported a VM content of 79.47 wt.% (Table 3) for a CS sample, a value close to that obtained in the present study; however, the standard method applied was not specified. Channiwalla and Parikh [36] also reported VM results obtained according to ASTM D3175-89 [50], which uses the burning temperature range of (950 ± 20) °C similar to ASTM D1762 (950 ± 5) °C [28], the standard method used in this study. However, for coconut shell and bagasse samples, Channiwalla and Parikh [36] used a temperature of 750 °C because ash fusion was observed at 950 °C. Both standards are aimed at coal analysis, ASTM D1762 for wood charcoal and ASTM D3175 for coal and coke [28,50]. The ISO 18123:2023 [51] standard is aimed at determining VM in solid biofuels, and therefore includes biomass in its scope, and indicates the burning temperature range of (900 ± 10) °C. Regarding the burning time, the ISO 18123 and ASTM D3175 standards present the same burning time (7 minutes), while ASTM D1762 indicates a total burning time of 11 minutes [28,50,51].

With respect to fixed carbon (FC), since it is calculated as the balance from ash and VM contents, it is directly influenced by the methodologies adopted for the determination of these two parameters.

Elemental analysis - CHNO e S

Analysis of elemental composition is essential for evaluating biomass conversion processes for energy purposes, as it is necessary for mass and energy balances, in addition to being associated with potential pollution complications [52]. The carbon contents varied between 42.75-52.63 wt.%, on a dry basis, with the following decreasing order: CS > AS > GCHF > RH > SCB > SCS. For hydrogen, the values oscillated between 5.45-7.64 wt.%, with the following order: CS > SCB > GCHF > RH > AS > SCS. With the exception of CS, which presented a significantly high value (4.57 wt.%), the other biomasses exhibited typical nitrogen contents, below 1 wt.%, with the

following decreasing order: CS > AS > GCHF > RH > SCS > SCB. As for the oxygen content, calculated by difference, CS presented the lowest value among the samples, 31 wt.%, while the other biomasses varied between 38-43 wt.%. Sulphur contents were below 0.1 wt.% for most samples, with the exception of CS (0.23 wt.%) and SCS (0.18 wt.%).

In this study, as the equipment used to determine CHN operates in the micro weighing range, the sample mass used is quite small, making sampling homogeneity a critical factor for the repeatability of results. The greater variations observed between replicates in the carbon results for SCB and hydrogen for CS can be associated with this.

The CHNOS contents in Table 3 are close to those obtained in this study (Table 2). However, in some cases, only the equipment used in the tests was mentioned, without due reference to the standard methods applied [34,35,38]. The experimental determination of CHNOS data requires special instrumentation. Since proximate analysis can be obtained using common equipment, elemental analysis prediction studies from proximate analysis are used [53-55]. Shen et al. [54] proposed one of these correlations for the prediction of C, H, and O. Applying this correlation to SCB, Shen et al. [54] found deviations of less than 4%, similar to the deviation calculated for this same type of sample in the present study. However, the authors suggested the need for additional studies to derive correlations based on experimental data obtained by the same standard methods.

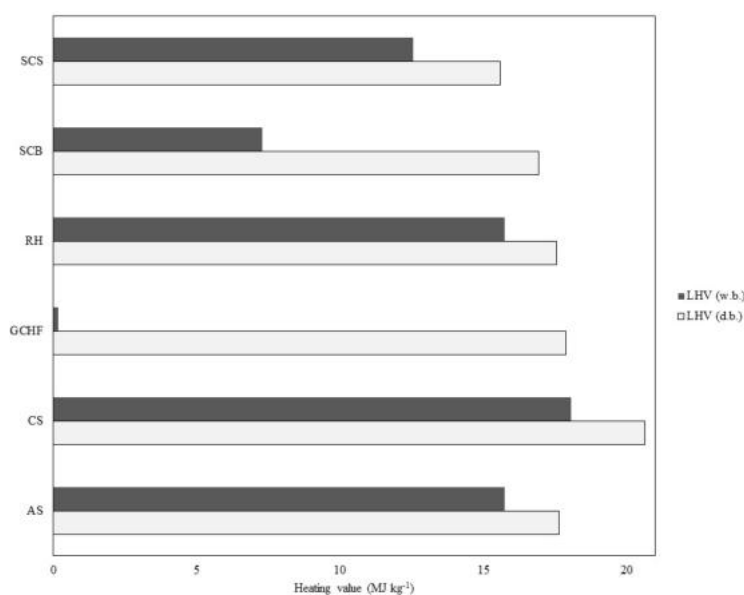
Regarding the determination of sulphur content, the standard method used (ASTM D4239 [32]) is for coal and coke. ISO 16994:2016 [56] describes analytical methods for determining total sulphur and total chlorine in solid biofuel samples. The recommended methods for quantifying total sulphur content are ion chromatography, inductively coupled plasma optical emission spectrometry (ICP-OES), and titrimetry. However, the standard also indicates that this determination can be made using other analytical techniques, such as high-temperature combustion in a tube furnace, the technique used in ASTM D4239 [32].

Heating value

Heating value is one of the most important parameters for choosing the thermochemical process to which the biomass will be processed. However, in order to correctly interpret this parameter, it is essential that the reference biomass basis (dry/wet) is clearly specified [57]. The LHV is a particularly important parameter in studies to estimate energy potential, assess biomass availability and plan energy use systems, and is used in inventories and regional mapping [19].

The HHV, on a dry basis, varied from 16.78–22.31 MJ kg⁻¹, in the following decreasing order: CS > GCHF > AS > RH > SCB > SCS (Table 2). Regarding the standard deviations, AS presented the greatest variation (0.73%). The LHV, on a dry basis and on a wet basis, are presented in Fig. 4, evidencing the strong impact of moisture on the useful energy LHV (w.b.) of biomass, mainly in GCHF and SCB.

Fig. 4. LHV on a dry and wet basis for AS, CS, GCHF, RH, SCB, and SCS biomasses.



Regarding the available methodologies for determining calorific value, ASTM D5865 [29], for coal and coke, used in this study, describes a methodology similar to ISO 18125 [58], which is specific to solid biofuels. Wachirapun Punkrawee [59] compared the calorific value obtained by these two standards for five different types of biomass, including SCB, RH, and coconut shell, and found no significant differences between the methodologies.

As shown in Table 3, the available data for HHV do not always reference the standard methods used and/or the basis on which the results were expressed (wet or dry basis) [34,35]. Some authors also report calorific values obtained by predictions based on other characterization parameters [36,54,59,60]. It should be noted, however, that predicted estimates have limitations associated with the database used in the correlations.

CONCLUSIONS

This study presented the physical and chemical characterization of six residual biomasses identified as representative of the Brazilian agroindustry, employing standardized methodologies. This approach is relevant for supporting both research and industrial applications in bioenergy, providing data for the selection of conversion routes, energy planning, and assessment of the technical feasibility of biomass use. It also contributes to filling a gap identified in the literature, as in many cases, the description of the methodologies employed is not adequately reported.

The biomass samples received at the laboratory were prepared in accordance with ISO 18134-1 and ISO 18134-3 standards to obtain the general analysis sample, which corresponds to subsamples with a nominal size equal to or less than 1 mm for characterization analyses. Although the particle size required by the standards was achieved, the subsamples were not fully pulverized due to the fibrous composition of some biomasses. In terms of composition, the biomasses, on a dry basis, showed wide variability: carbon contents ranged from 42.75 to 52.63 wt.%, ash contents from 1.73 to 13.17 wt.%, and net calorific values (LHV) from 14.90 to 19.37 MJ/kg. It is worth noting the high nitrogen content observed for CS (4.57 wt.%), an element associated with the formation of pollutant compounds (NO_x).

Future investigations are recommended to complement the characterization, including chlorine content, fusibility, and chemical composition of the ash, in order to deepen the understanding of potential operational limitations related to corrosion, slagging, and fouling in energy conversion processes.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Danilo Eiji Hirayama: Conceptualization; Methodology; Validation; Formal analysis; Investigation. Writing - Original Draft; Visualization

Fabiana Oliveira Alexandre: Methodology; Investigation; Writing - Original Draft

Maria Eduarda Pinheiro Gomes: Methodology; Investigation; Writing - Original Draft

Carina Ferrari Braga: Conceptualization; Methodology; Resources

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EFFECT OF IMPROVEMENTS IN SELECTIVE COLLECTION RATES ON LANDFILL GAS GENERATION: A CASE STUDY FOR MUNICIPAL SOLID WASTE IN THE MUNICIPALITY OF SANTO ANDRÉ/SP

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ABSTRACT

This study aimed to evaluate the energy recovery of municipal solid waste (MSW), through the capture of biogas in landfills, as a relevant strategy to generate electricity, in addition to reducing greenhouse gas emissions (GHG). The municipal solid waste (MSW) of Santo André, a municipality located in the Metropolitan Region of São Paulo, with 748,919 inhabitants and daily generation of 640.02 tons of MSW, was evaluated. The municipality has a selective door-to-door collection, serving all neighborhoods, with recycling rates of around 5%. Three scenarios were analyzed, considering different recycling rates and national targets for 2040. From secondary data on the gravimetric composition and the average rate of waste generation, for each scenario a mass balance was carried out to determine the quantity and composition of waste destined for landfills and the generation of biomethane. The study found that energy recovered from landfill gas could supply electricity to up to 6,100 city residents. However, this estimate may not be precise, as the IPCC Model is generic and does not account for local MSW generation or specific properties. The increase in recycling rates has resulted in a decrease in the theoretical global estimate of biogas, as predicted by the IPCC model (2006), which uses the total organic carbon of the different fractions of solid waste to calculate biogas production.

Keywords: Energy recovery, Landfill gas, Municipal Solid Waste, Selective Collection, biogas.

INTRODUCTION

In 2022, 13 years after the creation of the PNRS in Brazil, the National Solid Waste Plan (PLANARES) was established as an important instrument of the National Solid Waste Policy, establishing the guidelines for long-term integrated management. Management mechanisms are one of the main axes of PLANARES and, among them, is the proposal for energy recovery by converting MSW into fuel, thermal energy or electricity, through

processes such as anaerobic digestion, landfill gas recovery, direct combustion or co-processing.[1] The energy recovery of municipal solid waste is a highly widespread reality in developed countries such as Japan, Germany and Sweden. Thus, the energy recovery of MSW is a strategy that addresses both of today's major challenges: the increasing generation of municipal solid wastes in cities and the need for alternative renewable sources to diversify the energy mix.

Santo André, a municipality in the Metropolitan Region of São Paulo with 748,919 inhabitants and a daily generation of 640.02 tons of MSW, is recognized as an example in public policies that encourage sustainability practices in waste management, being classified as the second best in solid waste management in the State of São Paulo, behind only Campinas, according to the Urban Cleaning Sustainability Index (ISLU) published by ABREMA, in the year 2023. In this edition, the study included the analysis of 3,947 cities, considering four aspects: municipal engagement; financial sustainability; recovery of collected waste; and environmental impact. **[2]**

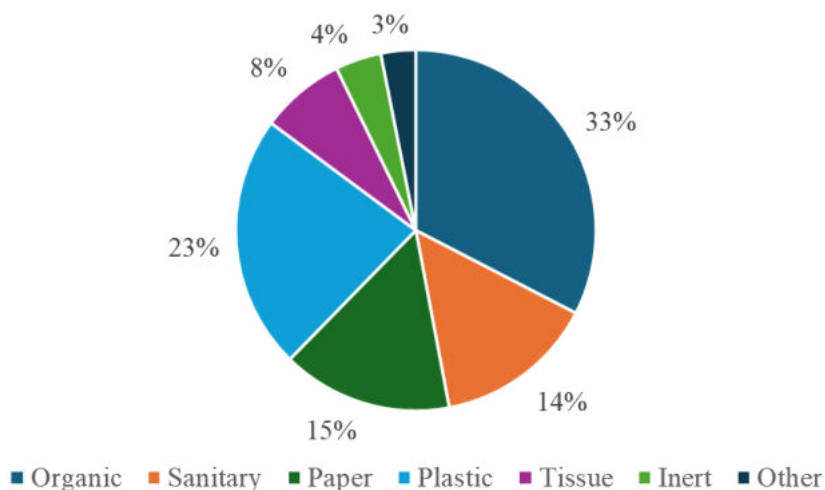
The waste management in the municipality of Santo André is responsibility of Municipal Environmental Sanitation Service of Santo André – SEMASA, which serves 99.8% of the 118 neighborhoods, divided into 15 sectors with mixed and selective collection. The information is available on the SEMASA website **[3]**. The selective collection program structured in the municipality is result of Municipal Law No. 7,733 of 1998, which instituted the Municipal Policy for Environmental Management and Sanitation of Santo André, contemplating the following instruments:

- Door-to-door collection, with source segregation, in which wastes are separated into two classes: dry materials (packaging, plastics, paper/cardboard, aluminum and glass) and biodegradable waste (kitchen waste, sanitary waste)
- Waste collection stations, called ecopoints: places destined for collection of recyclable wastes, rubble, electronic wastes, old furniture, tires, cooking oil, among others, with a volume of up to 1m³.

Municipal Solid Wastes are mostly composed of food scraps and sanitary wastes, mixed with other categories of materials (plastic, paper/cardboard, textiles, inert materials and others) that are contaminated or inappropriately disposed, once they

should be destined for selective collection. According to data from the last gravimetric analysis carried out in the municipality of Santo André, in 2015, these fractions represented more than 80% of the total waste generated, 50.81% of which were organic and 32.59% sanitary (Figure 1) [4]. Biodegradable wastes collection takes place three times a week by means of compactor trucks and the destination is the municipal landfill of Santo André. The recyclable, collected once a week, is sent to the cooperatives in compactor trucks. Currently, the door-to-door selective collection system accounts for 5% of the total waste collected in the municipality

Figure 1. Gravimetric Composition of Municipal Solid Waste in the municipality of Santo André - Year 2015



Source: Adapted from Drudi (2017) [4]

Currently, in the municipality of Santo André, the biodegradable wastes and cooperatives rejects are fully destined to the municipal landfill, which receives about 630 tons of wastes per day, with a generation rate of 0.85kg/day per inhabitant. The municipal landfill, with an area of 40 ha, which was closed between 2010 and 2014, was reopened after an area expansion. One of the key limitations associated with landfills is the requirement for extensive, suitably equipped spaces that meet specific criteria for the safe and effective final disposal of waste.[5, 6]

In Brazil, most waste goes to landfills, so capturing and using landfill gas for energy turns a disposal site into an energy resource. The National Solid Waste Policy (Law

12.305, 2010) calls for closing open dumps and requires all municipalities to dispose of waste in landfills, highlighting the need to address existing landfill operations. [7]. Capturing biogas for energy provides revenue that may lessen immediate need for waste reduction policies or delay investment in circular economy solutions, making ongoing waste reception more viable. However, biogas use is a temporary measure; its environmental value depends on progressing toward sustainable models. While landfills remain, methane capture is essential to reduce their impact. In addition, implementing biogas capture and energy recovery systems necessitates investment in suitable infrastructure, which may represent a significant expense for municipal administrators.

In evaluating the return on investment for these systems, a critical parameter to consider is the biogas capture rate, which fluctuates based on both the volume and composition of waste deposited in the landfill. In this sense, the present study aimed to evaluate the effect of the increase in recycling rates on the generation of electricity by the recovery of landfill gas for the municipality of Santo André.

OBJECTIVE

To estimate the potential for energy recovery by landfill gas in the municipality of Santo André for different scenarios of integrated management of municipal solid waste, considering improvements in the selective collection rate and recycling rates.

METHODOLOGY

Taking as a starting point the current scenario of waste management in the municipality, proposals for integrated management scenarios were made, considering the combination of different collection and sorting systems, in line with what is provided for in the legislation, so that this approach is aligned with the energy recovery guidelines of PLANARES, which establishes long-term goals [1]. The scenarios are summarized in Table 1.

Table 1. Definition of the Scenarios for integrated management of MSW based on selective collection rates

Scenario	Selective Collection Rate	Reference
1	0%	Reference rate
2	5%	Current
3	20%	Planares goal for 2040

For each of the proposed scenarios, a mass balance was carried out, applying the selective collection rates and the proposed sorting efficiency (manual and mechanized). Based on these results, the new gravimetric compositions of wastes destined for recycling and landfills were determined.

First, the selective and undifferentiated collections wastes mass were determined, according to Equations (1) and (2).

$$MSW_{und} = MSW_{total} - MSW_{sel} \quad (1)$$

$$MSW_{sel} = SCR \times MSW_{total} \quad (2)$$

Where: MSW_{und} = mass of MSW from undifferentiated collection (t); MSW_{total} = total MSW mass collected (t); MSW_{sel} = mass of MSW from selective collection (t); SCR = Selective collection rate (%)

To the waste from selective collection, the index that represents the efficiency of the sorting system was applied to determine the mass of recycled waste and the mass of rejects, according to Equations (3) and (4).

$$MSW_{rec} = SE \times MSW_{sel} \quad (3)$$

$$MSW_{rej} = MSW_{sel} - MSW_{rec} \quad (4)$$

Where: MSW_{rec} = mass of MSW destined to recycling (t); MSW_{rej} = mass of rejects (t); SE = Sorting system efficiency (%)

The mass destined to landfills (MSW_{land}) was then determined from Equation (5), as being the sum of the mass from undifferentiated collection and waste from the sorting system.

$$MSW_{land} = MSW_{und} + MSW_{rej} \quad (5)$$

Where: MSW_{land} = mass of MSW destined to landfills (t).

To determine the gravimetric composition of waste sent to landfills, the initial gravimetric composition (scenario 1) was used as a basis to determine the total mass of each of the categories in the mass collected from waste. Subsequently, from the base scenario, the gravimetry of the recyclables was determined, which was taken as a standard reference for mass calculation of each waste fraction in the total destined to the undifferentiated and selective collection systems.

To evaluate the recovery of energy from biogas, its burning in internal combustion engines with subsequent conversion into electrical energy was considered. To estimate the volume of methane generated from waste disposed of in landfills, the theoretical model proposed by the Intergovernmental Panel on Climate Change (IPCC), defined in Equations (6) and (7), was used as a basis.[8]

$$Q_{CH_4} = \frac{Pop \cdot RSU_{taxa} \cdot MSW_{rate} \cdot L_0}{\rho_{CH_4}} \quad (6)$$

$$L_0 = FCM \times COD \times COD_f \times F \times 3 \frac{16}{12} \quad (7)$$

Where: QCH₄ = volume of methane generated in the landfill in 1 year [m³ CH₄. year⁻¹]; Pop = Population of the municipality [hab]; MSW rate = Rate of MSW generation in the municipality [kg.inhabitant⁻¹.year⁻¹]; MSW = Mass fraction of MSW that is actually disposed of in landfills [kg disposed of in landfill. kg⁻¹ generated]; L₀ = MSW methane generation potential [kg CH₄.kg⁻¹ MSW]; ρCH₄ = methane density [kg/m³]; FCM = Methane correction factor [%]; COD = degradable organic carbon present in MSW [kg of COD. kg⁻¹ of MSW]; COD_f = Dissociable fraction of COD [%]; F = volumetric fraction of CH₄ in landfill biogas; 16/12 = Conversion factor of carbon to methane [kg CH₄.kg⁻¹ of C]

To estimate the electrical energy resulting from the burning of biogas in motor-generator sets, equations (8) and (9) were used, following the methodology described by Dalmo et al. (2019) [G].

$$P_t = \frac{Q_{CH_4} LHV_{CH_4}}{t} \eta_{CH_4} \quad (8)$$

$$E_{disponível} = P_t \eta_{motor} NHT \quad (9)$$

Where: P_t = Thermal Power generated in the burning of CH_4 in the engines [kW]; LHV_{CH_4} = Lower Heating Value of Methane [kJ/Nm³ of CH_4]; t = Time conversion factor: years to seconds [s.year⁻¹]; η_{CH_4} = efficiency of methane collection in landfills; η_{engine} = thermal efficiency of internal combustion engines; NHT = number of hours actually worked in a year, considering maintenance shutdowns.

The values for the parameters of equations (6) to (9) were defined based on data from the IPCC (1996) and Dalmo et al. (2019) [8,G].

RESULTS AND DISCUSSION

Table 2 presents the secondary data regarding the generation and management of waste in the municipality of Santo André, necessary for the calculations of mass balances and energy generation.

Table 2. Demographic and waste generation data of the municipality of Santo André

Secondary Data	Santo André	Source
Population	748,919	[8]
Annual MSW generation (t. day ⁻¹)	640.02	[10]
MSW generation rate (kg.inhab ⁻¹ .day ⁻¹)	0.855	Calculated

Table 3 presents the results regarding the collected mass and gravimetric composition of the MSW in the municipality of Santo André, for each scenario. Figure 2 illustrates the total masses of waste recycled and sent to landfills for each of the scenarios evaluated.

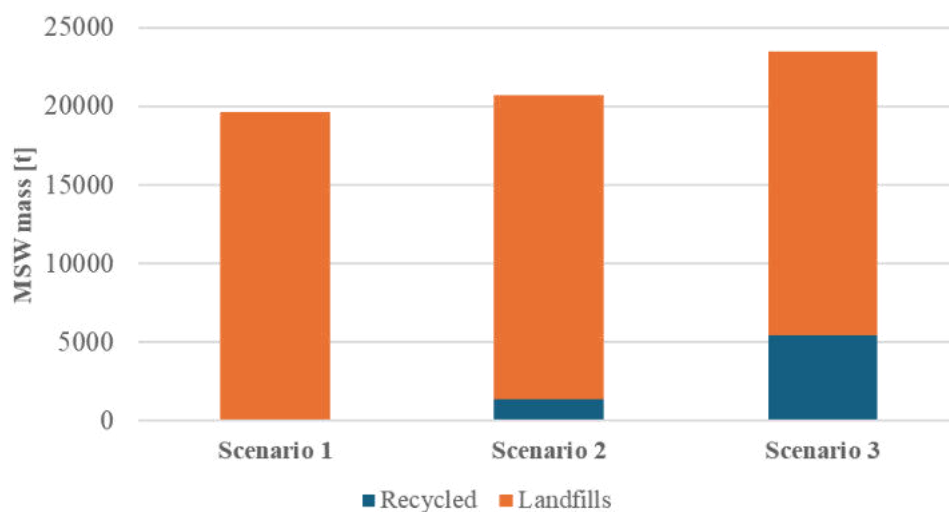
Table 3. Mass Balance and Gravimetric Composition of MSW sent to the landfills, for the municipality of Santo André, for different selective collection rates scenarios.

Category	Scenario 1		Scenario 2		Scenario 3	
	Collected mass [t]	Gravimetric composition [w/w]	Collected mass [t]	Gravimetric composition [w/w]	Collected mass [t]	Gravimetric composition [w/w]
Organic	90,660	39%	90,660	41%	90,660	48%
Sanitary	25,242	11%	25,242	11%	25,242	14%
Plastic	34,520	15%	30,266	14%	17,503	9%
Paper	25,990	11%	22,787	10%	13,177	7%
Tissue	20,894	9%	18,319	8%	10,594	6%
Inert	13,415	6%	11,762	5%	6,802	4%
Other	22,998	10%	22,998	10%	22,998	12%

(Source: Authors)

Data in Table 3 and Figure 2 show that, as expected, the increase in selective collection rates resulted in a reduction in the proportion of recyclables wastes sent to landfills. As a result, there is a reduction of between 1.5% (scenario 2) and 4.5% (scenario 3) of the total mass destined to landfills, with a consequent increase in their useful life. For this improvement to be more significant, it is necessary to consider greater efficiencies in the sorting systems, in addition to more expressive rates of selective collection.

Figure 2. Mass of waste recycled and destined to landfills, for the municipality of Santo André, for the different Integrated Management Scenarios.



Source: Authors

The data on energy recovery by landfill gas are presented in Table 4, The maximum and minimum values refer to different methane collection rates, with the maximum value corresponding to an efficiency of 50% and the minimum to 10%.

Table 4. Energy Generated [MWh/year] by landfill gas, based on the consolidated scenarios for the municipality of Santo André

Scenarios	Selective Collection Rate	Electrical Energy Generated [MWh/year]		% municipality's annual consumption	
		min	max	min	max
1	0%	3,050	15,250	0.145%	0.726%
2	5%	3,024	15,120	0.144%	0.720%
3	20%	2,946	14,730	0.140%	0.701%

Source: Author

Santo André is a municipality with 748,919 inhabitants who generate 640.2 tons of Municipal solid waste daily, resulting in an annual amount of 233,600 tons [5, 6]. A first analysis of the results in Table 2 shows that if all the waste from the municipality were sent to a landfill with a biogas-based electricity generation system, it would be possible to generate approximately between 3,000 and 15,000MWh.year⁻¹ of energy from renewable sources. Considering the average monthly consumption of 205.5kWh per inhabitant of the State of São Paulo, this amount represents the energy needed to serve between 1,250 and 6,100 people, approximately (EPE, 2025). However, it must be considered that this estimate is not precise, as the IPCC Model is generic and does not account for local MSW generation or specific properties, such as seasonal variations, landfill age, or local degradation conditions.

An analysis of the results obtained for scenarios 2 and 3, compared to the base scenario, shows that the increase in recycling rates resulted in progressive reductions in the energy recovery of landfill gas, of 0.85 and 3.4%, respectively, This result demonstrates that although selective collection does not involve the separation of organics and sanitary, other wastes that contribute to anaerobic digestion are also segregated, reflecting a reduction in the energy generated, This is also because the IPCC model considers the COD present in the samples of textiles, paper and

cardboard, These variations must be foreseen in the systems, however, they are irrelevant when considering the environmental, social and energy benefits of recycling.

CONCLUSIONS

The energy recovery of landfill gas in the municipality of Santo André can contribute to the generation of enough renewable energy to supply up to 6,100 inhabitants, if an efficiency of 50% in methane collection is considered, using the IPCC model for the estimation.

The separation of recyclables reduces energy generation by up to 3.4%, for the rates considered in this study.

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EFFECT OF TORREFACTION ATMOSPHERE ON THE COMBUSTION PERFORMANCE OF SUGARCANE BAGASSE BRIQUETTES.

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ABSTRACT

Torrefaction has gained significant attention as an effective thermal pretreatment technique to improve the physicochemical properties of biomass. Torrefied biomass generally has a better combustion performance. Most studies on lignocellulosic biomass combustion rely on thermogravimetric analysis under idealized conditions with small sample masses, while few investigate bench-scale combustion and the performance of torrefied briquettes under different torrefaction atmospheres. The present study aims to analyze and compare the combustion behavior of sugarcane bagasse briquettes torrefied under inert and oxidative atmosphere. Biomass was initially characterized and subsequently subjected to torrefaction at 200, 250 and 300 °C. Briquetting was conducted under consistent pressure, time, and temperature conditions. Bench-scale combustion tests were then performed on both raw and torrefied samples, followed by the evaluation of combustion indices to compare their performance. Torrefied Sugarcane bagasse at temperatures between 200 and 250 °C yield a torrefied material with improved physicochemical properties for combustion processes, with the highest combustion index observed at 250 °C under oxidative atmosphere, highlighting a notable advantage over the more costly inert torrefaction. The torrefaction temperature directly influences the physicochemical properties of the material, which in turn affects the briquetting pretreatment. Together, these factors determine the overall combustion performance.

Keywords: Bench-Scale, Inert torrefaction, oxidative torrefaction, Biomass, Combustion Index

INTRODUCTION

According to the International Energy Agency (IEA) [1], bioenergy is defined as the energy content in solid, liquid and gaseous products derived from biomass feedstocks and biogas. It includes solid bioenergy, liquid biofuels and biogases. Biomass is

renewable and carbon neutral, which is regarded as one of the most potential alternatives for fossil fuels [2]. From the perspective of energy storage, photosynthesis is considered as a global process to synthesize biomass in which solar energy is stored [3]. Biomass energy reserves are very abundant around the world; the total amount of converted standard coal is about 1 billion ~ 1.5 billion t/ year and about 80 % of the biomass can be effectively used [4]. In May 2021, the IEA published its landmark report *Net Zero Emissions by 2050: A Roadmap for the Global Energy Sector*. This report outlined a narrow but achievable pathway for the global energy sector to contribute to the Paris Agreement's goal of limiting the rise in global temperatures to 1.5 °C above pre-industrial levels. The Net Zero Roadmap quickly became a key benchmark for policymakers, industry, the financial sector, and civil society. Within this framework, greenhouse gas emissions must be reduced, and carbon dioxide–neutral, biomass-based fuels represent an efficient strategy to mitigate the rise in atmospheric CO₂ concentrations [5].

Lignocellulosic biomass, in particular, exhibits characteristics such as high moisture content, low calorific value, hygroscopicity, and low bulk density. These properties negatively affect conversion efficiency and complicated handling operations, including harvesting, comminution, storage, and transport [6].

As a result, untreated biomass is generally unsuitable for direct use as a fuel in energy systems. To address these limitations, torrefaction has gained significant attention as an effective thermal pretreatment technique to improve the physicochemical properties of biomass.

Torrefaction is a thermal pretreatment process aimed at enhancing biomass quality at temperatures between 200 to 300°C in an inert or oxidative atmosphere [7,8]. Through this process, biomass reduces its moisture content, enhances its heating value, improves grindability, and achieves more uniform feedstock properties. Additionally, torrefied biomass becomes hydrophobic, facilitating safer and more efficient storage [3,9] The main goal of torrefaction is to transform solid biomass into a more viable substitute for mineral coal [10].

This process shows strong potential for facilitating the large-scale utilization of biomass in industrial applications [11,12]. Previous researchers have stated that torrefied biomass generally has a better combustion performance [13,14]. Biomass combustion covers over 90% of the global contribution to bioenergy [15]. Torrefied biomass exhibits improved physical and chemical properties for direct combustion or co-combustion processes [16].

Several studies in literature have focused on the combustion analysis of various lignocellulosic biomasses, primarily based on thermogravimetric analysis (TGA/DTG) under idealized conditions using minimal sample masses. In contrast, there are few scientific papers that study combustion at the experimental bench level, and there is a lack of experimental information regarding the real performance of torrefied briquettes under different atmospheric conditions of torrefaction.

Quirino C Brito, 1991 [17], developed a combustion reactor specifically designed for testing charcoal briquettes and introduced the ICOM index as a metric to evaluate combustion performance. Their findings indicated that briquettes releasing higher amounts of heat during combustion experiments tend to consume a larger fraction of their mass to generate this energy, which consequently may lead to lower ICOM values.

Similarly, Paula et al. (2011) [18] developed a combustion reactor for briquette testing, building upon Quirino's original design with specific modifications. In their comparative analysis of different biomasses against charcoal, the results showed that charcoal exhibited the longest total combustion time, requiring approximately 120 minutes, and, unlike the biomasses, did not present a well-defined peak in temperature.

Yilgin et al. (2019) [19], studied the burning behavior of torrefied beech wood briquettes, under inert torrefaction with a nitrogen flow at 220, 260 and 300 °C. Their results showed that pellets became more porous as severity of torrefaction increased, their carbon combustion rates were generally lower than those of raw pellets and decreased with combustion temperature as well as torrefaction severity.

The present study aims to analyze and compare the combustion behavior of sugarcane bagasse briquettes torrefied under inert and oxidative atmospheres at three different

temperatures (200, 250, and 300 °C). The experiments were conducted at a bench scale using a combustion reactor based on Quirino's design with specific modifications, while employing larger sample masses during both torrefaction and combustion. This approach seeks to better approximate the conditions on a larger scale compared to the scale used in thermogravimetric studies.

MATERIALS AND METHODS

Samples preparation

Sugarcane bagasse (SCB) samples were obtained from a sugarcane processing plant located in Itaí, São Paulo, Brazil. The material was grounded using a Marconi MA-680 blade mill to ensure granulometric uniformity, followed by sieving with a Bertel electromagnetic shaker to isolate particles in the 250–500 µm size range. Subsequently, the SCB was oven-dried at 105 °C for 24 h. The processed samples were then stored in sealed bags until used in the pretreatment assays.

Torrefaction assessment

Torrefaction experiments were performed in a fixed-bed reactor. The system comprised compressed gas cylinders, a gas mixing and control panel, a collar-type heating element, fiberglass-based thermal insulation, a temperature monitoring and control unit, and a gas outlet line [20]. For each run, 135 ± 5 g of biomass were introduced into the reactor, which was then positioned inside the heating element and insulated with fiberglass. The heating procedure was conducted at three target temperatures (200, 250, and 300 °C), within the range of 200–300 °C, under two distinct atmospheres: an inert environment (99.999% N₂) and oxidative environment (80% N₂–20% O₂). In both cases, the gas flow rate was maintained at 100 mL/min, with a residence time of 30 minutes. The selected torrefaction conditions were based on optimal parameters reported in previous studies [21–24]. Following each experiment, the torrefied biomass was collected and stored in sealed bags to avoid contamination before further analyses. The samples were labeled according to the torrefaction atmosphere and temperature: 'TI' for inert atmosphere and 'TO' for oxidative atmosphere, followed by the respective torrefaction temperature (e.g., TI250, TO300).

Mass yield (MY) and energy yield (EY) were calculated using equations (1) and (2).

$$MY = \frac{m_t}{m_r} * 100\% \quad (1)$$

$$EY = MY * \frac{HHV_t}{HHV_r} \quad (2)$$

Where m_r is the sample mass (g). The subscripts "r" and "t" refers to the raw and torrefied material, respectively.

Characterization techniques

The proximate analysis of the biomass samples was carried out using a Marconi muffle furnace (model MA-385). Volatile matter content was determined in accordance with ASTM E872-24, ash content following ASTM E1755-24, and fixed carbon was obtained by difference.

The holocellulose fraction of the raw biomass was quantified according to the TAPPI T19m-54 procedure, while lignin content was estimated by subtraction. Cellulose content was determined using the TAPPI T203 cm-99 method, and hemicellulose content was calculated as the difference between holocellulose and cellulose contents.

Ultimate analysis was performed using an elemental analyzer (PerkinElmer 2400 Series II) to determine the contents of carbon (C), hydrogen (H), and nitrogen (N). Oxygen (O) content was calculated by difference.

The higher heating value (HHV) was measured with an IKA C5000 bomb calorimeter in accordance with the DIN 51900 standard. All analyses were performed in triplicate for each biomass sample to ensure reproducibility and reliability of the results.

Briquette preparation

Biomass was compacted into briquettes using a laboratory-scale briquetting press (model LB-32, Lippel). Briquettes were produced under a constant pressure of 180 bar, with a compression time of 5 minutes at a temperature of 120 °C and cooling period of 10 minutes. For each briquette, 25 ± 1 g of biomass was used. The briquetting

conditions were maintained constant across all experiments to ensure comparability of results.

Combustion assessment

The combustion performance in this study was evaluated using the combustion index (S), as proposed by Quirino C Brito (1991). The combustion index was calculated according to the following equation (3):

$$S = \frac{A \cdot B}{100 \cdot C} \quad (3)$$

Where A Eq. (4), B Eq. (5), and C Eq. (6) (Figure 1) represent, respectively:

$$A = \frac{\text{Time} > 150^{\circ}\text{C}}{\text{TestTime}} \times 100 \quad (4)$$

A: The percentage of the duration of the experiment during which the temperature remains above 150 °C relative to the total duration of the test.

$$B = M1 - N \frac{150}{\text{Max. Temperature}} \text{TU} \times 100 \quad (5)$$

B: The percentage of the maximum temperature reached in the experiment relative to the reference temperature of 150 °C.

$$C = m_a - m_b \quad (6)$$

C: The percentage of total mass consumed while generating temperatures above 150 °C.

For each combustion experiment, temperature and mass variations were recorded every 5 seconds, for 60 minutes, using a single time variable to synchronize both measurements and prevent data acquisition errors. This was achieved through a custom script developed in Python. Each combustion test was conducted using three briquettes and 15 ± 1 g of ethanol as an auxiliary fuel.

The combustion reactor (Figure 2) was designed and constructed following the configuration proposed by Quirino C Brito (1991), with structural modifications introduced to improve the combustion performance of the briquettes.

Figure 1. Typical “Temperature vs time” and “Normalized mass vs time” curves with their characteristic points, for obtaining S.

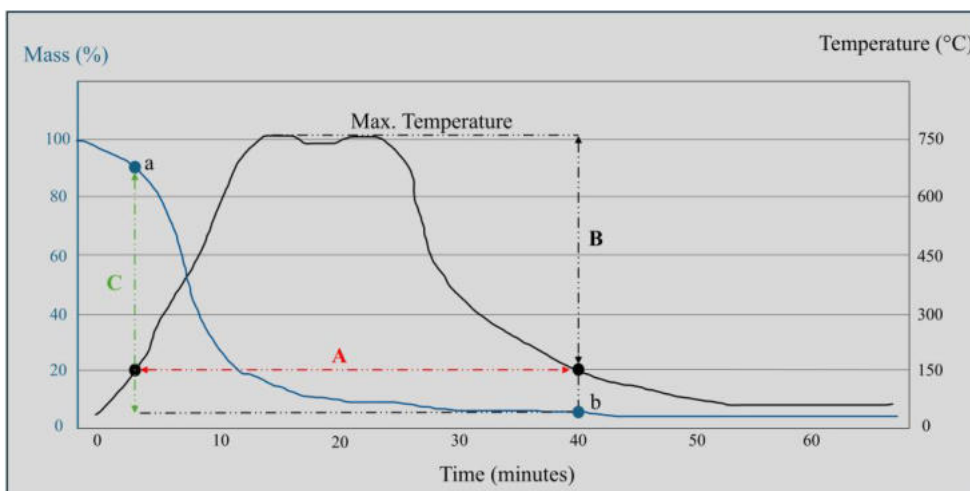


Figure 2. Briquette combustion reactor set-up

The system comprises a main combustion chamber (1), in which the combustion process takes place under natural convection, driven by ambient air entering from the surroundings. The airflow is directed around the airflow control wall (2) and subsequently guided downward toward the air inlet (9). The combustion tube was constructed with four symmetrically distributed openings to promote uniform air distribution across the cross-section. The airflow control wall (2) was specifically designed to regulate air circulation and avoid turbulent or undesired flow paths.

At the base of the reactor, an ash collection grid (3) was installed to retain solid residues generated during combustion. An auxiliary fuel container (4) was incorporated to facilitate ignition of the briquettes. A wooden support (5) was employed to allow ambient airflow beneath the system and to provide thermal insulation for the balance, which required operating temperatures below 40 °C; wood was selected due to its low thermal conductivity.

Mass measurements were carried out using a precision balance (6) (AD3300, Marte), which was connected to a computer for real-time monitoring in combination with a K-type thermocouple coupled to an Arduino system. The support grid (7) was designed to sustain the briquettes during combustion, featuring evenly distributed perforations to ensure a homogeneous and adequate air supply. Finally, the briquettes (8) were placed on the grid for combustion experiments.

RESULTS AND DISCUSSION

Fuel properties analysis

Table 1 presents the results of the lignocellulosic composition of raw sugarcane bagasse. Additionally, it includes a comparison of these properties with analytical data reported in previous studies from the literature.

Table 1. Experimental results of Sugarcane bagasse compositional analysis

Compositional Analysis				
Raw SCB				
Polymer	This study	Pratiksha Yadav et.al [25]	Alokika at.al [26]	S. Niju [27]
Hemicellulose	24 +- 0,001	25 < x < 30	20 < x < 32	25 < x < 30
Cellulose	46 +- 0,02	35 < x < 50	32 < x < 45	45 < x < 50
Lignin	30 +- 0,02	25 < x < 30	17 < x < 32	x ≈ 25

The composition of sugarcane bagasse varies according to several factors, such as sugarcane maturity, variety, environment, and milling conditions [28]. Bagasse, as a

type of lignocellulosic material, consists mainly of organic components (hemicellulose, cellulose, and lignin) which, when subjected to high temperatures, decompose into volatile products such as water, hydrogen, carbon dioxide, carbon monoxide, acetic acid, formic acid, furfural, levoglucosan, methanol, formaldehyde, etc [21].

Sugarcane bagasse is the fibrous fraction remaining after the extraction of sugarcane juice and contains about 50% cellulose, 25% hemicellulose, and 25% lignin [29]. Based on various reports available in the literature, dry bagasse contains 82–87% volatile matter, 1–7% ash, and 10–17% fixed carbon [30–32]. The alkali metal content of biomass, i.e., Na, K, Mg, P, and Ca, is especially important for any thermochemical conversion process, as these metals can react with silica and cause problems in boilers [33].

Table 2 presents the results of the proximate and ultimate analysis for all torrefied sugarcane bagasse samples under both inert and oxidative atmospheres.

Table 2. Experimental results of Sugarcane bagasse proximate and ultimate analysis for all the samples in inert and oxidative atmosphere

Sample	Proximate Analysis (Dry basis)			Ultimate Analysis (Dry basis)			
	VM	FC	ASH	C	H	N	O
Raw	78,99 +- 0,22	13,98 +- 0,27	6,92 +- 0,33	42,8	6,16	0,04	51
TI200	77,52 +- 0,26	14,81 +- 0,17	7,67 +- 0,29	45	5,82	0,12	48,22
TI250	69,12 +- 1,42	22,03 +- 1,02	8,58 +- 0,33	48,34	5,36	0,23	46,07
TI300	57,37 +- 0,25	32,34 +- 0,33	10,29 +- 0,38	63,63	4,82	0,9	30,65
TO200	76,81 +- 0,40	15,49 +- 0,05	7,96+- 019	45,41	5,7	0,16	48,73
TO250	68,71 +- 0,34	22,46 +- 0,21	8,84 +- 0,23	50,56	4,83	0,23	44,38
TO300	44,84 +- 0,50	40,65 +- 0,47	14,51 +- 0,30	61,24	4,44	0,35	33,57

It is possible to observe a decreasing trend in the volatile matter content as the torrefaction temperature increases. This behavior is evident in the volatile fraction remaining after the torrefaction pretreatment under both atmospheres. Moreover, it can be observed that, in the oxidative atmosphere, devolatilization is more

pronounced, even when compared to the inert torrefaction atmosphere. It is evident that, when comparing the samples torrefied at 200 and 250 °C, the difference in volatile matter content between the oxidative and inert atmospheres is not particularly significant, amounting to 0.71% and 0.41%, respectively.

This behavior is primarily attributed to the fact that, at temperatures below the threshold of mild torrefaction (250 °C), biomass devolatilization is minimal, and the release of volatiles is mainly associated with hemicellulose decomposition [34]. In contrast, for the samples torrefied at 300 °C, the difference reaches 12.53% between the two atmospheres. According to [35], this trend changes at 300 °C, where a more pronounced devolatilization is observed under the oxidative atmosphere, likely due to the enhanced decomposition of biomass promoted by the presence of oxygen in the carrier gas.

In contrast, it is possible to observe that the fixed carbon and ash contents in the samples tend to increase as the torrefaction temperature rises, with both being consistently higher under the oxidative atmosphere. This trend mirrors the behavior observed in the volatile matter comparison at 300 °C, where the difference in fixed carbon and ash contents between the TO300 and TI300 samples is considerably greater than in the samples torrefied at 200 and 250 °C.

For the samples torrefied under the inert atmosphere, the increase in fixed carbon content between the raw material and TI300 is 18.36%, whereas under the oxidative atmosphere it reaches 26.67%. This is attributed to the fact that sugarcane bagasse is a lignocellulosic biomass primarily composed of hemicellulose, cellulose, and lignin. When exposed to elevated temperatures, these components undergo thermochemical decomposition into volatile products such as water, hydrogen, carbon dioxide, carbon monoxide, acetic acid, formic acid, among others [36].

This behavior has been previously reported in the study by Ramos et al. [37], in which it was observed that the increase in oxygen concentration in the reaction atmosphere, at elevated temperatures, contributes to the surface oxidation of biomass as mass and heat transfer processes are intensified, and this increase is associated with a higher energy content and a reduction in reactivity.

The ash content increased by 3.37% in the TI300 sample compared to the raw material, and by 8.22% compared to the TO300 sample. This behavior can be explained by the fact that the addition of oxygen in the torrefaction atmosphere enhances the oxidation of volatile compounds, promoting further pyrolysis of organic matter and consequently leading to higher ash content in the torrefied biomass [11].

Similarly to fixed carbon and ash, the higher heating value (HHV) also increased in both atmospheres as a function of torrefaction severity, with higher values consistently observed in the samples torrefied under the oxidative atmosphere compared to those torrefied under the inert atmosphere at their respective temperatures. Unlike the previous parameters, however, the HHV showed only a slight increase under the oxidative atmosphere across the three temperature levels. Nevertheless, the increment was more pronounced for the TO300 sample compared to TI300, with a difference of 1.02 MJ/kg.

According to [38], the carbon content of torrefied samples increases relative to the raw material, whereas hydrogen and oxygen contents decrease as torrefaction severity rises. Consequently, both O/C and H/C ratios in torrefied samples decrease, primarily due to dehydration, decarboxylation, and depolymerization of the organic fraction during the torrefaction process. As a result of the decomposition of the organic fraction (i.e., hemicellulose) in biomass, the absolute content of carbon-rich lignin in the torrefied material increases. Lignin is also characterized by various interunit linkages, including ether and carbon-carbon bonds. Importantly, these bonds are predominantly C-C, which possess higher energy density compared to C-O and C-H bonds [39]. Therefore, the enrichment of lignin and C-C bonds in torrefied materials can partially explain the increase in the HHV of torrefied samples compared to the raw biomass.

The results of the ultimate analysis (Table 2) reveal two distinct trends. The first is that increasing the torrefaction temperature leads to higher carbon and nitrogen contents in the samples. Conversely, the second trend indicates a reduction in oxygen and hydrogen contents as the torrefaction pretreatment temperature increases.

It can be observed that samples torrefied under an oxidative atmosphere at 200 and 250 °C exhibit a higher carbon content compared to those torrefied under an inert atmosphere. This behavior can be explained by the fact that oxidative conditions promote a more pronounced removal of hemicellulose and cellulose, particularly oxygen and hydrogen, while to a lesser extent selectively preserving the lignin fraction. As a result, the torrefied biomass shows a higher carbon concentration than that obtained under inert conditions at the same temperature. [37].

Nevertheless, the TI300 sample exhibits a higher carbon content compared to the TO300 sample. This behavior may be attributed to heat transfer limitations in the fixed-bed reactor employed for biomass torrefaction, arising from the mass load used. More specifically, it is likely related to a layer-by-layer heat transfer mechanism, in which heating advances progressively from the outer surface toward the biomass core [40]. Such a mechanism can lead to a certain degree of heterogeneity in the resulting torrefied biomass.

It is also evident that the oxygen and hydrogen contents decrease in both atmospheres as torrefaction severity increases. This reduction is mainly associated with the degradation of hemicellulose and cellulose, accompanied by dehydroxylation and decarboxylation reactions that promote the release of water, CO₂, CO, CH₄, and other volatile compounds [37,41].

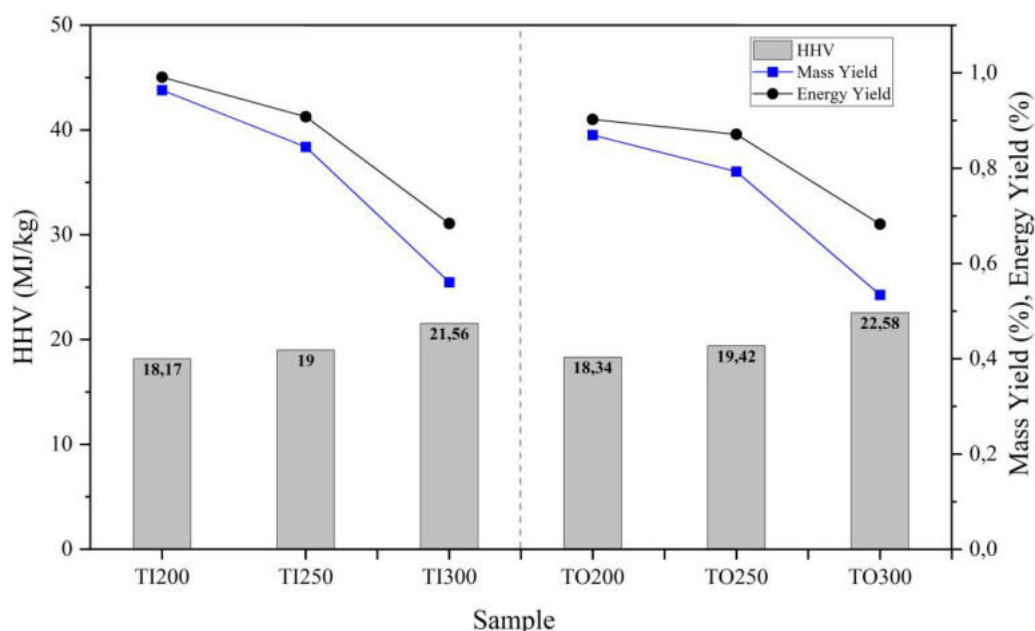
Torrefaction assessment

The mass yield (MY), energy yield (EY), and higher heating value (HHV) of the torrefied samples under inert and oxidative atmospheres are presented in Figure 3.

It is evident that for all torrefaction temperatures (200, 250, and 300 °C), the samples previously torrefied under oxidative atmosphere exhibit lower mass and energy yields compared to those torrefied under an inert atmosphere (TO: 87%, 79%, 53%; TI: 96%, 84%, 56%) for the mass yield, and (TO: 90%, 87%, 68%; TI: 99%, 91%, 68%) for the energy yield. This behavior has already been reported in several studies in the literature [22], where a higher oxygen concentration in the carrier gas promotes faster reactions, leading to an increased release of volatiles and oxidation of fixed carbon [42].

The mass yield difference between 200 °C and 250 °C (TI: 12% and TO: 8%) is less severe than the difference between 250 °C and 300 °C (TI: 28% and TO: 26%) for both types of samples. The variation in mass yield with increasing temperature is more pronounced under the inert atmosphere. The samples torrefied at 200 °C and 250 °C fall within the range of mild and intermediate torrefaction, while the sample torrefied at 300 °C corresponds to severe torrefaction, also referred to as mild pyrolysis. In this thermal region, mass loss becomes substantial, implying higher energy consumption and a significant reduction in yield for both atmospheres.

Figure 3. Mass yield (MY), energy yield (EY), and higher heating value (HHV) of samples torrefied under inert (TI) and oxidative (TO) atmospheres at different temperatures.



It is evident that for all torrefaction temperatures (200, 250, and 300 °C), the samples previously torrefied under oxidative atmosphere exhibit lower mass and energy yields compared to those torrefied under an inert atmosphere (TO: 87%, 79%, 53%; TI: 96%, 84%, 56%) for the mass yield, and (TO: 90%, 87%, 68%; TI: 99%, 91%, 68%) for the energy yield. This behavior has already been reported in several studies in the literature [22], where a higher oxygen concentration in the carrier gas promotes faster reactions, leading to an increased release of volatiles and oxidation of fixed carbon [42].

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This behavior has been consistently documented in previous studies [21,43], which report that under severe torrefaction conditions, biomass undergoes more extensive decomposition. Consequently, its physicochemical composition is considerably altered, leading to pronounced changes in its fuel properties.

The torrefaction process enhanced the higher heating value (HHV) by 18% under the non-oxidative atmosphere and by 21.71% under the oxidative atmosphere, compared to the raw biomass. The dehydration, dehydrogenation, and deoxygenation reactions occurring during torrefaction reduced the H/C and O/C ratios with increasing temperature, thereby improving the HHV of the samples [44].

In terms of energy and mass, the samples torrefied at 200 °C would represent a more attractive alternative considering their mass retention (TO: 87%; TI: 96%) and their energy yield (TO: 90%; TI: 99%). In this specific case, the TI200 sample shows higher mass and energy yields compared to the TO200 sample, with only a minimal variation in the heating value of both samples of 0.17 MJ/kg.

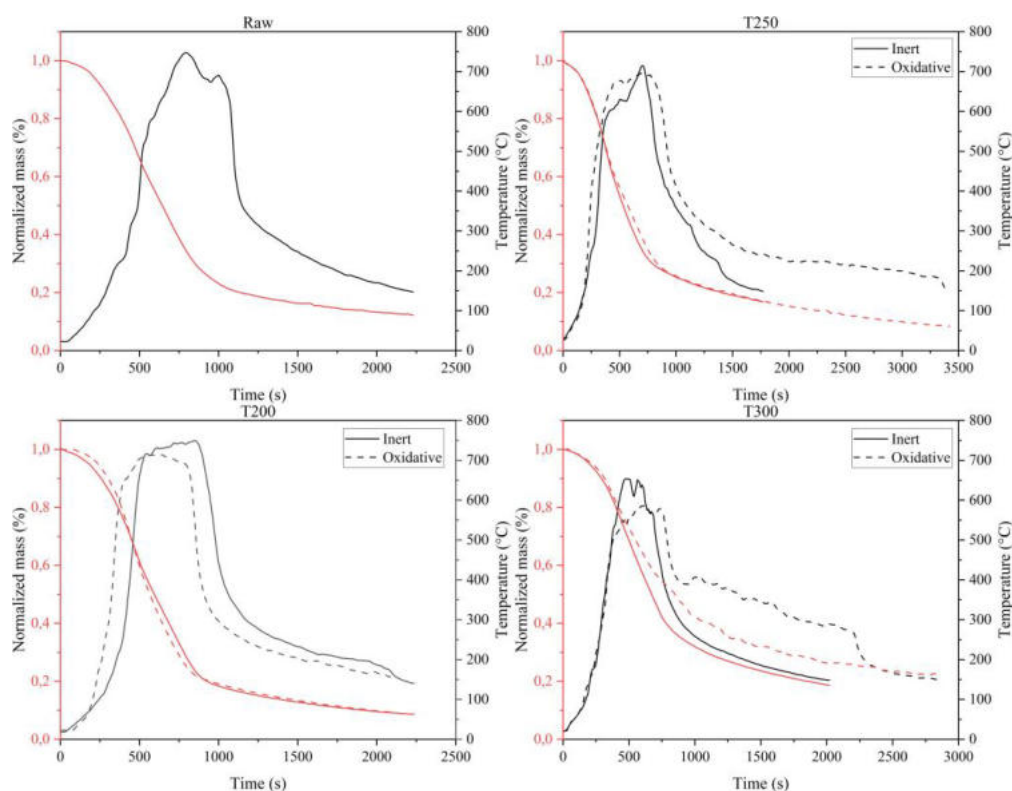
However, in economic terms, if the use of torrefied sugarcane bagasse is projected at an industrial scale for electricity generation, despite the samples previously torrefied in an inert atmosphere showing better mass and energy yields, the biomass samples torrefied in an oxidative atmosphere could represent a viable alternative due to lower operational costs compared to the inert atmosphere [4,11].

Combustion assessment

In Figure 4, the mass decomposition and temperature curves as a function of time are presented for all samples under both atmospheres.

For the samples previously torrefied at 250 and 300 °C, a rightward shift is observed in the oxidative atmosphere compared to the inert atmosphere. In the mass decomposition curve, this behavior indicates that briquettes produced from material torrefied under inert conditions decompose more rapidly than those torrefied under oxidative conditions. The reduction in reactivity observed in the combustion of TO250 and TO300 briquettes is mainly attributed to the higher devolatilization during torrefaction, promoted by the presence of oxygen, as well as to the increased fixed carbon content resulting from the pretreatment.

Figure 4. Normalized mass vs time (Red), Temperature vs time (Black) for all the samples in inert and oxidative atmosphere



For the samples previously torrefied at 250 and 300 °C, a rightward shift is observed in the oxidative atmosphere compared to the inert atmosphere. In the mass decomposition curve, this behavior indicates that briquettes produced from material torrefied under inert conditions decompose more rapidly than those torrefied under

oxidative conditions. The reduction in reactivity observed in the combustion of TO250 and TO300 briquettes is mainly attributed to the higher devolatilization during torrefaction, promoted by the presence of oxygen, as well as to the increased fixed carbon content resulting from the pretreatment.

The increase in fixed carbon content, which is more pronounced in the samples torrefied under an oxidative atmosphere, is associated with the rightward shift of the decomposition curves in oxidative conditions compared to those torrefied under an inert atmosphere. This effect is mainly due to the fact that samples with higher fixed carbon content burn more slowly than the raw biomass, which can result in a more efficient combustion process [45].

Regarding the temperature evolution over time, a similar rightward shift is observed for TO250 and TO300 compared to TI250 and TI300. This behavior is likewise associated with the lower volatile matter content and the higher fixed carbon concentration in the samples, which limit the maximum temperature achieved during combustion and moderate the temperature drop within a short period of time.

In the time range of 700 – 1000 seconds (transition stage from devolatilization and volatile combustion to char combustion), the temperature drop for the TO250 sample was from 696 to 421 °C, while for the TI250 sample it was from 710 to 363 °C. For the samples torrefied at 300 °C, the temperature decrease in TO300 was from 571 to 404 °C, whereas for TI300 it ranged from 549 to 261 °C.

This decrease in temperature in the samples previously torrefied in an inert atmosphere is mainly associated with the lower amount of fixed carbon and carbon content in the material. Conversely, since these values are higher in the samples torrefied in an oxidative atmosphere, their combustion is slower compared to the inert torrefied samples, and therefore the temperature drop is smaller.

The opposite behavior observed in the TO200 sample, in terms of both mass decomposition and temperature evolution, is primarily attributed to the physical structure of the briquettes during combustion. Briquettes torrefied under oxidative conditions exhibited a visibly weaker compacted structure compared to those torrefied under inert conditions. During combustion, this resulted in a more brittle

briquette surface, which increased the specific surface area and facilitated higher oxygen diffusion, thereby accelerating oxidation. According to Nanou et al., [46], during the storage of torrefied biomass, fragments of lignin may react with atmospheric O₂. As a consequence, the binding capacity of conifer lignin is reduced, resulting in lower-quality briquettes. The quality of the briquettes depends on the ability of lignin to act as a natural binder in the presence of moisture during densification.

It can be observed that the ignition time of samples torrefied under an oxidative atmosphere was shorter than that of those torrefied under an inert atmosphere, with the exception of the sample torrefied at 300 °C, which exhibited very similar behavior.

According to Aliyu et al. [47], the ignition time of briquettes increases with increasing compaction pressure. The observed increase in ignition time due to increased pressure may be due to increased compaction of the briquettes, thus eliminating the available porous spaces filled with air, which can promote ignition and subsequent combustion.

In this case, the compaction pressure of the briquettes of all samples was kept constant. However, in briquettes produced with biomass torrefied under an oxidative atmosphere, the physical structure was noticeably more fragile, which facilitated greater airflow and thereby promoted ignition.

Joseph [48], in his study, reported that the mechanical strength of briquettes decreases with increasing torrefaction temperature, primarily due to the degradation of hemicellulose and the removal of extractives and volatile components during the pretreatment. The loss of mechanical strength is also associated with the thermochemical degradation of lignin, a binding agent that contributes to material cohesion, resulting in a less stable structure. Consequently, this reduction in strength makes the briquettes more susceptible to breakage and fines generation.

Table 3 presents all the parameters used to calculate the combustion index according to Quirino for all samples under both torrefaction atmospheres.

Parameter A represents the percentage of time, relative to the total combustion duration, that the sample maintained a temperature above 150 °C. As shown in the table, all samples torrefied under oxidative conditions sustained longer periods above this threshold compared to their counterparts torrefied under inert conditions, at each

respective torrefaction temperature. The TO250 sample exhibited a value of 89%, indicating that during the 60-minute combustion test, the sample remained above 150 °C for 53.6 minutes. This behavior is primarily associated with the improved physicochemical properties of the material resulting from the applied pretreatments.

Table 3. Combustion index data analysis for all the samples in inert and oxidative atmosphere

Sample	A(%)	B(%)	C(%)	Tmax (°C)	Time > 150°C (min)	S
Raw	53	80	76	748	31,83	0,558
TI200	51	80	75	750,00	30,75	0,544
TI250	43	79	73	716,75	26	0,465
TI300	49	78	75	672,75	29,58	0,510
TO200	52	79	85	717,75	31,3	0,483
TO250	89	79	83	699,25	53,66	0,847
TO300	73	74	73	594,00	43,83	0,740

Although the torrefied samples TI200 and TO200 exhibited higher carbon and fixed carbon contents, the combustion time above 150 °C for the raw biomass sample was slightly longer. This is possibly associated with better physical characteristics of the raw briquette, including improved compaction.

Similarly, parameter B can be analyzed as the ratio between the maximum temperature reached by each sample and the reference temperature of 150 °C. Although only minor variations were observed among the samples, it was confirmed that with increasing torrefaction temperature, the maximum combustion temperature decreases due to the reduced volatile matter content, being lowest in the TO300 sample.

Parameter C, which evaluates the mass decomposition of the samples while combustion remained above 150 °C, shows that decomposition is greater at lower torrefaction severities. This behavior is mainly attributed to the higher degree of devolatilization occurring during the torrefaction process, which explains why the TO300 sample exhibited the lowest decomposition during combustion.

It is also evident that as the torrefaction temperature increases, the maximum temperature reached during combustion decreases, primarily due to the reduced content of volatile matter. This trend is further confirmed by the fact that torrefaction

under oxidative conditions results in a lower mass yield and therefore greater devolatilization, leading to lower maximum combustion temperatures in all TO samples compared to their TI counterparts.

Among all the samples, TO250 exhibited the best combustion index, which can be attributed mainly to its favorable physicochemical characteristics. At this torrefaction severity, the biomass still retains a significant proportion of lignin, enabling good compactability and structural integrity, in addition to ensuring adequate mass retention and consequently improved energy performance.

According to Quirino [17], briquettes, when burned, generate a large amount of heat; however, if they consume a significant amount of mass to produce this energy, would likely result in a low combustion index. This behavior can be observed in the TO200 sample. Although in the TO250 sample the mass consumption is high, with a C percentage of 83%, what leads to a high combustion index, on the other hand, is the length of time the sample remained above 150 °C.

According to the results of the combustion index as a function of each variable, it can be stated that, since variables B and C did not show significant variations among the different samples, the most representative variable affecting the combustion index would be variable A.

CONCLUSIONS

The physical condition of the briquettes during combustion plays a critical role in determining overall combustion performance. It is therefore essential to establish consistent briquetting conditions to ensure comparable physical behavior among briquettes and, consequently, obtain more reliable combustion results.

According to the torrefaction assessment conducted in this study, torrefied Sugarcane bagasse at temperatures between 200 and 250 °C yield a torrefied material with improved physicochemical properties for combustion processes using exclusively sugarcane bagasse.

The highest combustion index was obtained from the sample torrefied at 250 °C in a oxidative atmosphere, representing a notable advantage over inert torrefaction, especially given the higher costs associated with the latter

The material torrefied at 300 °C exhibited physicochemical properties more suitable for co-combustion with mineral coal.

Sugarcane bagasse torrefied above 250 °C under both atmospheres becomes considerably more difficult to compact due to the partial decomposition of its lignin content.

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ENHANCING COMBUSTION PROPERTIES OF ELEPHANT GRASS AND PALM EMPTY FRUIT BUNCH FIBRE THROUGH WATER LEACHING

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ABSTRACT

Elephant grass (EG) and palm empty fruit bunch fibre (EFB) have great potential for bioenergy. However, their high content of alkaline ash, chlorine and other contaminants hinders direct combustion by promoting slagging, fouling and pollutant emissions. To address this issue, the main goal of this study was to assess the effectiveness of water leaching as a mild and scalable pre-treatment to reduce the inorganic content of ash in EG and EFB, enhancing their suitability for thermochemical conversion. A factorial experimental design was applied to evaluate the effects of particle size, water-to-biomass ratio and leaching time on ash removal, using EG as a model biomass. Particle size was the most influential factor, enabling up to 41% ash reduction in milled biomass (<10 mm). Scale-up experiments under optimized conditions (14 L kg⁻¹, 10 min, <10 mm) validated the consistency of the selected parameters for both EG and EFB, with removal rates of 73.5-80% for Cl, 62.3-70.7% for K, and 50-60% for P. EG also showed a 57.1% reduction in N, contributing to NO_x mitigation. Dry basis energy efficiency remained above 93.5%, while mass losses were below 9%. Although residual moisture (~70%) may limit direct combustion, mechanical dewatering is suggested. The leachate exhibited high conductivity and dissolved organic carbon, especially for EFB, suggesting potential for anaerobic digestion. Overall, pre-milling followed by water leaching proved to be an efficient strategy to reduce corrosive and ash-forming elements in EG and EFB, contributing to an improved inorganic profile of the biomass.

Keywords: biomass pre-treatment; water leaching; particle size; ash removal; elephant grass; palm empty fruit bunch fibre

INTRODUCTION

The use of biomass as a renewable energy source has gained increasing relevance in supplying thermal and electrical demands, particularly in countries with extensive agricultural land, such as Brazil [1,2]. Approximately 7.5% of the national territory – equivalent to 65 million hectares – is dedicated to agricultural activities [3], encouraging decentralized bioenergy applications in rural and agro-industrial regions [2]. Biomass feedstocks are diverse, and their properties vary depending on soil type, water availability, climate, and management practices [4], which often limits its direct use for energy.

In this context, elephant grass (EG) – (*Pennisetum purpureum*) – and palm empty fruit bunch fibre (EFB), a lignocellulosic residue from palm oil processing (*Elaeis guineensis*), present high potential for bioenergy due to their high productivity and favourable energy characteristics [5-8]. EG can reach dry matter yields above 40 t ha⁻¹ yr⁻¹ under suitable conditions [9]. Meanwhile, in 2023, the state of Pará produced about 2.9 million tons of fresh fruit bunches, generating more than 600 thousand tons (wet basis) of EFB as a by-product [11]. The valorisation of such biomass streams aligns with national policies for energy diversification and waste reduction, and supports international agendas such as the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible Consumption and Production).

Despite their bioenergy potential, both EG and EFB exhibit high contents of ash, alkali metals and chlorine, which hinder their direct use in combustion systems by promoting slagging, fouling, and corrosion. These challenges demand pre-treatment strategies to improve fuel quality [5,7,12,13].

Among such strategies, water leaching has emerged as a simple, cost-effective method for removing soluble salts and ash-forming species from biomass [13-15]. The mechanism involves the diffusion and dissolution of water-soluble salts, such as potassium, sodium, and chlorine, from the biomass matrix into the leaching solution. This process is influenced by parameters including water-to-biomass ratio, particle

size, and contact time, as well as on temperature, which influence ash removal and organic matter retention [14,16,17].

Previous studies have reported the potential of water leaching in different biomasses. Yu et al. [15] reported 61% Na, >99% K, and 85% Cl removal from rice straw after six hours of leaching with distilled deionized water at room temperature (22 °C) under agitation, with melting temperatures increasing by 500 °C due to changes in ash composition. Sugars and organic acids were identified as the main organic compounds extracted. Similar improvements in fuel properties have also been observed in other biomasses, even under low leaching ratios. Chin et al. [13] achieved 78% ash removal in EFB with improved slagging behaviour after leaching, while Bandara et al. [16] obtained removals up to 95% K₂O and 83% P₂O₅ from rice husks at 50 °C and smaller particle size. Braga et al. [7] showed that hot water or acid washing of EG reduced ash content from 6.9% to ~2.5% and increased its higher heating value to 16.6 MJ kg⁻¹. Babinszki et al. [17] confirmed significant reductions in K, Na, and Cl (up to 99%) across various biomasses, enhancing torrefaction condensate quality.

According to Jiang et al. [18], the treatment of certain biomass types through water washing significantly increases the initial deformation temperature of biomass ash. This effect is attributed to the removal of alkali metals, particularly K₂O, with extraction efficiencies ranging from 69% to 90% across six different biomass samples. The improvement in ash fusibility was especially pronounced in corn straw and wheat straw samples. Additionally, the study recommends a washing temperature of 30 °C as optimal for maximizing the effectiveness of the process in enhancing ash melting temperatures.

In this context, Park et al. [19] demonstrated that the combination of a non-catalytic mechanical system with wet washing is an effective strategy for ash removal from biomass. The process involves milling the biomass followed by washing with deionized water at room temperature, without the addition of catalysts, which enhances the contact between water and inorganic constituents. This approach achieved high removal efficiencies of potassium (96–98%) and chlorine (73–98%), significantly improving ash behavior during combustion. The analysis showed a reduction in ash agglomeration by 61–95% compared to raw biomass combustion and an increase in

ash melting temperature to values exceeding 1300 °C. These results confirm the potential of leaching processes to mitigate ash-related issues in combustion systems and thermochemical conversion processes.

EG and EFB were selected for this study due to their availability on a large scale and complementary profiles: EG is a purpose-grown energy crop, while EFB is a major agro-industrial residue from palm oil production. Their combined evaluation provides insights into both dedicated and residual lignocellulosic feedstocks.

This study aims to evaluate the efficiency of water leaching as a pre-treatment for the removal of undesirable inorganic compounds from EG and EFB. The specific objectives were: (i) to investigate the influence of water-to-biomass ratio, particle size, and contact time on ash and elemental removal using EG as a model biomass through a full-factorial (2^3) experimental design; (ii) to analyse the impact of these parameters on the demineralization of the main ash-forming elements, mass conservation and energy efficiency of the treated biomass; (iii) to conduct a preliminary analysis of the leachate characteristics through electrical conductivity (EC); (iv) to estimate the carbon and mass balance to support integrated and sustainable valorisation strategies for agro-industrial lignocellulosic residues.

MATERIALS AND METHODS

EG and EFB were the biomasses used in this study and the samples were provided by Brasil BioFuels S.A. (BBF) company. The experimental part was organized in three stages: (1) physical-chemical characterization of the *in natura* and leached biomasses; (2) application of the full factorial experimental design to evaluate and select the optimal condition for the leaching process, using EG as a model biomass; and (3) scale-up experiments for both biomasses.

Physicochemical characterization of biomass

The *in natura* and leached biomasses were characterized in duplicate. Sampling followed the quartering method, with two 250 g portions separated for analysis.

Samples were pre-dried at $105\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ overnight in an air-circulating oven and milled to 60 mesh using a Willey knife mill.

Proximate, ultimate analyses and chloride analyses

Proximate and ultimate analyses were performed based on standard methods. Residual moisture was determined by drying at $105\text{ }^{\circ}\text{C} \pm 2\text{ }^{\circ}\text{C}$ overnight in an air-circulating oven [20], and ash content by calcination at $575\text{ }^{\circ}\text{C} \pm 25\text{ }^{\circ}\text{C}$ in muffle furnace [21]. Volatile matter was analysed in a muffle furnace according to ASTM D1762-84 [22], with fixed carbon calculated by difference [23]. Carbon (C), hydrogen (H), and nitrogen (N) contents were obtained using a CHN analyser [24], while sulphur (S) content was measured by infrared detection [25]. Oxygen (O) was calculated by difference [26]. Chloride (Cl) ions were determined in pre-dried and milled samples by ion chromatography [27,28], following sample extraction through heating in an oven. Higher heating value (HHV) was determined using an automatic isoperibolic calorimeter [29], and lower heating value (LHV) was estimated according to Eq. (1).

$$LHV = HHV - (0,2155 \times H) \quad (1)$$

Major ash-forming elements

The major ash-forming elements (Al, Ca, Fe, K, Mg, Na, P, Si, Ti, Ba, and Mn) were determined by inductively coupled plasma optical emission spectrometry (ICP-OES) after acid digestion of *in natura* samples using a microwave-assisted digestion furnace in a closed system. For reporting as oxides, theoretical oxide concentrations (%O_x) were estimated assuming complete stoichiometric conversion of each element to its most stable oxidized form, as described in Eq. (2):

$$\%O_x = \frac{[E] \times M_{O_x}}{n \times M_E} \quad (2)$$

where $[E]$ is the experimental content of element E (wt. %), M_E is the molar mass of the element (g mol^{-1}), M_{O_x} is the molar mass of the oxide (g mol^{-1}), and n is the number of atoms of element E in the oxide formula.

Experimental design: EG leaching

The full factorial experimental design method (2^3) was adopted to statistically evaluate the effect of varying three parameters of the leaching process (a) water-to-biomass ratio, (b) particle size, and (c) leaching time. A total of 11 experiments were performed applying two levels of analysis, an upper (+1) and a lower (-1), in addition to a central level (0) for triplicates. Table 1 presents the actual values of the levels of each of the parameters (factors) evaluated in the experimental design.

Table 1 – Factors and levels evaluated in the full factorial experimental design (2^3).

Factors	Levels		
	-1	0	+1
water-to-biomass ratio (a)	7 L kg ⁻¹	11 L kg ⁻¹	15 L kg ⁻¹
particle size (b)	<10 mm	50% <i>in natura</i> / 50% <10 mm	<i>in natura</i>
leaching time (c)	9 min	19,5 min	30 min

Chin et al. [13], evaluated the leaching of residual biomass obtained from the palm extraction process and it was observed that the ash removal rate ($\%A_R$) followed the removal of soluble compounds such as KCl, K₂SO₄, K₂CO₃ etc. Considering this evaluation parameter as a reference, A_R (%) was the response variable evaluated and expressed in Eq. (3).

$$A_R = \frac{100 (Ash_0 - Ash_L)}{Ash_0} \quad (3)$$

where Ash_0 and Ash_L are the ash contents (% w/w) determined in EG before and after the leaching test, respectively.

The main and interaction (binary) effects (θ) of each of the factors varied in the leaching process on the $\%A_R$ of EG were also determined, representing the difference in $\%A_R$ between two distinct operational conditions. The experimental design was performed in random order. Statistical treatment was performed in Microsoft Excel® using analyses of variance (ANOVA) and F test (Fisher) in a significance level of 95% [30].

Biomass preparation

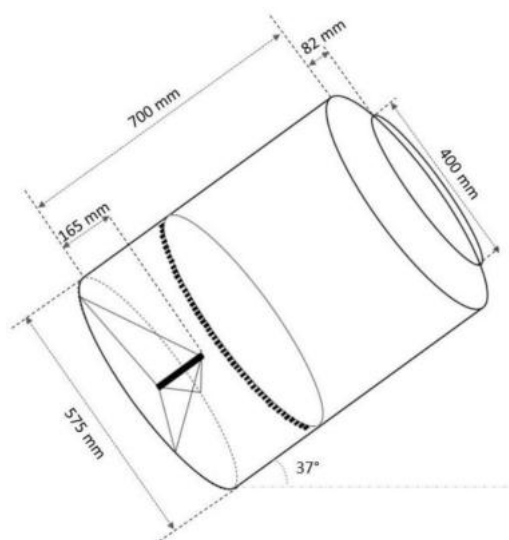
To evaluate the effect of particle size distribution, the fraction with a size below 10 mm was obtained from the milling process using a knife mill (30 HP, 380 V motor)

approximate capacity of 800 kg h^{-1} , shaft with 3 rotating knives and 10 mm circular passage mesh.

Water leaching process

The water leaching method was used in the pre-treatment of biomass, adopting the solid-liquid extraction mechanism. Municipal water supply at room temperature was used as the water source (electrical conductivity of 1.171 mS m^{-1}). The experiments were performed in an open rotating drum with fixed rotation as illustrated in Fig. 1. After leaching, all material was transferred to a 1.2 mm aperture sieve and the retained solid fraction was dried in an oven with air circulation at $105 \text{ }^{\circ}\text{C} \pm 2 \text{ }^{\circ}\text{C}$ for 24 hours before the physicochemical characterization (*section 2.1.1*).

Fig. 5. Schematic diagram of the rotating drum used in the leaching experiments.



Liquid fraction of leachate

For some of the experiments, the electrical conductivity (EC) of the liquid fraction of the leachate was determined using a conductivity meter with automatic temperature compensation and AgCl/Pt electrolytic cell. However, due to the measuring range of the electrode, 200 mS m^{-1} , a dilution procedure was adopted. First, the liquid fraction leached was centrifuged using a refrigerated benchtop centrifuge to remove

suspended particles, followed by dilution of the solids-free leachate in a ratio of 1:5 of the volume of centrifuged leachate to the volume of deionized water, respectively.

Scale-up experiments

Based on the best conditions observed in the statistical results obtained from the experimental design, the leaching tests with increased load were reproduced again for EG and for the EFB. Loads of approximately 5 kg of biomass milled to a particle size < 10 mm were used. The leaching procedure was the same as described in *section 2.4*, except for the sieve aperture, i.g., 1.0 mm, in the dewatering stage due to the greater generation of fine particles obtained in the milling of the EFB.

Efficiency of the leaching process - Mass balance

The mass balance was performed with the aim of determining the mass loss from the solid phase to the leachate phase represented in Eq. (4).

$$m_{loss} = \frac{100 \cdot Pm_0 - m_f Q}{m_0} \quad (4)$$

where m_{loss} refers to the biomass mass loss during the leaching process, resulting either from the dissolution of soluble components or from the entrainment of fine particles by the liquid flow, m_0 is the dry mass of biomass fed into the rotating drum and m_f corresponds to the final dry mass of biomass after leaching.

Efficiency of the leaching process - Energy efficiency of the leaching process (E_f) and Contaminant removal rate (R_{ri})

The energy efficiency of the leaching process (E_f) was calculated as the ratio between the energy content of the leached biomass and the original biomass, both on a dry and wet basis, as shown in Eq. (5):

$$E_f = \frac{100 \cdot (m_L \cdot LHV_L)}{(m_0 \cdot LHV_0)} \quad (5)$$

where, m_0 and m_L are the masses of *in natura* and leached biomass, respectively, and LHV_0 and LHV_L are their respective lower heating values.

The contaminant removal rate (R_{ri}) for each element i (e.g., K, Cl, N, etc.) was calculated analogously to Eq. (3), replacing ash content with the concentration of the specific element.

Empirical parameters - predictive indexes of combustion impact

The impact of leaching on the combustion behaviour of the biomass samples in boiler systems was predictively assessed using empirical indices [31-34]. The indicators and their corresponding equations are presented in Table 2.

Table 2 – Equations for the impact assessment indexes of biomass combustion.

Title	Formula	Eq.
Alkali Index (AI)	$AI = \frac{ash (Na_2O + K_2O)}{HHV}$	(6)
Sulphur protection (I_c)	$I_c = \frac{[2S]}{[Cl]}$	(7)
Aerosol particle emission (A_e)	$A_e = 6(K + Na + Cl + S)$	(8)
Elemental N content	$N, \% \text{ w/w}$	(9)
Slagging formation (Si_{cl})	$Si_{cl} = \frac{Cl + K_2O + Na_2O}{SiO_2 + Al_2O_3}$	(1)
Dolomitic effect (Do)	$Do = \frac{[Si] + [K] + [P]}{[Mg] + [Ca]}$	(2)
Alkaline-to-alkaline earth oxides ratio (I_{Ao})	$I_{Ao} = \frac{K_2O + Na_2O}{MgO + CaO}$	(3)
Potassium release (R_K)	$R_K = \frac{Cl}{Si}$	(4)

RESULTS AND DISCUSSIONS

Experimental design: evaluation of the leaching process variables on A_R

EG was selected as a model in the experimental design based on its higher ash content in the *in natura* condition (9.0 wt%), compared to EFB (6.7 wt%) as shown in Table 3. This criterion was adopted considering the relevance of ash removal in the context of thermochemical conversion, since high inorganic contents can compromise the process performance and favour the formation of deposits and slag [7,12,13]. The leaching experiments with EG were conducted according to a 2^3 full factorial design, considering triplicates at the central point. Table 4 presents the experimental matrix, the ash contents after pre-treatment and the respective A_R .

Table 3 - Physical-chemical characterization, on a dry basis, of *in natura* and leached biomass based on the process parameters applied in the scale-up experiments.

Property	EG <i>in natura</i>	EG leached	EFB <i>in natura</i>	EFB leached
HHV, MJ kg ⁻¹	18,48	18,55	21,25	21,86
LHV, MJ kg ⁻¹	17,7	17,26	19,81	20,37
Proximate analyses – wt. %				
Ash	9,0	8,1	6,7	5,2
Volatile matter	76,6	73	75,3	77,8
Fixed carbon	14,4	18,9	18	17
Ultimate analyses – wt. %				
Carbon	45,3	46,50	50,7	51,9
Hydrogen	6,08	5,98	6,69	6,9
Nitrogen	1,4	0,60	0,8	0,8
Sulphur	0,19	0,13	0,15	0,13
Oxygen	37,54	38,56	34,66	35,01
Chloride ions	0,49	0,13	0,30	0,06
Major ash-forming elements – wt. %				
Al	0,22	0,07	0,13	0,09
Ca	0,32	0,18	0,17	0,16
Fe	0,21	0,09	0,04	0,08
K	2,01	0,59	1,75	0,66
Mg	0,19	0,14	0,16	0,15
Na	0,03	n.d.	0,04	n.d.
P	0,15	0,06	0,08	0,04
Si	2,93	2,03	0,35	0,80
Ti	0,01	< 0,01	< 0,01	< 0,01
Ba	< 0,01			
Mn	0,01	< 0,01	< 0,01	< 0,01

(n.d.) not detected (lower limit of detection 0.0058 ppm)

Table 4 – Full factorial design (2^3) with triplicates at the central point, ash content after pre-treatment and A_R for the experiments with EG.

Experiment	water-to-biomass ratio	particle size	leaching time	Ash (wt%)	A_R (%)
1	+1	+1	-1	6,8	24,44
2	-1	-1	-1	6,5	27,78
3	+1	-1	+1	5,3	41,11
4	+1	-1	-1	6	33,33
5	-1	-1	+1	5,8	35,56
6	-1	+1	+1	7,6	15,56
7	-1	+1	-1	7,7	14,44
8	+1	+1	+1	7,2	20,00
9	0	0	0	6,6	26,67
10	0	0	0	7,4	17,78
11	0	0	0	7,6	15,56

Based on the leaching experiment results, water leaching of EG showed A_R ranging from 14% to 41%, with the highest values for milled biomass (<10 mm), reaching 27% to 41%. In contrast, *in natura* biomass had lower A_R (14%–24%), with the water-to-biomass ratio positively influencing results – up to a 10% increase in A_R at 15 L kg⁻¹, even without longer leaching time. A 50/50 particle size mixture showed moderate A_R improvements (15–27%), indicating that partial size reduction enhances exposure of inorganic constituents. This is attributed to increased surface area from milling, which improves constituent exposure and mass transfer. Larger particles, by contrast, require more wetting time and show greater diffusion resistance, limiting ash removal efficiency [16].

The main effects analysis (θ) in Table A.1 (Appendix A) shows the average influence of process variables on EG leaching A_R . Particle size had the greatest main effect. Reducing size to <10 mm improved A_R by an average of 15.8% compared to untreated biomass. Leaching time had the lowest effect ($\theta = 3.1\%$), indicating minimal benefit when increasing duration from 9 to 30 minutes.

ANOVA results (Table A.2, Appendix A) confirmed that only particle size significantly affected A_R under the evaluated conditions. Neither the water-to-biomass ratio (7–15 L kg⁻¹) nor leaching time (9–30 min) had relevant effects. No significant interactions between variables were detected. Thus, milling before leaching is the key factor for process efficiency.

From the experimental data, a linear model (Eq. A.1) was developed to estimate A_R based on encoded variables x_1 (water-to-biomass ratio), x_2 (particle size), and x_3 (leaching time), within $[-1, 1]$. The model ($R^2 = 82.45\%$) was validated against observed data (Fig. 2). Although it slightly underestimated the lowest and highest A_R values (14.44% and 41.11%), predicting 12.25% and 39.33%, respectively ($\approx 2\%$ deviation), the results demonstrate reasonable accuracy. The discrepancies likely stem from the model's inability to capture non-linear behaviours or ash-forming element variability [13].

Fig. 6. Observed and predicted A_R values according to the linear model.

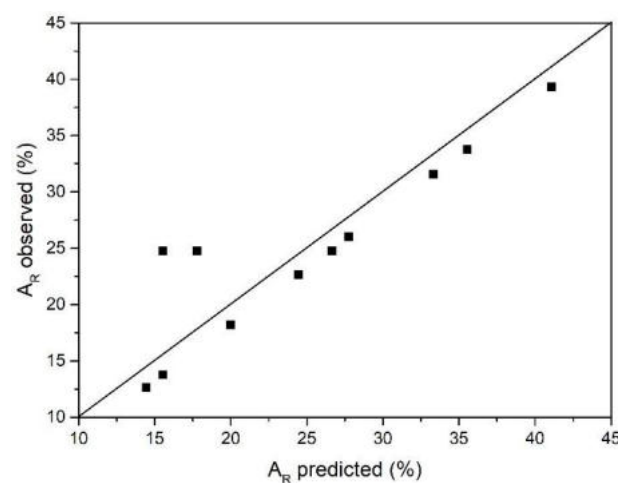
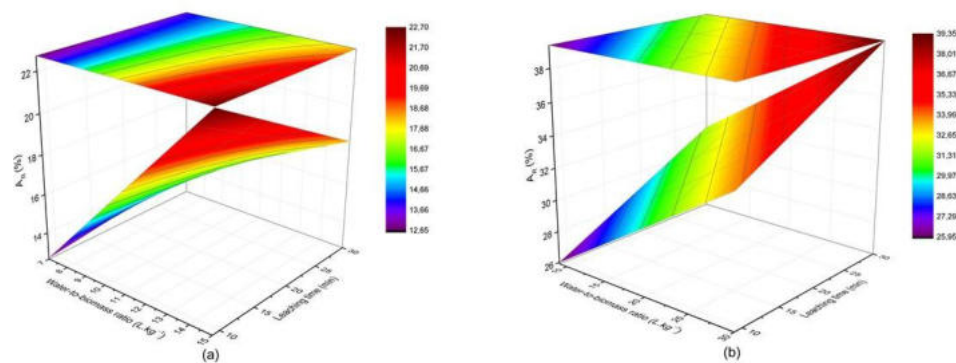


Fig. 3 shows the individual and combined effects of leaching time and water-to-biomass ratio on ash removal (A_R) for (a) in natura EG and (b) milled EG (<10 mm). Both contact time and liquid-to-solid ratio enhanced A_R , as expected for aqueous extraction of water-soluble inorganics. Particle size had a marked impact: while in natura biomass showed A_R between 13–23%, milled biomass reached 26–39%. These results suggest that optimizing biomass physical properties via mechanical pre-treatment can be as important as adjusting process parameters. Similar trends are reported for other biomasses like switchgrass and rice husk, where finer particles yield higher A_R [16,35]. In this context, Braga et al. [7] observed up to 63% A_R in EG using hot water (60 °C) and very fine particles (0.074–0.104 mm), highlighting the synergy of temperature and particle size. Although this study used milder conditions, the results underscore the importance of increased surface area and mass transfer. Particle size reduction often surpasses the impact of other parameters such as temperature or time. Still, while lab-

scale leaching effectively alters fuel composition, industrial-scale application requires evaluating technical and economic feasibility, especially considering the energy costs of fine milling and leachate treatment [1].

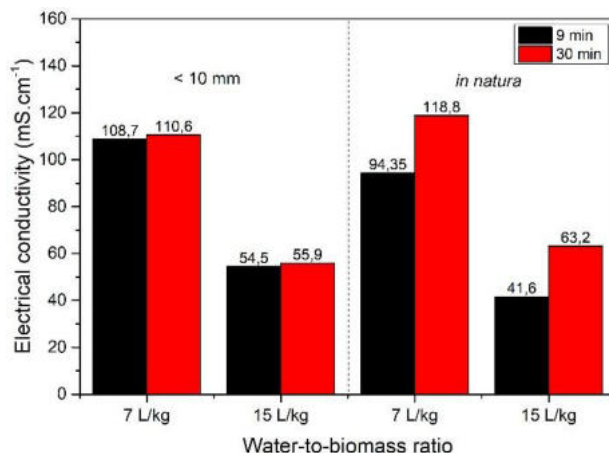
Fig. 7. Effects of leaching time and water-to-biomass ratio on ash removal (A_R) for (a) EG in natura and (b) EG <10 mm.



Experimental design: Liquid fraction of leachate

Fig. 4 shows the effect of leaching time and water-to-biomass ratio on the EC of leachates from EG. Although the data were not analysed statistically, the results show trends regarding the leaching process variables. For milled biomass (< 10 mm), the EC remained practically constant (difference < 2 mS m⁻¹) between 9 and 30 minutes, particularly at the ratio of 7 L kg⁻¹, indicating effective extraction of soluble salts. In contrast, for *in natura* biomass, a significant increase in EC was observed with leaching time, reflecting a slower release of ions due to intra-particle diffusion resistances. In addition, for both EG particle size, lower water-to-biomass ratios yielded higher EC values, reflecting greater ionic concentration in the leachate under more restricted dilution conditions. A rapid rise in conductivity followed by stabilization was observed by Bandara et al. [16] who attributed the faster leaching in smaller particles to higher surface area and reduced diffusion path length. The particle size played a crucial role in determining the rate and extent of soluble salt extraction.

Fig. 8. Effect of leaching time and water-to-biomass ratio on the electrical conductivity (mS m^{-1}) of leachates from EG.



Tests with scale-up experiment: EG and EFB

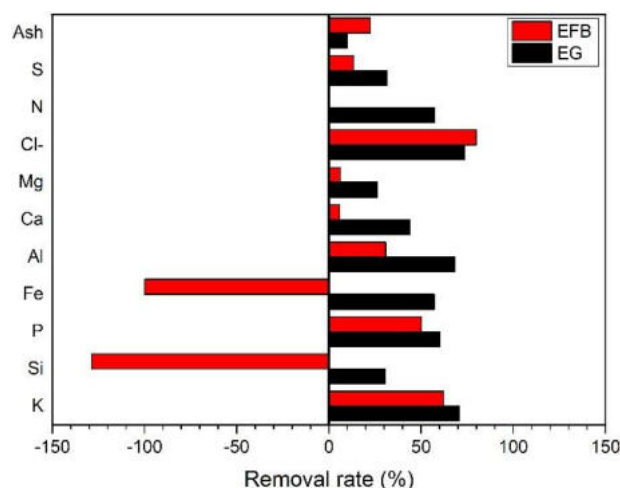
Evaluation of removal rates

The results of the experimental design demonstrated that particle size was the factor with the greatest impact on ash removal, as well as on the reduction of diffusive resistances of the liquid phase of the leachate. The scale-up experiments for EG and EFB were performed after milling to particle size < 10 mm, leaching time of 10 min and water-to-biomass ratio of 14 L kg^{-1} . The removal rates of ash and critical elements are shown in Fig. 5. Ash and chloride removal were satisfactory for both EFB (22% and 80%, respectively) and EG (10% and 73%). In EG, the lower ash removal compared to previous factorial experiments (up to 41%) may be attributed to operational factors, such as the use of a finer drainage mesh and increased biomass loading, which favoured the retention of fine particles with ashes during the process. Although no significant nitrogen reduction was observed for EFB, a substantial decrease was achieved for EG (57.1%). For both biomasses, sulphur content was also reduced (13–32%). These changes indicate a potential to mitigate SO_x and fuel-derived NO_x emissions during combustion.

Although sodium removal is not shown in Fig. 5, its concentrations dropped below detectable levels in both leached biomasses, indicating near-complete extraction. Potassium and phosphorus contents were also substantially reduced, with removal rates of 70.7% and 61.7% for EG, and 62.1% and 46.2% for EFB, respectively. These

reductions are comparable to those reported in the literature, where K and Na removal often exceeded 60% and P removal ranged from 40% to 65% depending on biomass type and pre-treatment intensity [13,15,36]. The decrease in these alkali and phosphorus species is relevant given their well-established contribution to slagging, fouling, and low ash melting temperatures during biomass combustion [37,38].

Fig. G. Ash and elemental removal rates in EG and EFB after water leaching pre-treatment.



A significant impact of the employed process on chlorine removal rates was also observed, with values ranging from 73.5% to 80%. Chlorine is a critical element due to its association with high-temperature corrosion in combustion systems. These removal rates are consistent with those reported by Park et al. [19], who achieved chlorine removal efficiencies between 73% and 98% using similar leaching processes. However, it is important to note that in Park et al. [19] study, the biomass underwent an integrated milling and leaching process, in which it was directly mixed with deionized water, enhancing the contact between inorganic constituents and the liquid medium. Although this approach led to superior contaminant removal performance, it also significantly increased the complexity and operational costs of the process.

Evaluation of predictive indices for combustion impact

The use of predictive indices is a valuable tool for assessing the operational risks and suitability of treated biomass for thermal conversion [39]. These indices, presented in

Table 5, were calculated based on the theoretical oxide composition of key ash-forming elements (Table 4), derived from the elemental analysis of the *in natura* biomass. Although this approach is commonly applied, it may differ from values calculated using experimentally determined ash compositions, which consider only the non-volatile fraction remaining after combustion. Some studies, such as those by Jenkins et al. [30] and Garcia-Maraver et al. [39], have shown that while absolute values may vary depending on the calculation basis, the observed trends – particularly the relative improvement after pre-treatment – remain valid for assessing combustion behaviour.

Table 5. Predictive indices for assessing the impact on the combustion of *in natura* and leached biomass.

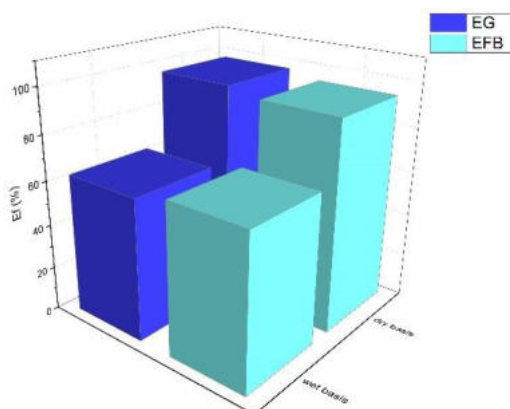
Predictive indices	EG		EFB	
	<i>in natura</i>	leached	<i>in natura</i>	leached
AI	1,34	0,38	1,02	0,36
I_c	0,86	2,22	1,10	4,04
A_e	27179,7	8492,0	22385,3	8640,0
N, wt. %	1,4	0,6	0,8	0,8
Si_{Cl}	0,416	0,177	2,355	0,437
Do	10,165	10,260	5,539	4,577
I_{AO}	3,603	1,880	4,883	1,914
R_K	0,132	0,050	0,674	0,070

Leaching significantly improved the combustion behaviour of both biomasses, particularly EFB, by reducing slagging and fouling tendencies. The I_{AO} , a key slagging indicator, decreased by 72% for EG and 65% for EFB. Elevated I_{AO} values are known to enhance ash fluxing behaviour due to excess K_2O and Na_2O [32,37]. The R_K also declined by over 60%, indicating reduced volatilization of K and a shift toward greater retention in stable solid-phase compounds, a trend associated with decreased alkalis vapor-phase enrichment and deposit formation [36,38]. Similarly, the $SiCl$ index – which reflects the slagging risk from K – Cl – Si interactions – was reduced, especially in EFB (81%), suggesting lower potential for the formation of low-melting $KCl-SiO_2$ mixtures. Although the N-related index remained unchanged for EFB, the significant N removal previously observed in EG may still contribute to fuel- NO_x mitigation during combustion.

Evaluation of mass balance and energy efficiency

The overall mass and energy balances for the solid phase during leaching are summarized in Table B.1 of the Appendix B and Fig. 6. Total dry mass losses remained below 9% for all biomasses, with slightly higher losses in EFB (8.8%), likely due to fine particle drag during draining. Moisture content after dewatering remained high ($\sim 70\%$), limiting direct use in combustion systems. As noted by Morais et al. [2], EG presents high biomass yield and favourable energy balance but requires moisture adjustment to optimize combustion. Although mechanical dewatering was not applied in this study, methods such as pressing or milling could lower moisture to $\sim 50\%$ (w.b.), as well occurs in sugarcane mills during bagasse combustion in various types of boilers. On a dry basis, energy efficiency was well preserved, particularly for EG (96.9%), reflecting higher inorganic removal with minimal loss of organic matter. In contrast, efficiencies on a wet basis were lower (63.5% to 75.0%), underscoring the critical role of residual moisture in determining usable energy output.

Fig. 10. Energy efficiency of the EG and EFB leaching process on dry and wet basis.



Leachate evaluation: conductivity, carbon losses and potential for use

Leaching resulted in the solubilization of inorganic compounds and organic matter from the biomasses into the liquid phase. The electrical conductivity of the diluted leachate (1:5 v/v) was high for both biomasses, with average values of 67.19 ± 1.93 mS/cm for EG and 65.84 ± 0.13 mS/cm for EFB. However, this measurement does not reflect the potentially available organic load, since the insoluble solid particles were previously separated by centrifugation. The estimation of mass and carbon balance

analysis of the liquid phase (Table B.2. of the Appendix B) revealed that, although the total mass of leachate was similar for both biomasses, the carbon concentration in the EFB leachate stream was approximately seven times higher than that of EG (2545.4 mg L⁻¹ vs. 350.3 mg L⁻¹). Yu et al. [15] identified high concentrations of inorganic salts in the liquid fraction of the leachate, including K⁺, Cl⁻, Na⁺, Ca²⁺ and Mg²⁺, with removals of up to 99% of potassium and 85% of chlorine in some biomasses, in addition to trace elements such as Mn, Fe, Cu, Ni and Al. These compounds give the leachate a high ionic charge and potential environmental impact, requiring additional characterizations (pH, COD, BOD, alkalinity, heavy metals, etc.) before its use in routes such as anaerobic digestion or agricultural reuse. Thus, the use of leachate could represent a relevant opportunity in integrated biorefinery systems like circular strategy of nutrients in biomass, as long as its physical-chemical properties are adequately evaluated.

CONCLUSIONS

This study demonstrated that particle size reduction combined with water leaching is an effective and simple pre-treatment to improve the combustion properties of EG and EFB. Under mild conditions, significant removal of ash-forming and corrosive elements was achieved, particularly for Cl, K, P, and N, contributing to improved slagging behaviour and maintaining high dry basis energy efficiency (>93.5%). Although residual moisture and leachate management remain operational challenges, the preliminary results indicate opportunities for valorising the liquid fraction through biotechnological routes. Further investigations are recommended to optimize dewatering strategies and to assess the feasibility of leachate reuse in integrated biorefinery concepts.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Vittor Rodrigues Santos Alves: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing – original draft, Writing – Review C Editing, Supervision.
Renata Moreira: Validation, Writing – original draft, Writing – review C editing, Writing – Review C Editing, Visualization.

Dênis Correa Meyer: Validation, Writing – review C editing, Visualization.

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Breno Villa Rubio Bezerra: Resources.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author(s) used OpenAI/ChatGPT in order to improve the language and readability of the work. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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EVALUATION OF WASTE-TO-ENERGY PROCESS THROUGH THE COMBUSTION AND CO-COMBUSTION OF PALM RESIDUAL BIOMASS

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ABSTRACT

The increasing demand for renewable energy in industrial and agro-industrial sectors has encouraged the substitution of fossil fuels by lignocellulosic biomass in cogeneration systems. In this context, the residues generated in the palm oil agroindustry - specifically palm mesocarp fiber and palm empty fruit bunch fiber - stand out due to their high energy potential and wide availability. This study aimed to evaluate the combustion behaviour of these biomasses, both individually and as a 1:1 volumetric blend, by applying predictive indices based on ash composition and conducting combustion trials in a pilot-scale bubbling fluidized bed reactor. The analysis focused on gaseous emissions (NO_x , SO_2 , CO , HCl), thermal performance, and solid effluent generation. The predictive indices indicated a high propensity for slagging and fouling in PMF, while PEFBF presented lower operational risks. Pilot-scale tests confirmed that parameters such as excess air, bed temperature, and gas residence time significantly influenced the emission profiles. The co-combustion condition yielded the lowest emissions of CO and SO_2 , the highest combustion efficiency, and the lowest particulate matter release. Optimal performance was achieved at bed temperatures slightly below $800\text{ }^\circ\text{C}$ and freeboard temperatures approaching $900\text{ }^\circ\text{C}$, enabling rapid volatile release and complete oxidation in the upper zone of the reactor. These conditions also contributed to mitigating sintering and deposit formation in the combustion chamber. The findings demonstrate the technical feasibility of utilizing palm residues for energy generation and underscore the importance of integrating empirical tools with experimental validation to optimize biomass combustion and ensure regulatory compliance.

Keywords: Biomass combustion; Combustion predictive indexes; Energy efficiency; Emissions; Palm oil residues.

INTRODUCTION

The growing concern over the depletion of natural resources and the environmental impacts of the linear economic model has driven the adoption of strategies based on the principles of the circular economy. This model seeks to preserve the value of products, materials, and resources in the economy for as long as possible through practices such as reuse, recycling, and waste recovery, thus promoting more efficient and sustainable resource use [1–3].

In this context, biorefineries have emerged as key components by integrating biomass conversion and valorisation processes for the production of biofuels, bioenergy, and high value-added bioproducts [4]. Unlike conventional fossil-based refineries, biorefineries rely on renewable feedstocks and align with environmental, social, and economic sustainability principles.

The synergy between the circular economy and biorefineries offers a promising pathway for the development of more resilient and sustainable production systems, particularly in agro-industrial supply chains, where lignocellulosic residues and other waste biomasses can be efficiently utilised as raw materials in integrated and high-performance processes [1,5].

In Brazil, the share of primary energy derived from renewable sources remains relatively modest, accounting for around 40% of the total energy produced in 2023. Within this group, biomass resources are prominent, with sugarcane-based derivatives representing 14% and fuelwood-based sources contributing 7% of the national energy matrix [6]. These lignocellulosic materials and other agro-industrial residues hold significant potential to enhance the share of clean energy in the country's energy mix.

Such materials can be used for thermal and electrical energy generation or for the production of biofuels. The growing demand for renewable energy has, in turn, increased the demand for biomass, potentially placing additional pressure on forest ecosystems. In this scenario, the use of residual biomass for energy generation has gained interest due to its widespread availability and potential contribution to decarbonisation efforts [7].

According to the Brazilian Agricultural Research Corporation (Embrapa) [8], the oil palm tree (*Elaeis guineensis* Jacq.), primarily cultivated for palm oil (also known as dendê oil), has the highest expansion potential among globally relevant agricultural crops. Brazil has the largest suitable area for oil palm cultivation, estimated at approximately 75 million hectares, mostly concentrated in the North and Northeast regions, particularly in the states of Pará, Bahia, and Amapá. Recognised as the most productive oilseed crop in the world, oil palm can reach an average yield of up to 5 tonnes of oil per hectare per year, making it a strategic feedstock for national biofuel production, especially biodiesel.

Meesters and Bakker [9] presented a detailed assessment of the energy potential of the residues generated during palm oil production, including palm empty fruit bunch fibre (PEFBF), palm mesocarp fibre (PMF), palm kernel shell, and palm oil mill effluent (POME), based on the amount of fresh fruit bunch (FFB) processed. In terms of energy content, PEFBF and PMF each account for approximately one-third of the energy value of the FFB, while the remainder is distributed between the shell and POME. Currently, only the energy contained in PMF and the shell is widely recovered at an industrial scale, primarily for steam and electricity generation within the palm oil production process [9].

Although PEFBF presents high energy content, its large-scale application in combustion processes is limited due to the high chlorine (Cl) and potassium (K) contents in its ash, which hinder stable operation. Consequently, this residue is commonly used as fertiliser to replenish soil nutrients in palm plantations [9].

The use of biomass in thermal conversion processes must be carefully evaluated, particularly due to the presence of inorganic elements that negatively affect system efficiency and operational reliability. Several studies in the literature have examined the influence of elements such as silicon (Si), chlorine (Cl), sulphur (S), nitrogen (N), phosphorus (P), and alkali and alkaline earth metals on the formation of undesirable phenomena during combustion, including slagging, fouling, gaseous emissions, and related operational issues [10–14].

Oxygen (O), sulphur (S), and chlorine (Cl) act as catalysts in high-temperature reactions, enhancing the volatilisation of alkali compounds that, in the presence of magnesium (Mg), calcium (Ca), phosphorus (P), and silicon (Si), promote the formation of deposits on heat exchange surfaces, slagging of refractory linings, bed agglomeration in fluidised bed systems, corrosion of superheaters and boiler tubes, particulate emissions, and the lowering of ash fusion temperatures [7].

To anticipate potential operational problems associated with high-ash biomass combustion, several empirical parameters—commonly referred to as predictive indices—have been employed. Initially developed for coal combustion, these indices are based on chemical and experimental analyses of fuel ash and have been increasingly adapted for use with biomass fuels [15].

This study aims to experimentally investigate the combustion behavior of two lignocellulosic residues from palm processing in a pilot-scale bubbling fluidized bed reactor. The objective is to diagnose the impact of ash behavior, gaseous emissions, and thermal performance, providing insights into the potential challenges associated with the large-scale direct use of these residues. By mapping possible adverse effects, the study seeks to support the development of strategies to mitigate operational and environmental risks in industrial applications.

MATERIALS AND METHODS

Feedstock treatment and properties

The PEFBF and PMF samples were provided by the company Brasil BioFuels (BBF). Initially, the materials were subjected to sample splitting to ensure representativeness. A portion of the “as-received” material was separated for characterization, while the remainder was ground and sieved to obtain a particle size below 10 mm, suitable for combustion unit. For the co-combustion tests, both biomasses were mixed in a volumetric ratio of 1:1 (PEFBF:PMF).

Physicochemical analyses were conducted only for the PEFBF and PMF samples. The composition of the blend was estimated by mass balance, considering the bulk densities of each biomass.

Particle size distribution analyses were carried out to determine the particle diameter (D_p) of the as-received biomasses. To estimate the bulk density, a known mass of each biomass sample was placed into a graduated measuring cylinder without compaction. The volume occupied by the material was recorded, and the bulk density was calculated as the ratio between the mass and the occupied volume, expressed in kg/m^3 .

Moisture content was measured based on ASTM E1756-08(2020) [16] using an air-circulating oven (Orion 520, Fannem). Ash content was determined based on ASTM E1755-01(2020) [17] in a muffle furnace (Fornitec), and volatile matter was measured according with ASTM D1762-84(2021) [18]. Fixed carbon was calculated by difference as per ASTM D3172-13(2021)e1 [19]. The higher heating value (HHV) was determined using a constant-volume isoperibolic calorimeter (Parr 6400) in based on ASTM D5865/D5865M-19 [20].

Carbon, hydrogen, and nitrogen contents were determined using a CHN analyzer (Flash 2000, ThermoFisher) based on ASTM D5371-21 (Method A) [21]. Oxygen content was estimated by difference according to ASTM D3176-15 [22]. Chloride concentration was determined by ion chromatography (ICS 3000, Dionex), based on DIN 51727:2011 [23] and ASTM D4327-17 [24].

The concentrations of the main ash-forming elements (Al, Ca, Fe, K, Mg, Na, P, Si, Ti, Ba, and Mn) were determined by inductively coupled plasma optical emission spectrometry (ICP-OES). Inorganic oxide contents ($\%O_x$) were calculated assuming complete stoichiometric conversion to their most stable oxidized forms (Al_2O_3 , CaO , Fe_2O_3 , K_2O , MgO , Na_2O , P_2O_5 , SiO_2 , TiO_2 , BaO , and MnO), using Eq. (1):

$$\%O_x = ([E] \times M_{O_x}) / (n \times M_E) \quad (1)$$

where $[E]$ is the experimental elemental concentration (% w/w), M_E is the molar mass of the element (g mol^{-1}), M_{O_x} is the molar mass of the corresponding oxide (g mol^{-1}), and n is the number of atoms of the element in the oxide formula.

Predictive indexes

Silica is the main component found in slag samples derived from biomass combustion, indicating that the fusion of silicon-rich compounds is one of the primary causes of slag formation [25]. Additionally, chlorine acts as a catalyst in reactions between potassium and silica, favouring the formation of molten glassy deposits under typical boiler operating temperatures.

One of the most widely used indicators for predicting the tendency for slagging and fouling is the basic-to-acid ratio (B/A), which relates the proportion of basic oxides to acidic oxides present in the ash, as shown in Eq. (2):

$$B/A = (K_2O + P_2O_5 + Fe_2O_3 + Na_2O + MgO + CaO) / (SiO_2 + Al_2O_3 + TiO_2) \quad (2)$$

In general, acidic compounds increase the ash fusion temperature, while alkalis compounds reduce it. This index was originally developed for coal - where K_2O and P_2O_5 are often negligible - but has since been adapted for biomass due to the greater presence of these elements. B/A values below 0.5 indicate low slagging potential, whereas values above 1.0 indicate high propensity, with values above 1.75 considered severe [25,26].

The Babcock index (R_s), presented in Eq. (3), is a variation of B/A that incorporates the sulphur content of the biomass, which is associated with the formation of thermally unstable alkali sulphates [25].

$$R_s = (B/A) \times S_d \quad (3)$$

The fouling index (Fu), given in Eq. (4), also derives from the B/A ratio but incorporates the alkali oxide content (Na_2O and K_2O), which may form low-melting eutectic compounds with silica, thus promoting fouling [25].

$$Fu = (B/A) \times (Na_2O + K_2O) \quad (4)$$

The slag viscosity index (S_r), shown in Eq. (5), indicates the tendency for slag deposition by comparing the proportion of silica to the main basic oxides (excluding alkalis) [25].

$$S_r = SiO_2 \times 100 / (SiO_2 + Fe_2O_3 + CaO + MgO) \quad (5)$$

The bed agglomeration index (BAI), defined by Eq. (6), seeks to predict agglomeration phenomena in fluidised bed reactors, which are among the most critical operational issues in biomass combustion [25].

$$\text{BAI} = \text{Fe}_2\text{O}_3 / (\text{Na}_2\text{O} + \text{K}_2\text{O}) \quad (6)$$

Potassium and sodium are alkali metals that form low-melting compounds, with potassium being predominant in most biomasses. The alkali index (AI), Eq. (7), quantifies the mass of alkali oxides per unit of fuel energy (g/GJ) [26,27].

$$\text{AI} = (\text{Na}_2\text{O} + \text{K}_2\text{O}) / \text{HHV} \quad (7)$$

The oxide contents must be expressed on a dry weight basis, and the HHV (higher heating value) in dry basis as well. A fouling tendency is considered low for values below 0.17 g/GJ and high for values above 0.34 g/GJ [26]. Although limited, the AI can serve as a complementary tool for combustion assessment [27].

The concentrations of K, Cl, S, Si, and Al in biomass ash are strongly associated with slag formation in high-temperature regions of boilers. Niu et al. [28] proposed the slagging index (SI), Eq. (8), based on a mechanistic analysis of slag formation in biomass-fired boilers. According to the proposed mechanism, slag formation occurs in two stages: the initial deposition of aerosols containing alkali salts (KOH, KCl, K₂SO₄, NaCl, Na₂SO₄), followed by deposition of Si, Fe, and other reactive elements.

$$\text{SI} = (\text{Cl} + \text{K}_2\text{O} + \text{Na}_2\text{O}) / (\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{TiO}_2) \quad (8)$$

SI values greater than 1.9 indicate a high slagging potential, while values below 0.5 suggest low risk [28].

The sulphur protection index (SP), Eq. (9), estimates the ability of sulphur to mitigate chlorine-induced corrosion by forming more stable alkali sulphates (e.g., K₂SO₄), which inhibit chlorine diffusion toward metal surfaces in superheaters [29]:

$$\text{SP} = 2[\text{S}] / [\text{Cl}] \quad (9)$$

SP values above 4.0 suggest favourable conditions for protective sulphation reactions, while values below 2.0 indicate a high risk of high-temperature corrosion in superheater sections.

Table 1 summarises the typical threshold values for the predictive indices discussed above, grouped by their relevance to slagging and fouling behaviour.

Table 1 - Limits of predictive combustion indexes.

Index	Impact			
	Low	Medium	High	Extremely High
Silica content	< 20	20 – 25	> 25	-
Chlorine content	< 0.2	0.2 – 0.3	0.3 – 0.5	> 0.5
B/A	< 0,5	0,5 – 1,0	1,0 – 1,75	> 1,75
Rs	< 0,6	0,6 – 2,0	2,0 -2,6	> 2,6
Fu	< 0,6	0,6 – 2,0	2,0 -2,6	> 2,6
Sr	> 72	65 – 72	< 65	-
BAI	-	-	< 0,15	-
AI	< 0,17	0,17 – 0,34	> 0,34	-
SI	< 0,5	0,5 – 1,9	> 1,9	-
SP	> 4	2 - 4	< 2	-

Combustion unit

The combustion unit used for the in natura and co-combustion biomass trials comprises five integrated subsystems: (i) solid fuel feeding system, (ii) bubbling fluidised bed reactor, (iii) cyclone for particulate removal, (iv) gas cooling and scrubbing system, and (v) exhaust fan with chimney for flue gas discharge, as illustrated in Fig. 1.

The reactor is internally lined with refractory material and operates continuously under bubbling fluidised bed conditions, at atmospheric pressure, with a solid fuel processing capacity ranging from 5 to 10 kg.h⁻¹. Fuel is fed through a silo connected to a water-cooled screw feeder with rotational speed control, which delivers the material into the reactor. Primary air is injected through distributor nozzles at the base of the

bed, while secondary air is introduced in the upper region to ensure complete combustion.

Fig. 1. Laboratory-scale combustion unit.



The flue gases are directed to a cyclone for removal of entrained particulates from the bed, and subsequently to a gas cooling system comprising a heat exchanger and a wet scrubber. After treatment, the gases are discharged through a chimney equipped with sampling ports for particulate matter and acid gas analysis.

To define the operating parameters for each test, the AComb simulation application was employed [30]. Based on the physicochemical characteristics of the biomass samples, the software enabled estimation of the stoichiometric air-to-fuel ratio and adiabatic flame temperature under different excess air conditions.

During the combustion trials, key operational parameters — including fuel feed rate, total air flow rate, excess air, and furnace temperature — were continuously monitored under steady-state conditions. The average values for each biomass are reported in Section 3.3.

Flue gas composition

The composition of the flue gases was continuously monitored by diverting a portion of the gas stream directed to the chimney, using a vacuum pump. Real-time analysis of O₂, CO₂, CO, SO₂ and NO_x concentrations was carried out using a portable multi-gas analyser Horiba PG-350, calibrated according to the manufacturer's specifications.

For the quantification of acid gases (HCl), halogens (Cl₂), and fine particulate matter, isokinetic sampling was performed in accordance with U.S. EPA Methods 5 and 26A [31,32]. The samples were collected from the exhaust duct downstream of the gas scrubbing stage, using a sampling probe positioned at a representative point of the chimney to ensure reliable characterization of the treated effluent.

The results of gaseous and particulate emissions obtained from the combustion experiments were compared with the regulatory limits established by the Resolution SIMA No. 47/2020 [33], issued by the Secretariat for Infrastructure and Environment of the State of São Paulo (Brazil). This regulation sets specific emission thresholds for biomass-fired industrial boilers and is widely referenced in national environmental licensing processes. Its adoption in this study provides a relevant framework for evaluating the environmental performance of palm biomass combustion under conditions representative of real-world industrial applications.

RESULTS

Characterization of palm biomass

Table 2 presents the results of proximate and ultimate analyses, moisture content, higher heating value (HHV), and inorganic ash composition for PMF, PEFBF, and the calculated values for their mixture (Blend). The biomass samples exhibited high volatile matter and energy content, with PEFBF showing the highest carbon content and HHV. Ash content was significantly higher in PMF, while the blend presented intermediate values. The inorganic composition revealed a high presence of alkali oxides (Na₂O and K₂O), particularly in PMF, which is a relevant factor for assessing ash behavior during combustion.

In addition to chemical analyses, other physical properties of the biomass can directly influence the combustion process, particularly in fluidised bed reactors. These include mean particle diameter, bulk density, and thermal fuel ratio reactivity (estimated by the mass ratio of volatiles to fixed carbon) [34]. Such parameters provide valuable insights into the behaviour of solid fuels during feeding and combustion. The physical properties determined for the raw biomass samples are presented in Table 3.

Table 2 - Characterization of the raw biomass and the blend.

	PMF	PEFBF	Blend
Proximate analysis (wt.% on dry basis)			
Volatiles	69,70	75,30	73,15
Fixed carbon	17,40	18,00	17,77
Ash	12,90	6,70	9,08
Ultimate analysis (wt.% on dry basis)			
C	47,40	50,70	49,43
H	6,01	6,69	6,43
N	1,50	0,80	1,07
S	0,26	0,15	0,19
Cl	0,40	0,30	0,34
O	31,93	34,96	33,46
HHV (MJ/kg dry)	20,20	21,25	20,85
Moisture (wt.%)	8,50	8,92	8,02
Ash composition (wt.% on dry basis)			
Fe2O3	0,41	1,47	0,99
Na2O	28,57	64,20	48,07
K2O	42,98	12,94	26,54
SiO2	2,97	2,77	2,86
P2O5	0,13	0,15	0,14
TiO2	5,47	1,60	3,35
Al2O3	0,31	0,08	0,19
CaO	0,01	0,02	0,02
MgO	5,51	4,71	5,07
MnO	8,10	6,34	7,14
BaO	5,54	5,71	5,63

Table 3 - Physical properties of the biomass fuels fed into the combustion process.

Property	PMF	PEFBF
D _p (mm)	0,47	0,52
Bulk density (kg/m ³)	169,0	155,9
Thermal fuel ratio reactivity	4,01	4,18

Predictive Indexes

Based on the ash composition of the biomass fuels, the main predictive indices associated with the risk of slagging, fouling, and corrosion in combustion systems were determined. The results obtained for each biomass are presented in Table 4.

Although these indices also depend on the system characteristics and operational conditions, they allow a preliminary assessment of the potential risks associated with the use of each biomass. The results reveal high trends of corrosion and slag formation,

especially for PMF, as indicated by the chlorine, alkalinity (B/A), and sulfur protection (SP) indices.

Table 4 - Results of the predictive indices based on the ash compositions of each biomass.

Indice	PMF	PEFBF	Blend
SiO ₂ (%)	0,80	3,54	1,85
Cl (%)	0,40	0,30	0,34
B/A	2,96	0,57	1,29
Rs	0,77	0,09	0,24
Fu	6,40	0,72	2,34
Sr	50,93	82,75	70,93
BAI	0,15	0,06	0,13
AI	1,07	0,60	0,87
SI	2,44	0,40	1,00
SP	0,65	0,50	0,56

Note: The calculated values for the predictive indices can be classified according to the limits presented in Table 1.

Although the chlorine content is relatively high, the low silicon content observed suggests a lower risk of forming chlorinated compounds with low melting points. The low SiO₂/Al₂O₃ ratio in the samples also supports this behaviour. Comparatively, PEFBF showed the lowest potential risks, with only three indices classified as high. These results indicate that its use may represent the safest option among the conditions evaluated.

Determination of combustion process operational parameters

Based on the results from the elemental analysis of the biomass fuels (Table 2) and with the assistance of the AComb simulation software, the main theoretical combustion parameters required for the planning of the experimental tests in the pilot plant were estimated (Table 5). The air/fuel stoichiometric ratio is an intrinsic characteristic of each biomass and depends solely on its elemental chemical composition.

Table 5 - Air/fuel stoichiometric ratio and adiabatic flame temperature calculated with the assistance of the AComb software for each biomass.

Biomass	Air/fuel stoichiometric ratio (kg/kg - d.b.)	Adiabatic flame temp (°C)
PMF	6,14	1603,8
PEFBF	6,61	1589,9
Blend	6,48	1588,5

In the same table, the values of the adiabatic flame temperature are presented, calculated considering a reference of 5% volume O₂ (dry basis) in the combustion gases, combustion air at 250°C, and biomass moisture content of 30% (wet basis), conditions representative of the actual process. The simulated parameters were used as the basis for the initial adjustment of the operational conditions in the pilot plant.

After conducting the experimental tests, the average operating conditions in the furnace for each biomass were determined (Table 6), considering exclusively the steady-state period - that is, without significant fluctuations in temperatures and flow rates. This approach ensures greater representativeness of the data, with lower associated uncertainty.

Table 6 - Average operating conditions in the combustion chamber for each biomass.

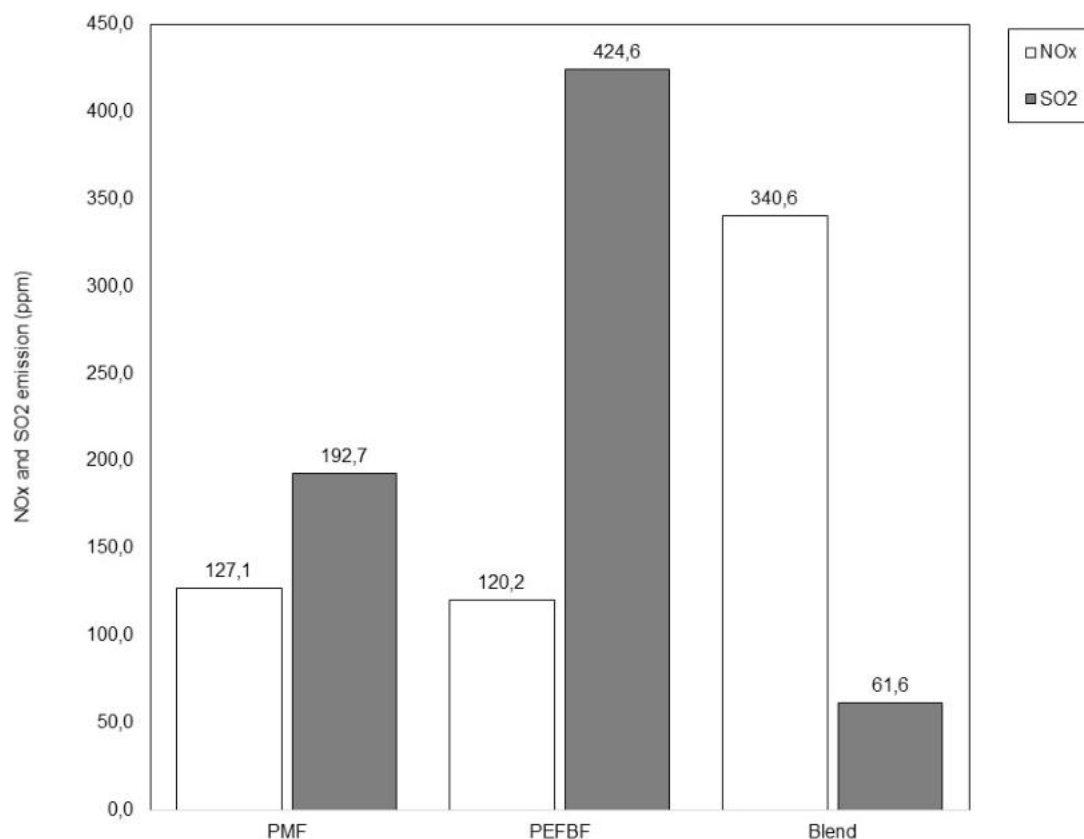
Biomass	Feed flow rate (kg/h)	Total air (Nm ³ /h)	Excess air (%)	Bed temperature (°C)	Freeboard temperature (°C)
PMF	6,31	51,96	189,1	884,42	819,7
PEFBF	7,83	51,94	142,1	878,42	862,38
Blend	8,45	43,41	111,1	800,98	830,5

Analysis of the Fuel Gas Composition

NO_x and SO₂ Emissions

During the combustion tests, the concentrations of the main combustion gas components were continuously monitored, allowing the evaluation of the influence of operational parameters - such as bed temperature (T_b), freeboard zone temperature (T_f), and oxygen content - on the emissions. Fig. 2 presents the average emissions of NO_x and SO₂ during the combustion of PMF, PEFBF, and the 1:1 blend, with the values corrected to 8 vol.% O₂ (dry basis).

Fig. 2. NO_x and SO₂ emissions in the combustion gases at 8 vol.% O₂ (d.b.).



PMF exhibited the highest nitrogen content among the raw biomass fuels (1.5% by mass), which explains its higher propensity for NO_x formation. Additionally, its higher calorific value may have contributed to higher flame temperatures and, consequently, increased thermal NO_x formation. The highest NO_x emissions were observed during co-combustion, likely due to higher temperatures in the freeboard zone and a longer residence time of the gases, conditions that favour NO_x formation.

A distinct behavior was observed for SO₂ emissions. Despite the lower sulfur content, PEFBF exhibited the highest emission levels, which can be attributed to the higher temperatures observed in the freeboard during its combustion (average of 862.4°C), promoting the oxidation of sulfur species. Qi et al. [35] reported an increase in SO₂ emissions above 800°C, while NO_x emissions were mainly correlated with the nitrogen content of the fuel.

Curiously, the blend showed the highest sulfur content (1.07% by mass), but the lowest SO₂ emissions. This can be explained by the retention of sulfur in the bed due to the presence of inorganic compounds in the ash, such as potassium salts (KCl) and iron

compounds, which act as sorbents or catalysts in the conversion of SO_2 to SO_3 , in addition to being associated with the formation of slag deposits [36].

Comparing the results with the limits set by Resolution SIMA No. 47/2020 [33], NO_x emissions remained below the legal limit (350 mg/Nm^3) under all conditions, although they were close to the maximum value during co-combustion. This highlights the importance of operational control, especially of temperatures and residence time. Regarding SO_2 , the limits (65 mg/Nm^3) were exceeded in the combustion of raw biomass fuels, with the limit only being met by the blend, indicating its potential as a strategy for mitigating sulfur emissions.

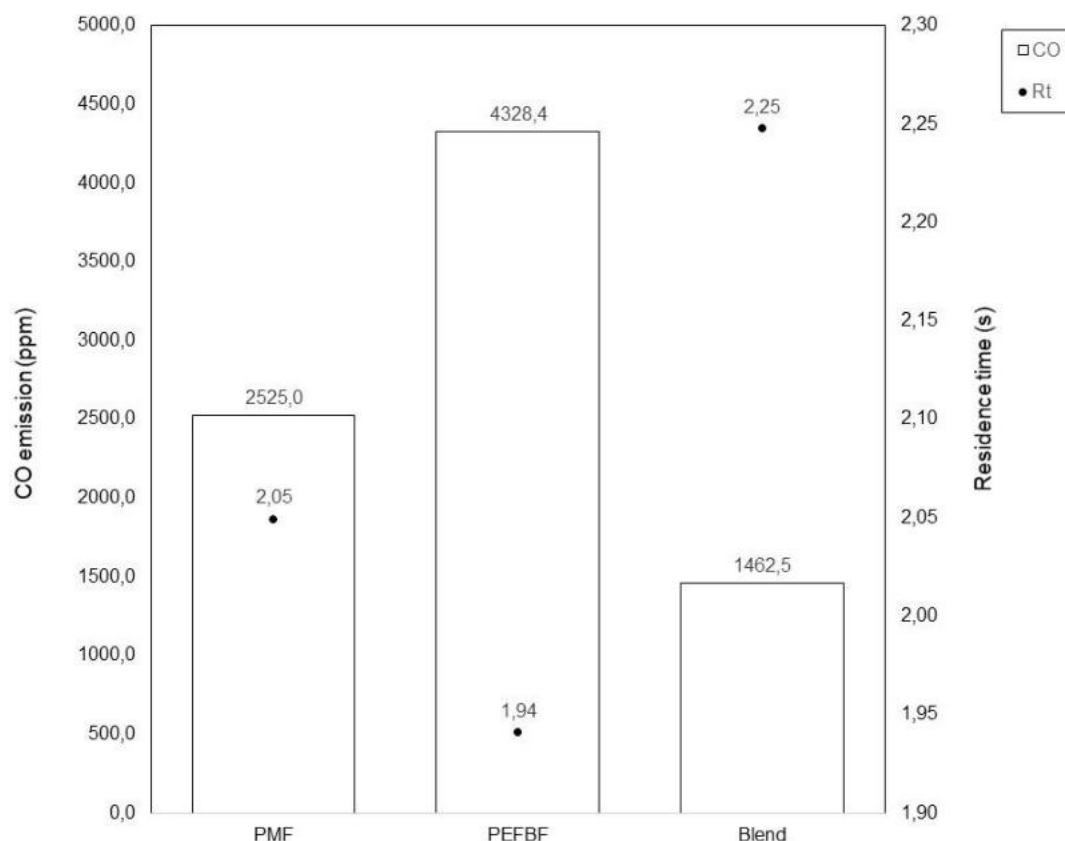
CO emissions

The control of carbon monoxide (CO) emissions is essential due to both its environmental and health impacts, as well as reflecting inefficiency in the total conversion of the energy contained in the fuel, since CO is a byproduct of incomplete combustion [37].

Fig. 3 presents the average CO emissions and the residence times (Rt) of the gases in the reactor for the different biomass fuels tested. PEFBF exhibited the highest reactivity and elevated temperatures, particularly in the freeboard. Still, the CO emissions were significant, suggesting that the rapid release of volatiles was not accompanied by their complete oxidation.

In the combustion of PMF, the highest temperature in the bed and the lowest in the freeboard indicate a combustion more confined to the base of the reactor. This resulted in a reduction of approximately 40% in CO emissions compared to PEFBF. According to Siegmund et al. [38], the oxidation of CO to CO_2 requires high temperatures, although it can also favour reactions such as the water-gas shift.

Fig. 3. CO emissions in the combustion gases at 8 vol.% O₂ (d.b.).



The biomass blend, operating with a lower air flow and under conditions closer to stoichiometry, exhibited the lowest CO emissions (<1500 ppmv), even with lower temperatures in the bed. The longer residence time of the gases, provided by the lower total air flow, favoured the complete combustion of the volatiles. This scenario indicates that operation with moderate excess air, temperatures around 800°C, and adequate residence time (i.e., thermal load fed) is effective in reducing CO emissions during the combustion of palm biomass, in addition to contributing to bed preservation.

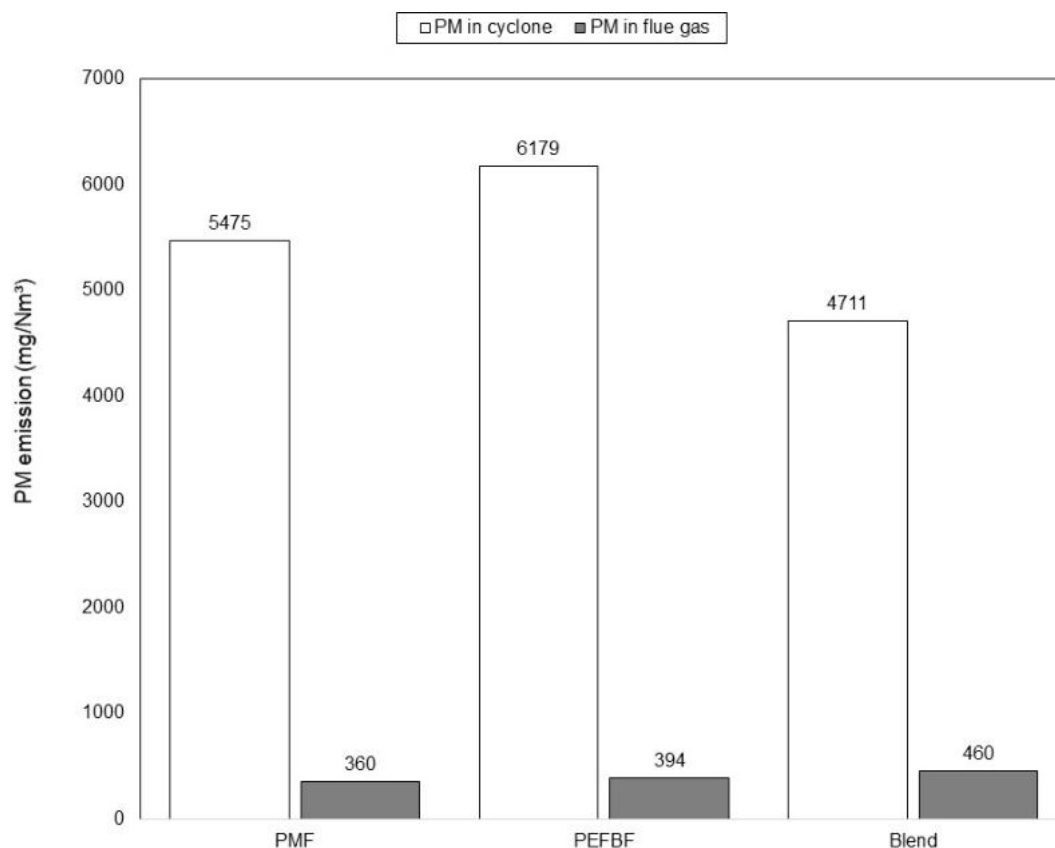
These results highlight that the simultaneous control of temperature and residence time is more decisive for the complete oxidation of CO than the fuel's reactivity alone.

Particulate matter emissions

Fig. 4 presents the average particulate matter (PM) concentrations at the cyclone outlet and in the chimney for the three combustion conditions evaluated. The total emissions

were influenced by the characteristics of the biomass fuels and the operational conditions, particularly the flow rate and excess air.

Fig. 4. MP emissions in the combustion gases at 8 vol.% O₂ (d.b.).



The combustion of the blend exhibited the lowest total PM emissions, possibly due to the lower air flow and excess air applied. This condition tends to reduce turbulence and the upward velocity of the gases, limiting the drag of fine particles into the exhaust system, which favours their retention by mechanical separation devices, such as the cyclone [39].

However, the PM concentration in the chimney was higher for the blend, suggesting the predominance of ultrafine particles. This behaviour may be associated with the lower temperatures in the bed and the freeboard, which favour the formation of PM through nucleation and condensation of inorganic vapours [40].

On the other hand, PMF, despite operating under higher excess air and elevated bed temperatures, showed lower PM concentration in the chimney. Higher temperatures

promote the oxidation of volatile compounds and the formation of larger particles through agglomeration mechanisms, facilitating their removal by the cyclone [39,40].

Resolution SIMA No. 47/2020 [33] establishes, for biomass boilers with a capacity equal to or greater than 50 t/h of steam, a particulate matter emission limit of 130 mg/Nm³, corrected to 8% O₂. Considering the results obtained, at least one of the tested operational conditions has the potential to meet this limit, especially the combustion of PMF. The blend condition, although exhibiting a lower total PM load, may exceed this value due to the predominance of ultrafine particles in the residual fraction. Compliance with environmental legislation, therefore, may require the adoption of supplementary control systems, such as scrubbers or bag filters, particularly in large-scale units.

Acid Gas Emissions

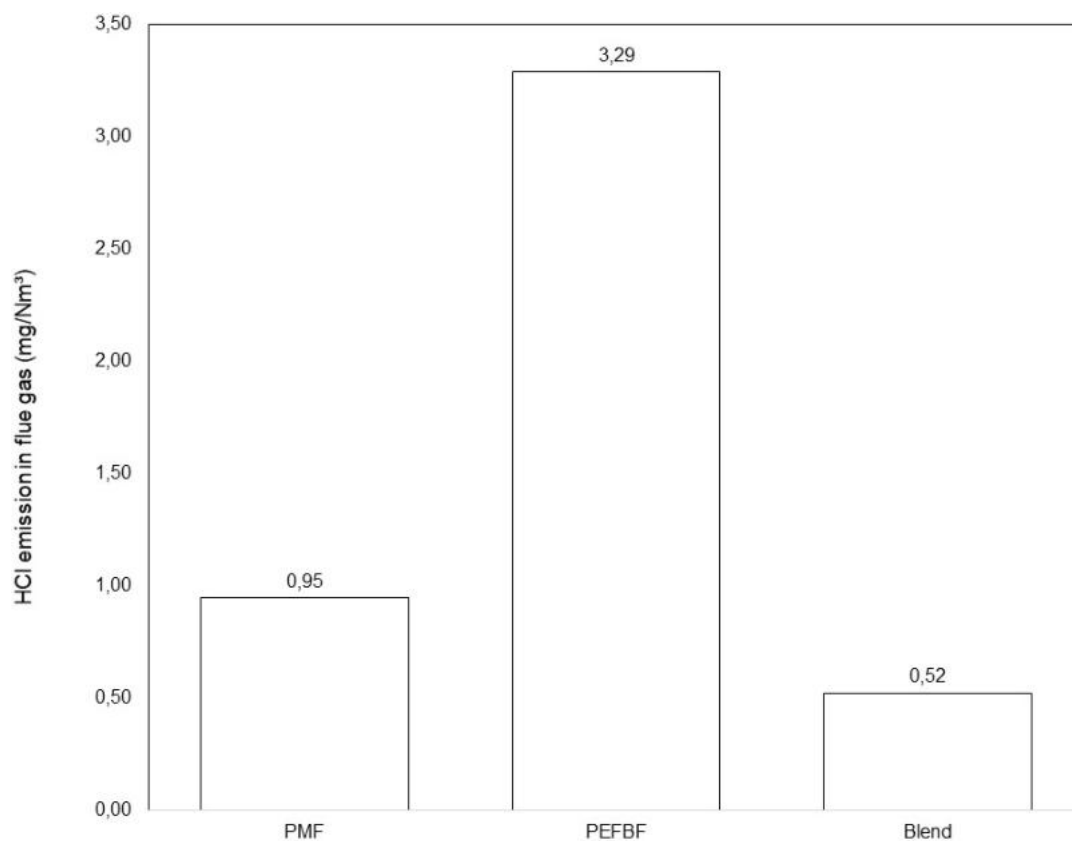
HCl emissions were influenced not only by the chlorine content of the biomass fuels but also by the inorganic composition of the ash, especially by alkaline metal oxides. Fig. 5 presents the HCl emission results from the combustion process present in the flue gas.

Although mesocarp fibre (PMF) exhibited the highest total chlorine content (0.40%, dry basis), the highest HCl emission was observed for palm empty fruit bunch (PEFBF), which contained a lower chlorine content (0.30%). This result can be attributed to the high K₂O content present in PEFBF. HCl emissions are directly associated with the volatilisation of chlorine-rich salts, such as KCl, during combustion, and are also influenced by the thermal conditions of the process. Temperatures above 700°C favour the release of HCl into the gas phase, while the presence of certain metal oxides can promote chlorine retention reactions in the ash [41].

The biomass blend, on the other hand, exhibited the lowest HCl emissions among the samples. This result is related to the dilution of chlorine content and alkaline oxides, in

addition to the lower average combustion temperature recorded in this test, which reduces the volatilisation of HCl precursors.

Fig. 5. HCl emissions in the combustion gases at 8 vol.% O₂ (d.b.).



Additional factors may also influence HCl concentrations in the flue gas. Due to its high solubility in water—up to ten times greater than that of SO₂ at temperatures below 50 °C—the residence time of the gases within the wet scrubber system can significantly affect the degree of HCl absorption, thereby reducing the measured concentration downstream [42]. Furthermore, under combustion conditions favourable to the formation of organic pollutants (i.e., temperatures between 300–500 °C and excess oxygen), a portion of the available chlorine may be incorporated into polychlorinated compounds such as dioxins and furans, decreasing the amount of free HCl in the flue gas [43].

All emission values recorded were well below the limit established by Resolution SIMA No. 47/2020 [33], which sets the maximum allowable value at 13 mg/Nm³ (corrected to 8% O₂) for biomass industrial boilers with a capacity of 50 t/h or greater. The results,

therefore, highlight the environmental feasibility of using the studied biomass fuels, including the blend, in terms of acid gas emissions.

CONCLUSIONS

This study demonstrated that palm oil residual biomasses (PMF and PEFBF) possesses suitable physicochemical characteristics for energy generation via combustion. However, with challenges related to the presence of ash rich in alkaline elements and chlorine. The integration of predictive indices with experimental combustion tests in a pilot-scale bubbling fluidized bed reactor, allowed for the identification of significant risks of slagging, fouling, and corrosion, especially for PMF.

Pilot-scale tests confirmed that operational conditions have a strong influence on emissions. NO_x and CO emissions were directly impacted by reactor temperatures and gas residence time, while SO_2 and HCl emissions were more closely related to the elemental composition of the biomass fuels and the interaction between the inorganic compounds in the ash.

The co-combustion of biomass (PMF + PEFBF) proved promising, showing better overall performance: lower CO and SO_2 emissions, higher thermal efficiency, and reduced environmental impact. The results indicate that, even without pre-treatment, the joint use of these biomass fuels can represent a viable strategy for energy generation, provided that appropriate operational control measures are adopted and, when necessary, emission mitigation systems are implemented.

Thus, this work reinforces the importance of detailed fuel characterization and the application of predictive and experimental tools to ensure the safe, efficient, and environmentally compatible operation of combustion systems powered by residual biomass fuels. Pretreatment techniques and scaling effects require further evaluation to enhance the feasibility of these residues in industrial systems.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author(s) used OpenAI/ChatGPT in order to improve the language and readability of the work. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Appendix A – Experimental design for EG leaching process

Table A.1. Main effects on A_{R_r} of the experimental design for EG.

	<i>Main effects</i>		<i>Iteration (Binary)</i>	<i>Effects</i>	<i>Iteration (Binary)</i>	<i>Effects</i>
water-to-biomass ratio		<i>A)</i>		<i>A[†]B</i>		<i>A[†]BC</i>
A	6,4		0,833		-1,389	
particle size		<i>B·</i>		<i>A[†]C</i>		
B	-15,8		-1,389		-	
time		<i>C)</i>		<i>BC</i>		
C	3,1		-4,722		-	

Eq. (A.1). Linear model equation for the ash removal rate as a function of the leaching process variables analysed.

$$y = 24,74 + 3,19x_1 - 7,92x_2 + 1,53x_3 + 0,42x_1x_2 - 0,69x_1x_3 - 2,36x_2x_3 - 0,69x_1x_2x_3$$

Table A.2. Analysis of variance (ANOVA) of the data for the experimental design for EG leaching.

Source	SS	DF	MS	F_{cal}	F_{tab}
water-to-biomass ratio	104,32	1	104,32	2,24	
particle size	501,39	1	501,39	10,79	
leaching time	18,67	1	18,67	0,40	
water-to-biomass ratio x particle size	1,39	1	1,39	0,03	10,13
water-to-biomass ratio x leaching time	3,86	1	3,86	0,08	
particle size x leaching time	44,60	1	44,60	0,96	
water-to-biomass ratio x particle size x leaching time	3,86	1	3,86	0,08	
Residue	139,42	3	46,47	1,00	
Total	817,51	10	-	-	-

Note: SS – Sum of Squares; DF – Degrees of freedom; MS – Mean Squares.

Appendix B – Scale-up experiments: EG and EFB

Table B.1. Global mass balances for the solid phase in the scale-up leaching system of the EG and EFB.

Data/Unit		EG	EFB
Leach tank feeding	mass, kg (w.b.)	4,999	5,000
	moisture, % mass (w.b.)	11,39	7,67
	mass, kg (d.b.)	4,430	4,617
Unloaded and drained charge	solid drained mass, kg (w.b.)	15,037	14,225
	moisture, % mass (w.b.)	71,70	70,40
	total mass leached, kg (d.b.)	4,270	4,211
	total mass loss, %	3,61	8,79

Table B.2. Estimation of the mass and carbon balance of the liquid fraction of the leachate of the EG and EFB.

Leachate properties	EG	EFB
Water feed, kg	69,9	69,9
Leachate mass, kg	59,8	60,6
Density of leachate, kg/m ³	988,1	994,7
Mass of C lost by biomass (g)	21,2	155,2
Total C in leachate (mg/L)	350,3	2545,4

FEASIBILITY ANALYSIS OF IMPLEMENTING A BIOGAS PLANT IN THE MUNICIPALITY OF ROSANA

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ABSTRACT

This study aims to analyze the feasibility of implementing a biogas utilization plant for energy generation in the municipality of Rosana (SP), with a focus on the proper management of municipal solid waste (MSW). The research addresses the context of increasing demand for sustainable waste treatment solutions, highlighting current legislation such as the National Solid Waste Policy and the New Legal Framework for Basic Sanitation. The adopted methodology included population projection based on a constant growth rate, estimates of per capita waste generation, and the use of the LandGEM® software to simulate methane production over 20 years. Equations were also applied to calculate the energy potential of biogas and to assess the economic feasibility through Net Present Value (NPV). The results indicate that, despite having a small population, Rosana has the potential to generate energy from biogas, with a financial return expected from the sixth year of operation. The initiative would contribute to the decentralization of the energy matrix and the mitigation of environmental impacts associated with municipal solid waste, aligning with the principles of sustainability and energy efficiency.

Keywords: municipal solid waste, biogas, sustainability.

INTRODUCTION

Global mobilization in favor of environmental preservation and sustainability has materialized in response to climate change. Prior to the Industrial Revolution, solid waste was predominantly composed of organic material that naturally degraded in the environment. However, with consumerism and the advancement of communication technologies, the accumulation of waste has become a significant problem, resulting in large mountains of refuse. According to Catapreta [4], improper waste disposal can contaminate soil and air, as well as groundwater, leading to various diseases.

The Overview by the Brazilian Association of Public Cleaning and Special Waste Companies (ABREMA, 2024) [22], which analyzes the municipal solid waste (MSW) generated in Brazil in 2022, found that the country produced 81,811,506 tons annually—approximately 224 thousand tons per day. The report notes a decrease in waste generation due to the COVID-19 pandemic, during which people stayed at home. It states that 60.5% of MSW is properly disposed of.

According to Law No. 12,305/2010 [3], which establishes the National Solid Waste Policy, urban waste must be disposed of in an environmentally appropriate manner by August 2014. This measure aims to ensure the proper treatment of municipal solid waste. Law No. 14,026/2020 [23], which outlines the New Legal Framework for Basic Sanitation, mandates that open dumps be deactivated by December 2024 and replaced by sanitary landfills or alternative solutions.

The main goal of the National Solid Waste Policy is to establish guidelines for the proper management of MSW, ranging from waste prevention to reduction, reuse, recycling, and treatment. It also includes environmental labeling and awareness campaigns to promote sustainable practices among consumers (São Paulo State Government, 2014) [8].

Biogas is one form of energy diversification in Brazil's energy matrix. According to Santos et al. (2015) [17], sanitary landfills present an opportunity for small- and micro-scale energy generation, aiding in energy matrix decentralization. Catapreta (2008) [4] discusses various forms of waste disposal, such as open dumps, direct land disposal, controlled landfills, and sanitary landfills—the latter being the method recommended by Law No. 14,026/2020 [23].

Sanitary landfills offer a solution for urban solid waste disposal, designed to minimize environmental impacts and reduce public health risks. According to Andrade (2022) [1], a sanitary landfill is an engineering project in which a suitable location, far from urban centers, is selected for waste disposal. This site uses an impermeable liner to cover the soil, controls emitted gases (which can be reused for energy generation), and manages leachate ponds to prevent bacterial proliferation.

The main objective of this study is to analyze the feasibility of implementing a biogas utilization plant for energy generation in Rosana, managing municipal solid waste in a way that minimizes environmental impacts. Additionally, the study seeks to demonstrate the economic feasibility of the project.

THEORETICAL FRAMEWORK

Sanitary Landfills

The Ministry of the Environment states that sanitary landfills function as large reactors, in which there is control over both the input of waste and the output of leachate and biogas generated during the decomposition process (MINISTRY OF THE

ENVIRONMENT, n.d.) [24]. According to Lopes and Conde (2008), the term "bio-reactor" is used to describe the operation of sanitary landfills, detailing the microbiological processes involved in the decomposition of organic matter [12].

According to data from the Brazilian Institute of Geography and Statistics (IBGE, 2022), the municipality of Rosana has a population of 17,440 [25]. However, not all residents have access to regular waste collection. About 83.84% of the population is served by the municipal collection system with environmentally appropriate waste disposal. On the other hand, 13.48% of residents burn the waste produced on their properties (a practice harmful to both the environment and public health). Additionally, 1.62% of residents bury their waste, while 0.7% dispose of it improperly, such as in vacant lots, hillsides, public areas, or through other unregulated methods (BETA, 2023) [26].

According to the Municipal Secretary of the Environment in Rosana, the municipality complies with the CETESB technical standard for trench-type sanitary landfills, which is recommended for locations with a population of less than 20,000 and daily waste production of less than 10 tons [5].

The municipal administration reported that the daily waste production is approximately 9 tons. The system in place includes trenches with dimensions of 60 meters in length and 3 meters in width, totaling 180 m² per unit. Currently, the landfill has 95 trenches, occupying a total area of 17,100 m². The facility is environmentally licensed until the year 2026.

Figure 1. Situation of the Rosana Sanitary Landfill



Source: Author's own.

During our visit to the controlled landfill in Rosana, we observed that, as illustrated in Figure 1, certain adjustments are still required for full compliance with the established regulations.

Energy Generation from Biogas

Landfill gas, or biogas, is a methane-rich fuel. It can be used for various purposes, such as electricity and thermal energy generation, cooking gas, injection into the natural gas grid, and fuel cells. The treatment required depends on the intended use of the gas (SANTOS et al., 2015) [17].

Authors Pavez and Azevedo (2020) highlight that biogas is a fuel with a calorific value equivalent to natural gas, and can be used for electrical, thermal, and mechanical energy generation [14].

Moravia (2010) states that the anaerobic degradation process is a biochemical process composed of various reactions, each involving specific bacterial populations. Factors influencing this biodegradation process include: "particle size, composition, age, moisture content, specific weight, degree of compaction of the waste, quantitative and qualitative aspects of nutrients, temperature, and pH of the liquids present in the landfill." [13]

Anaerobic digestion is a metabolic process that occurs in the absence of oxygen, relying on microbial activity to transform waste into carbon dioxide and methane. This process is divided into four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (KUNZ; STEINMETZ; AMARAL, 2022). [11]

Hydrolysis involves the breakdown of lipids, polysaccharides, and proteins into soluble organic compounds through extracellular enzymes produced by hydrolytic bacteria. This step proceeds faster for carbohydrates and proteins but is slower for materials like lignocellulose and lignin (KUNZ; STEINMETZ; AMARAL, 2022) [11].

Based on Costa, Barbosa, and Giordano (2014) and Kunz, Steinmetz, and Amaral (2022), during acidogenesis, organisms operate anaerobically, converting hydrolysis substrates into short-chain fatty acids—molecules with 1 to 5 carbon atoms (such as butyric, propionic, and acetic acids). The partial pressure of hydrogen controls the amount of carbon. Carbohydrates like glucose are broken down into lactic acid or ethanol by yeasts. The final products of acidogenesis include ketones, ammonia, carbon dioxide, and hydrogen sulfide [6;11].

Acetogenic bacteria, which are endothermic, degrade compounds such as propionic acid, converting them into acetate and carbon dioxide. In this stage, oxidation of organic compounds occurs, leading to methane formation. The aqueous environment becomes more

acidic due to acetate formation, which also generates hydrogen (H₂), thereby lowering the pH (COSTA; BARBOSA; GIORDANO, 2014) [6].

The formation of short-chain fatty acids, which are thermodynamically stable, occurs along with the digestion of gaseous hydrogen by methanogenic archaea. to Kunz, Steinmetz, and Amaral (2022) [11], the representative acetogenesis reaction is:



The final step of anaerobic digestion is methanogenesis, during which methane is produced from substances like acetic acid, hydrogen, and carbon dioxide, in an exothermic reaction.

Methanogenic bacteria are divided into two groups: acetoclastic and hydrogenotrophic. [11]

- Acetoclastic methanogens convert acetate into methane; this pathway is sensitive to pH and high ammonia concentrations.
- Hydrogenotrophic methanogens use hydrogen and carbon dioxide as substrates to produce methane, with CO₂ and H₂ being the main reactants (KUNZ; STEINMETZ; AMARAL, 2022) [11].

Moravia (2010) presents the five phases of waste stabilization, as described by Pohland and Harper (1986) [13]:

1. Phase I – Initial aerobic phase: Occurs immediately after waste deposition, involving aerobic microorganisms beginning the degradation of organic matter.
2. Phase II – Anaerobic transition: Electron acceptors shift from oxygen to nitrates and sulfates, until oxygen is fully replaced by carbon dioxide. At the end of this phase, volatile fatty acids accumulate in the leachate.
3. Phase III – Acidogenesis: Hydrolysis intensifies, resulting in high concentrations of volatile fatty acids and a significant pH drop, which increases the solubilization of inorganic compounds and nutrient consumption.
4. Phase IV – Methanogenesis: Intermediate acids are fermented by methanogenic bacteria, generating methane and carbon dioxide. In this phase, pH stabilizes, sulfates and nitrates are converted into sulfide and ammonia, and metals are removed from leachate by complexation and precipitation.
5. Phase V – Maturation: Available nutrients become limited, microbial activity decreases, and with the eventual return of oxygen, degradation slows significantly.

The Bandeirante sanitary landfill in São Paulo, created in 1979, received approximately 37

million tons of solid waste before its closure in 2007. After closure, biogas collection began for electricity generation, with 24 motor generators installed, each with a capacity of 925 kW. However, by 2023, only three generators were operational. The landfill also participates in carbon credit trading (GRAVINA, 2023) [9].

Fernandes et al. (2022) present equations and functions to estimate the energy potential and economic feasibility of energy generation from solid waste in six municipalities with varying characteristics. The results indicate that factors such as population, waste generation, and climatic conditions directly influence energy potential. However, they conclude that the analyzed cities do not demonstrate financial feasibility for energy generation in landfills [7].

According to Santos, Barros, and Tiago (n.d.), their study proposes an analysis of the energy recovery potential of waste, including efficiency values of materials. The authors emphasize the need for greater solid waste generation to make the technology economically viable. Implementing this solution may contribute to increasing renewable sources, decentralizing the energy matrix, and reducing greenhouse gas emissions. Considering economic, energy, and environmental aspects, five scenarios were analyzed, of which three were considered viable for energy recovery [18].

METHODOLOGY

Population Projection

The municipality of Rosana, located in the interior of the state of São Paulo, was selected as the data base for this analysis. For future population estimates, a constant growth rate model was adopted, taking into account the demographic instability observed in the region (QASIN, 1999) [16].

This model assumes that the population grows at a fixed percentage rate over time. According to IBGE data (2022), Rosana's population growth rate is less than 1% per year, reflecting the absence of significant migration events. Therefore, for simulation purposes, the average annual growth rate is considered approximately zero [25].

The model is represented by an exponential function, expressed by the following equation:

$$P_{trc} = P_0 \cdot (1+r)^t \quad (2)$$

Where:

- $P(t)$ = population estimated using the constant growth rate model for year t ;
- P_0 = historical population data over the years;
- r = average percentage growth rate of the city;

- t_{tt} = current year.

3.2 Waste Production and Energy Recovery Estimate

Table 1 presents the estimated data on annual total waste generation and daily per capita waste collection, expressed in kg/person/day, calculated using Equation (3) (FERNANDES et al., 2022 [7]).

According to the National Observatory on the Right to Water and Sanitation (BETA, n.d.), the daily per capita waste generation in Rosana is 1.42 kg/person/day. Based on this value, the estimated annual per capita waste generation corresponds to 0.5183 tons per person per year [26].

$$R_t = 365 \times (I_{gert} \times P_t) / 1000 \quad (3)$$

Where:

- R_t = total annual waste generation in tons;
- I_{gert} = per capita waste generation in kg/person/day;
- P_t = population for the given year.

Table 1. Population data, projection models, and waste generation in the studied city

City	Population			Daily Waste Generation (t/day)	Projection Model	Avg. Temperature (°C)	Precipitation (mm/year)
	2019	2020	2022				
Rosana	16643	16281	17440	24,7648	Constant population growth rate model	29,6°C	1,35

Source: IBGE (2022); National Observatory on the Right to Water and Sanitation (BETA, n.d.); authors.

Following the methodology proposed by Fernandes et al. (2022a), the estimation of biogas production was performed using LandGEM® software (USEPA, 2005)[28], which estimates the generation of methane, carbon dioxide, oxygen, and other gases. The model is based on the first-order decay equation (SOUZA et al., 2019) [21], with a 20-year landfill simulation. The methane generation rate constant (k) and the methane production potential (L_0) are considered.

$$Q_{CH_4} = \sum_{i=1}^n \sum_{j=0,1}^1 k L_0 \left(\frac{M_i}{10}\right) e^{-kt_{ij}} \quad (4)$$

Where:

i = time increment of 1 year;

n = year of calculation – initial year of waste acceptance;

j = time increment of 0.1 year;

k = methane generation decay rate in 1/year;

L_0 = potential for CH_4 generation in m^3/ton ;

M_i = mass of waste accepted in the i -th year in tons;

t_{ij} = age of the j -th section of residual mass accepted in the i -th year.

The authors point out that the methane generation decay rate (k) is widely debated in literature due to value variability. However, based on consulted sources, k was defined as a function of annual precipitation (P , in mm/year), according to the methodology presented by Krause et al. (2011) [10]. The parameter L_0 was set at $170 m^3/ton$, based on Zavarise et al. (2021) [30] and Fernandes et al. (2022) [7].

$$k = 3,2 \times 10^{-5} \times P + 0,01 \quad (5)$$

From these results, the collected gas values (Equation 6) and available power (Equation 7) were determined. Based on this data, landfill sizing and economic feasibility analysis were conducted.

$$Q_{collected} = Q_{biogas} \times \eta_{collected} \quad (6)$$

$$P = Q_{collected} \times \eta \times PCI \times 3,1536 \cdot 10^{-7} \times 10^{-3} \quad (7)$$

$$E = (P \times F_c \times t) / 1000 \quad (8)$$

Where:

$Q_{collected}$ = biogas flow collected each year, in $m^3/year$;

$\eta_{collected}$ = collection efficiency, where a value of 55.50% was adopted — average of the values reported by Silva et al. (2013) [20] and Watermolen et al. (2012) [29];

P = available power in kW;

η = energy conversion efficiency = 0.33 (COMPANHIA DE TECNOLOGIA DE SANEAMENTO AMBIENTAL, 2006)[5];

LHV = lower heating value of biogas, $22,106 J/m^3 CH_4$ (COMPANHIA DE TECNOLOGIA DE

SANEAMENTO AMBIENTAL, 2006)[5];

3.1536×10^{-7} = constant for converting flow from m³/year to m³/s;

10^{-3} = constant for converting power from W to kW;

E = annual available energy, in MWh/year;

F_c = capacity factor, 80%, according to Santos et al. (2018)[17];

t = operating time, in h/year.

Economic Feasibility Analysis

In Nova Andradina, operational costs for a sanitary landfill were calculated. Although it is located in another state, the city is only 85.8 km from Rosana and shares similar climatic conditions, which justifies using its solid waste cost as a reference (PREFEITURA MUNICIPAL DE NOVA ANDRADINA, 2020) [27].

Based on Fernandes et al. (2022), Net Present Value (NPV) was calculated using Equation (9) to assess economic feasibility (SILVA et al., 2020)[7;9].

$$VPL = \sum_{t=1}^m \frac{(E_n T) - C_{om}}{(1+i)^n} - I \quad (8)$$

Where:

E_n = energy produced from optimal power in the year of analysis;

T = energy selling tariff, in R\$/MWh;

C_{om} = operation and maintenance cost, in R\$/year;

i = interest rate, assumed to be 7% per year;

I = initial investment, in R\$; m = project lifetime, in years;

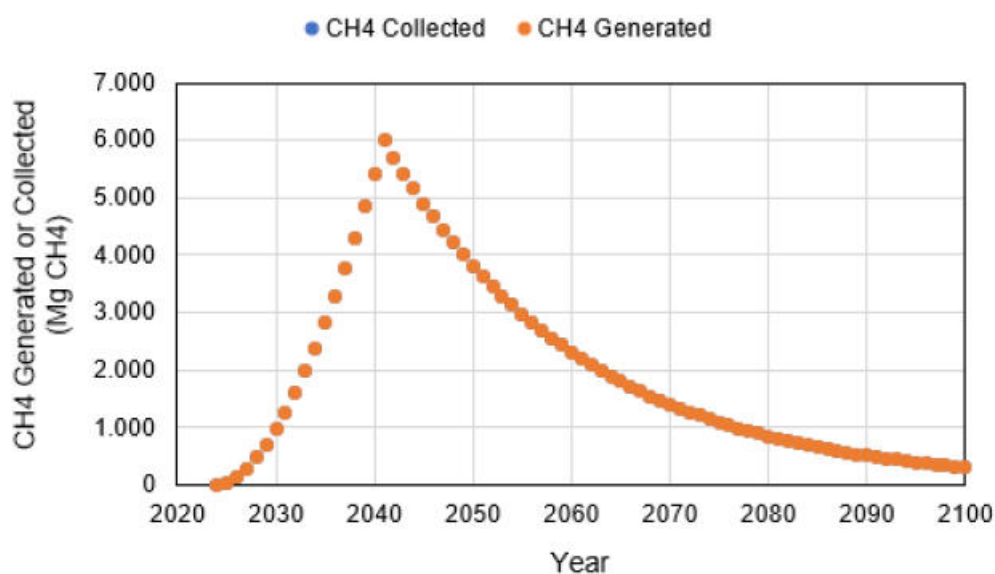
n = year of analysis;

RESULTS AND DISCUSSION

The population projection was kept constant, with a fixed estimate of 17,440 inhabitants, since the growth rate used in the model was considered to be zero. However, the demographic data presented in Table 1 show that the population does not follow a defined pattern over the analyzed years. These fluctuations make it unfeasible to apply other population projection models, as no consistent trend of growth, decline, or stability could be identified. Thus, the population behavior could not be classified as increasing, decreasing, or stable.

In Figure 2, it can be observed that the methane production peak occurs right after the first year following landfill closure (i.e., the 20th year). The decline in flow rate from that point forward represents residual methane production after the site has ceased operations, when decomposition occurs exclusively in already-deposited waste, without new input. By the year 2040, the accumulated waste is estimated to reach 153,665.58 tons/year, with methane collection estimated at 5,994.01 m³/year, resulting in an installed capacity of 1,978.02 kW.

Figure 2. Methane Flow Rate in m³/year



Based on data from the Nova Andradina Municipal Government (2020), annual operational costs are estimated at R\$ 2,085,965.00, with a lower population than Rosana and a unit cost of R\$ 292.00 per ton [27]. The installation cost is R\$ 1,008,938.56 per year, and the NPV (Net Present Value) indicates a return starting in the sixth year, as shown in Figure 2.

Figure 3. Net Present Value (NPV)



The economic feasibility calculations were performed using the estimated operational costs from the Nova Andradina Municipal Government (2025) [27]. Adopting an average cost of R\$ 292.00 per ton of waste, an annual operational cost of R\$ 2,085,965.00 was estimated for Rosana. The installation cost of the system was calculated at R\$ 1,008,938.56 per year. Based on these estimates, the project's Net Present Value (NPV) indicates a return beginning in the sixth year of operation, as illustrated in Figure 3, confirming the project's economic viability.

CONCLUSION

To ensure that waste disposal occurs in an environmentally appropriate manner (reducing the existence of open dumps and controlled landfills), it is necessary to expand the sanitary landfill so that it can gradually replace inadequate disposal systems. In addition, the potential for energy recovery from the biogas generated in sanitary landfills becomes an important advantage, contributing to environmental sustainability and the energy efficiency of the system.

Consortium-based sanitary landfills are advantageous for reducing operational costs, resulting in greater efficiency in waste treatment and final disposal. Considering energy generation from municipal solid waste, sanitary landfills represent a sustainable solution for energy recovery.

It is well known that, for the construction of a sanitary landfill, it is essential to analyze the environmental impacts that such a project may cause. Therefore, it is important to highlight that, for the implementation of this project, it must be verified whether, according to the size of the sanitary landfill, the preparation of an Environmental Impact Study (EIA) and an Environmental Impact Report (RIMA) will be required, as these documents are essential for assessing and mitigating potential environmental impacts.

The present study sought to demonstrate the economic feasibility of implementing a sanitary landfill in the municipality of Rosana. The results obtained were positive, even considering that it is a city with a relatively small population. The analysis confirmed that the project is economically viable, reinforcing its relevance for the proper management of municipal solid waste.

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HYDROGEN PRODUCTION VIA BIOMASS ENTRAINED-FLOW GASIFICATION IN A TWO-STAGE REACTOR USING ASPEN PLUS

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ABSTRACT

The growing demand for hydrogen in the energy and industrial sectors has prompted the search for alternative and renewable production routes. Biomass gasification has emerged as a promising pathway for hydrogen generation and warrants further investigation. In this study, a process model for hydrogen production from energy cane bagasse gasification in a two-stage entrained-flow reactor was developed using Aspen Plus V10. A parametric analysis assessed the impact of equivalence ratio (0.35–0.46) and water/feed ratio (0.30–0.40) on gasifier temperature, syngas composition, hydrogen yield, and cold gas efficiency (CGE). At ER = 0.46 and water/feed = 0.30, typical operating temperatures of an E-Gas™ type gasifier—approximately 1504 °C in the first stage and 997 °C in the second—were reached, yielding 78.0 kg H₂ per ton of dry biomass. Overall, the two-stage entrained-flow gasifier produced hydrogen yields comparable to other gasification technologies, with the added benefit of simplified downstream gas cleaning due to low tar content. However, the requirement for high-purity oxygen may limit practical implementation.

Keywords: Hydrogen, entrained-flow gasification, biomass, Aspen Plus

INTRODUCTION

According to the International Energy Agency (IEA), global hydrogen demand has steadily increased over the past few decades, reaching a record high of 97 million tonnes in 2023. Currently, hydrogen is primarily used in the chemical industry (for ammonia and methanol production), petroleum refining, and steel manufacturing. The

majority of this demand is met by hydrogen produced from unabated fossil fuels, mainly natural gas and coal [1].

The Paris Agreement seeks to limit the increase in global average temperature to well below 2 °C above pre-industrial levels, while pursuing efforts to restrict it to 1.5 °C [2]. Achieving the more ambitious 1.5 °C target requires reaching global net-zero CO₂ emissions by 2050 [3]. In this context, replacing unabated fossil fuels with clean, renewable energy sources is essential for the transition to net-zero emission energy systems [4].

By 2030, it is estimated that nearly two-thirds of low-emission hydrogen will be produced through water electrolysis, positioning it as the leading technology for future hydrogen generation [5]. However, electrolysis faces a significant limitation: high production costs—ranging from USD 3 to 8 per kg of H₂ [6]—driven mainly by its substantial electrical energy requirements [7].

As a complementary pathway, biomass gasification offers several advantages, including continuous (non-intermittent) operation, fossil fuel independence, renewability, scalability, and the co-production of value-added byproducts such as biochar, heat, and electricity. Feedstocks suitable for thermochemical conversion include woody biomass, herbaceous biomass, and municipal and agro-industrial waste. Among these, energy cane stands out as a particularly promising option. This high-yielding sugarcane variant is obtained by backcrossing commercial varieties with ancestral *Saccharum* species. Compared to conventional sugarcane, energy cane accumulates more biomass, exhibits greater tolerance to water and nutrient stress—allowing cultivation in marginal soils—requires fewer herbicides and pesticides, and achieves much higher productivity (about 180 ton/year), which is two to three times greater than that of conventional sugarcane. Additional benefits include higher tillering capacity and an increased number of harvests [8].

Gasification technologies include fixed-bed, fluidized-bed, and entrained-flow gasifiers. This study focuses on the slurry-fed, two-stage entrained-flow gasifier used in E-Gas™ technology. Key features of this system include continuous slag removal in the first stage, high operating pressures (~27.6 bar), elevated operating temperatures

(>1000 °C) achieved using high-purity oxygen (~95 mol%), high carbon conversion efficiency (~97–98% for less reactive fuels), and the production of syngas with negligible tar content [9–11].

The IEA Bioenergy Technology Collaboration Programme (Task 33) has identified road transport (fuel cell vehicles), iron and steel manufacturing, and aviation and maritime fuels as sectors where hydrogen from biomass gasification could have a significant impact. These applications typically require hydrogen purity levels of 99.5% or higher [1].

Previous studies have examined hydrogen production from biomass gasification in fixed-bed and fluidized-bed reactors. For instance, Gubin et al. [12] demonstrated the technical feasibility of producing high-purity hydrogen (≥ 99.977 vol%) from wood chips gasified in a downdraft fixed-bed reactor coupled with water–gas shift and PSA purification units at pilot scale, achieving yields of 55.1 g H₂ per kg of dry biomass with an adsorption time of 450 s. Fail et al. [13] reported hydrogen production at 99.97 vol% purity (dry basis) and 80% recovery from syngas generated via steam gasification in a dual fluidized-bed reactor, using a three-stage water–gas shift reactor, a rapeseed oil methyl ester (RME) scrubber, and a PSA unit. Erdem et al. [14] conducted a parametric study using Aspen Plus® to simulate steam co-gasification of plastic and biomass in a fluidized-bed reactor. Increasing the High-Density Polyethylene (HDPE) content in the feedstock from 0% to 100% at a steam-to-fuel ratio of 1.0 increased the lower heating value (LHV) from 15.9 MJ/kg to 25.2 MJ/kg, while hydrogen yield rose from 680.8 to 1558.7 Nm³/ton of feed. Likewise, adjusting the steam-to-fuel ratio from 0.5 to 2.0 for an equimolar biomass blend (cotton husk + HDPE) increased the hydrogen yield from 983.3 to 1316.1 Nm³/ton of feed.

Despite growing interest in low-emission hydrogen, studies on biomass gasification in entrained-flow reactors remain limited. This work aims to evaluate hydrogen production from biomass gasification in a two-stage entrained-flow reactor based on E-Gas™ technology. A process model was developed in Aspen Plus® V10 to assess gasification parameters and performance indicators, including gasifier temperature, syngas yield, hydrogen yield, lower heating value (LHV), and cold gas efficiency (CGE).

A parametric analysis was conducted by varying the equivalence ratio (ER) and the water-to-feed ratio.

METHODOLOGY

Biomass Characterization

The biomass used in this study is energy cane bagasse, and its characterization included high heating value (HHV), proximate analysis, and ultimate analysis. Detailed methodologies of sample preparation and equipment used for the analyses are available in a previous study by the authors [15].

Table 1: Proximate and ultimate analysis and higher heating value for energy cane bagasse.

Parameter	Value	Parameter	Value
Ultimate (wt.%) on dry basis		Proximate (wt.%) on dry basis	
Carbon	48.97	Ash	1.36
Hydrogen	7.48	Volatile Matter	78.97
Oxygen	42.92	Fixed Carbon	18.34
Nitrogen	0.36	Moisture	6.76
Sulfur	0.27	Calorific value (dry basis)	
		HHV (MJ/kg)	19.55

Process Description

A schematic representation of the biomass gasification process for hydrogen production is illustrated in Figure 1. Initially, the biomass is mixed with water to form a slurry. For the E-Gas™ entrained-flow gasifier, the typical water content in the slurry ranges between 30–50% [16]. The slurry enters the reactor in two separate stages. In the first stage, approximately 80 wt% of the slurry is introduced and reacts with sub-stoichiometric oxygen at a purity of 95 mol% [17]. At this stage, the ash present in the feedstock melts due to the high temperatures generated by the combustion reactions (Eqs. 1–3) presented in Table 2, forming slag, which is subsequently removed from the reactor [10]. The energy released in the first stage sustains devolatilization and subsequent reduction reactions involving CO₂, H₂, and H₂O with char (Eqs. 5–7) in the second stage, where the remaining 20% of the slurry is fed without additional oxygen input [17, 18].

Figure 1: Process schematic representation.

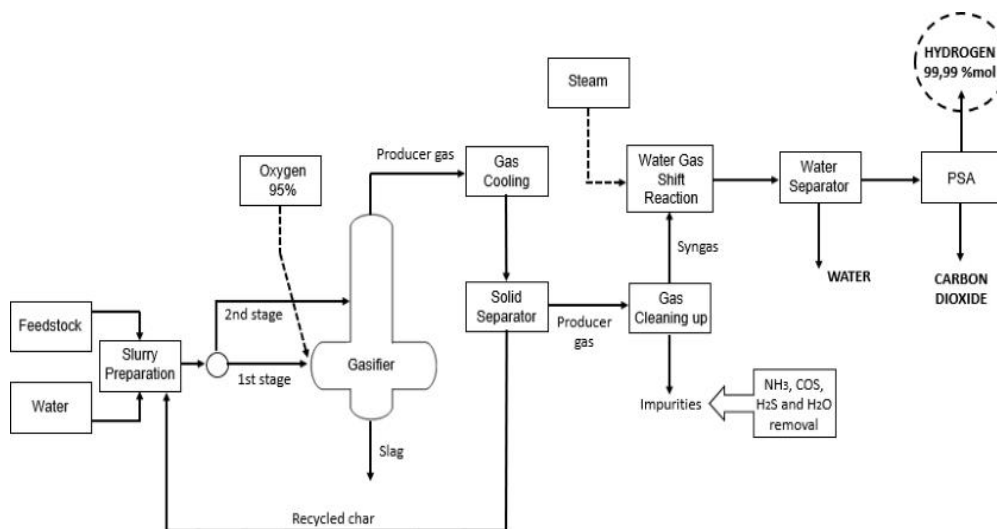


Table 2: Key chemical reactions in biomass gasification [S].

Equation	Chemical Reaction	Heat of reaction (kJ/mol)
1	$C + O_2 \rightarrow CO_2$	-394
2	$C + 1/2O_2 \rightarrow CO$	-111
3	$CO + 1/2O_2 \rightarrow CO_2$	-284
4	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	+206
5	$C + CO_2 \leftrightarrow CO$	+172
6	$C + H_2O \leftrightarrow CO + H_2$	+131
7	$C + 2H_2 \leftrightarrow CH_4$	-74.8
8	$CO + H_2O \leftrightarrow CO_2 + H_2$	-41.2

The gas produced from gasification, also referred to as *producer gas*, is cooled using a heat exchanger before entering the solid separation unit, which removes unreacted biochar particles via a porous candle filter [11]. The unconverted biochar is reintroduced into the system through a recycle stream [18]. Subsequently, the particle-free producer gas enters a cleaning unit, where contaminants and impurities such as NH_3 , COS , and H_2S —originating from the gasification stage—are removed. This step is essential, as even trace amounts of these contaminants can poison the catalysts used in the downstream water-gas shift reactors, significantly reducing their performance [19]. The removal of these contaminants is carried out in multiple stages: COS is hydrolyzed to form H_2S ; NH_3 is separated by condensation from the producer gas; H_2S

is absorbed using a methyl-diethanolamine (MDEA) solution; and finally, the MDEA solvent is regenerated for reuse in the absorber [20].

The cleaned gas, now referred to as *syngas*, is fed into water-gas shift reactors to enhance hydrogen production through the addition of steam, following the reaction described in Equation 8 (Table 2). To maximize hydrogen production, steam is fed at a mass flow rate that ensures a carbon monoxide molar concentration of 1 mol% at the outlet of the low-temperature water-gas shift reactor [21]. The product gas is then cooled, and the condensed water is removed from the process. Subsequently, the gas stream is directed to a pressure swing adsorption (PSA) unit, where hydrogen is separated, yielding a stream with up to 99.99 mol% purity [19]. This level of purity is required for applications such as fuel cell vehicles, internal combustion engines, and the production of hydrogen-based liquid fuels for the aviation sector [22].

Model Assumptions

The model was developed based on the following assumptions [9, 18, 23, 24]:

The process operates under steady-state conditions.

All gasification reactions are assumed to be fast and reach chemical equilibrium.

In the water-gas shift reactors, the reaction is considered to reach thermodynamic equilibrium.

Char is assumed to consist entirely of graphite (100% C).

Ash converted to slag is considered an inert compound.

Tar and heavy hydrocarbon formations are not considered.

Feedstock conditioning steps (e.g., grinding to <75 μm particle size, typical of entrained-flow gasifiers) are not included in the model.

The following species were included as potential equilibrium products in the RGibbs reactor: H_2O , N_2 , O_2 , H_2 , C, CO, CO_2 , CH_4 , H_2S , COS, SO_2 , SO_3 , NH_3 , NO, and NO_2 .

Aspen Model Description

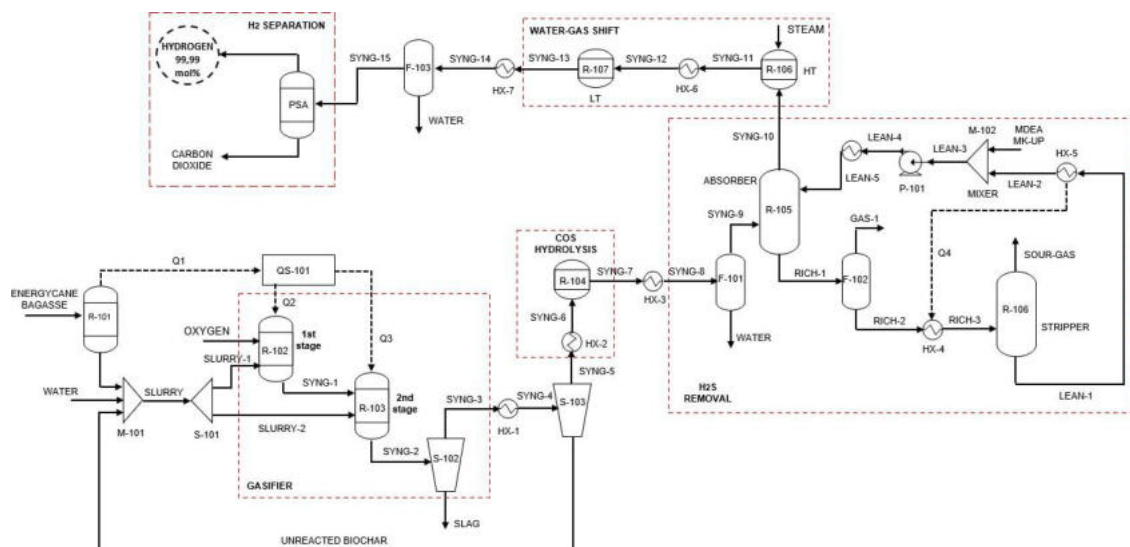
Due to the nature of biomass and the characteristics of the gasification process, the Peng–Robinson equation of state was employed to estimate the thermodynamic properties of the process streams, except in the H₂S removal section, where the electrolyte-nonrandom two-liquid (ELEC-NRTL) activity coefficient model was applied to account for the non-ideality of the liquid phase resulting from gas dissolution and electrolyte formation in the aqueous medium [23, 24].

The model developed in Aspen Plus® V10 was structured in several stages (Figure 2). The first step involves the feeding of biomass into the E-Gas™ reactor, which is capable of processing approximately 3000 tons/day (125 tons/h) of feedstock; therefore, this value was selected as the initial mass flow rate [10]. Since biomass is a non-conventional substance in Aspen Plus, a hypothetical decomposition of the feed stream into its reactive constituents (such as C, H₂, N₂, O₂, S, and H₂O) is required [18]. This decomposition is implemented using an RYield block (R-101), based on proximate and ultimate analysis data, and executed via FORTRAN statements in a calculator block. The decomposed biomass is mixed with water and a recycled stream of unreacted biochar. These streams are combined in a Mixer block (M-101). The resulting stream (SLURRY) is split using an FSplit block (S-101) to simulate its distribution into the two stages of the gasifier. Approximately 80% of the mass flow is fed into the first stage and 20% into the second [17]. The heat released during the biomass decomposition in the RYield reactor is transferred through the heat stream Q1 to the gasification section. This energy is further divided in proportion to the mass flow entering each gasifier stage.

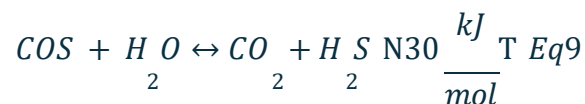
The gasification reactor is modeled using two RGibbs reactors. Oxygen is introduced only in the first stage, and its mass flow rate can be adjusted to achieve the target temperature. In this study, the selected temperatures correspond to the typical operating conditions of the E-GAS™ gasifier, which range from 1300 to 1500 °C in the first stage and from 1000 to 1050 °C in the second stage [10]. This first stage is characterized by the highest temperatures in the process and provides the energy required for the endothermic reactions taking place in the second stage (Eqs. 4–6).

The output stream from the second gasification stage passes through an **SSplit** block (SYNG-2) to remove the slag (a non-conventional component). The gas is then cooled to 370 °C using a **Cooler** block (HX-1) and passed through a second **SSplit** block to remove particulate matter (unreacted biochar), which is recycled back into the process. The particle-free gas is further cooled to 204 °C using another **Cooler** block (HX-2) before entering the COS hydrolysis unit.

Figure 2: Hydrogen production via biomass entrained-flow gasification plant.



To reduce sulfur-containing compounds in the syngas to levels that prevent catalyst deactivation in the water-gas shift reactors, the gas undergoes a COS hydrolysis stage followed by H₂S removal. COS is hydrolyzed to H₂S because the latter is more effectively removed by absorption using the chemical solvent MDEA in the subsequent purification steps [23]. During COS hydrolysis, COS reacts with water in the presence of an aluminum- or titanium-based catalyst to form H₂S and CO₂ (Eq. 9) [25, 26].



The reaction is simulated using a stoichiometric reactor (RStoic) with a fixed COS conversion of 99% [23], operating isothermally at approximately 204 °C [27] with a pressure drop of 7% [25]. The syngas is then cooled to the operating temperature of the H₂S absorber (~30 °C) using a built-in Cooler block (HX-3). The condensed phase resulting from this temperature drop is separated in a Flash Drum (F-101), the gaseous stream exiting this unit (SYNG-9) is fed into an absorber unit designed to reduce H₂S

concentrations to below 0.1 ppm—the tolerance limit for commercial low-temperature Cu/Zn-based catalysts [28]. The absorber column (R-105) operates at approximately 20 bar using an aqueous methyl-diethanolamine (MDEA) solution to absorb acid gases (H_2S and CO_2) [23, 25]. The MDEA solution enriched with H_2S and COS (RICH-1) is depressurized via a Flash Drum (F-102) to the operating pressure of the downstream stripper column (~ 1.5 bar) [23, 25]. The liquid stream exiting Flash Drum (RICH-2) is preheated through Heater block (HX-4) with the overhead gas stream from the stripper. In the stripper (R-106), the lean MDEA solution (LEAN-1) is regenerated and conditioned for recirculation to the absorber. This conditioning includes:

Cooling to $\sim 35^\circ\text{C}$ via heat exchange in an isobaric Cooler block (HX-5),

Addition of a make-up stream to compensate for MDEA losses in the GAS-1 and SOUR-GAS streams, and

Pressurization to 20 bar using a Pump block (PUMP) with an isentropic efficiency of 75% [25]

Both columns are simulated using a RadFrac model with the equilibrium approach. Isobaric conditions are assumed for both columns, and the following components are treated as Henry's components: H_2S and CO_2 . Equations 10–18 (Table 3) represent the chemical reactions involved in the amine scrubbing system [23]. A partial condenser and a reboiler were implemented for the stripping column. The main operating parameters of the H_2S absorption and stripping systems are summarized in Table 4.

Table 3: Main chemical reactions involved in the amine scrubbing system.

Equation	Chemical Reaction
10	$\text{MDEA}^+ + \text{H}_2\text{O} \leftrightarrow \text{MDEA} + \text{H}_3\text{O}^+$
11	$2\text{H}_2\text{O} \leftrightarrow \text{H}_3\text{O}^+ + \text{OH}^-$
12	$\text{CO}_2 + 2\text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{HCO}_3^-$
13	$\text{HCO}_3^- + \text{H}_2\text{O} \leftrightarrow \text{H}_3\text{O}^+ + \text{CO}_3^{2-}$
14	$\text{H}_2\text{O} + \text{H}_2\text{S} \leftrightarrow \text{HS}^- + \text{H}_3\text{O}^+$
15	$\text{H}_2\text{O} + \text{HS}^- \leftrightarrow \text{S}^{2-} + \text{H}_3\text{O}^+$
16	$\text{HCN} + \text{H}_2\text{O} \leftrightarrow \text{H}_3\text{O}^+ + \text{CN}^-$
17	$\text{NH}_3 + \text{H}_2\text{O} \leftrightarrow \text{NH}_4^+ + \text{OH}^-$

The wet syngas stream (SYNG-10) exiting the stripper enters the water-gas shift (WGS) reaction section, which is simulated using two REquil blocks operating isothermally.

The first reactor corresponds to a high-temperature (HT) shift reactor using an Fe/Cr-based catalyst, and the second is a low-temperature (LT) shift reactor using a Cu/Zn-based catalyst. The selected operating temperatures were 400 °C for the HT reactor and 200 °C for the LT reactor, with an assumed pressure drop of approximately 0.4 bar [23]. A cooling step is required to reduce the gas temperature before entering the LT reactor. This is simulated using a Cooler block (HX-6), adjusting the temperature to 200 °C. Steam is fed into the HT reactor at 400 °C and 20 bar, with a mass flow rate sufficient to achieve a residual CO molar concentration of 0.1 mol% in the outlet stream of the LT reactor (SYNG-13) [28]. The LT reactor outlet stream (SYNG-15) is then sent to the hydrogen purification section. First, the syngas is cooled to approximately 30 °C using a Cooler block (HX-7), assuming a pressure drop of 1%. This cooling results in a vapor–liquid phase mixture, which is processed in a Flash Drum (F-103). The liquid phase, consisting mainly of water, is removed from the process, while the gaseous fraction is sent to a Pressure Swing Adsorption (PSA) unit. This unit is simulated using a Separator block (PSA) to produce a hydrogen stream with a purity of 99.99 mol% and 80 % H₂ recovery [13, 29].

Table 4: H₂S absorber and desorber operating parameters.

Unit	Parameter	Basis	Value
Absorber	Stages	number	5
	MDA solution composition	Mass fraction	50 wt% MDEA
	MDEA solution temperature	°C	30
	Pressure	bar	20
Stripper	Stages	number	5
	Pressure	bar	1.5
	Reflux ratio	mass	1.9

Table 5: Block description used in Aspen Plus® model.

Block name	Aspen Plus ID	Description
R-101	RYield	Decomposes biomass (non-conventional component) into a conventional component
R-102	RGibbs	Simulates oxidation reactions through the Gibbs free energy minimization
R-103	RGibbs	Simulate reduction reactions through the Gibbs free energy minimization
R-104	RStoic	Simulates the COS hydrolysis reaction
R-105	RadFrac	Simulates the H ₂ S absorber
R-106	RadFrac	Simulates the H ₂ S stripper

R-107	REquil	Simulates the high-temperature water-gas shift reactor
R-108	REquil	Simulates the low-temperature water-gas shift reactor
M-101	Mixer	Mixes the streams of energy cane bagasse, water, and unreacted material
M-102	Mixer	Mixes the lean MDEA solution stream with the make-up stream
S-101	FSplit	Splits the material streams entering the gasifier
S-102	SSplit	Separates the slag from the gas
S-103	SSplit	Separates the unreacted biochar from the gas
QS-101	QFSplit	Splits the energy streams entering the gasifier
HX-1	Cooler	Cools the hot gas to 370 °C
HX-2	Cooler	Cools the syngas to 204 °C
HX-3	Cooler	Cools the syngas to 30 °C
HX-4	Heater	Heats the H ₂ S-enriched MDEA solution
HX-5	Cooler	Cools the lean MDEA solution to 35 °C
HX-6	Cooler	Cools the lean MDEA solution to 30 °C
HX-7	Cooler	Cools the syngas to 200 °C
HX-8	Cooler	Cools the syngas to 30 °C
F-101	Flash2	Separates the condensed phase from the syngas
F-102	Flash2	Separates the liquid phase (H ₂ S-enriched MDEA solution) from the gas phase
F-103	Flash2	Separates the condensed phase from the syngas
P-101	Pump	Pressurizes the lean MDEA solution to the absorber operating pressure
PSA	Sep	Simulates hydrogen purification in a Pressure Swing Adsorption (PSA) unit, yielding a high-purity hydrogen stream

Model Validation

Due to the limited availability of experimental data on biomass gasification in E-Gas™ entrained-flow reactors, it was necessary to rely on studies that used coal as the feedstock. The reference data for comparison were obtained from the National Energy Technology Laboratory (NETL) CFD model results [30]. The deviation between the two models was quantified using the root mean square error (RMSE) (Eq. 18), and the results indicate a reasonable agreement in the composition of the main syngas components between the models, except for methane, where the largest deviation was observed (Table 6).

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (\hat{y}_i - y_{reference})^2}{N}} \quad q. 18$$

Where y_i is the model value obtained in this work, $y_{\text{reference}}$ is the corresponding value from the selected reference used for comparison, and N is the total number of data points.

Table C. Comparison between model results for syngas composition produced from coal gasification in a two-stage entrained-flow gasifier

	Reference [30]	This work
Component	%vol wet basis	% vol wet basis
CO	33.71	35.44
CO ₂	12.05	12.00
H ₂	28.03	32.32
CH ₄	1.60	0.80
RMSE		0.0591

Performance Parameters

The process performance was evaluated based on key parameters such as gasifier temperature, syngas composition, hydrogen yield, and cold gas efficiency (CGE). These parameters were assessed through a sensitivity analysis by varying the feed moisture content and the equivalence ratio (ER). The equivalence ratio was determined using Eq. (19).

$$ER = \frac{\dot{m}_{O_2, \text{inlet}}}{\dot{m}_{O_2, \text{stoichiometric}}} \quad \text{Eq. 19}$$

Where $\dot{m}_{O_2, \text{inlet}}$ represents the actual inlet mass flow of oxygen, and $\dot{m}_{O_2, \text{stoichiometric}}$ corresponds to the mass flow of oxygen required for the complete combustion of the biomass.

The hydrogen yield was calculated using Eq. (20).

$$Y_{H_2} = \frac{P\dot{m}_{H_2}Q_{\text{produced}}}{P\dot{m}_{\text{Biomass, dry base}}Q} \quad \text{Eq. 20}$$

Where $\dot{m}_{H_2, \text{produced}}$ represents the hydrogen mass flow rate at the outlet of the PSA unit (in kg/h), and $\dot{m}_{\text{Biomass, dry base}}$ corresponds to the mass flow rate of dry biomass fed into the process (in ton/h). On the other hand, the CGE was calculated using Eq. (21).

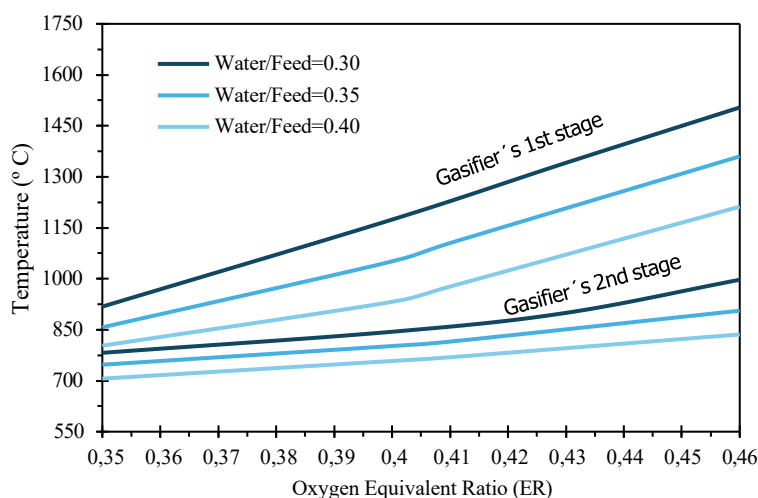
$$CGE = \frac{m_{producer\ gas} \cdot HHV_{producer\ gas}}{m_{Biomass} \cdot HHV_{Biomass, dry\ base}} * 100 \quad Eq. 21$$

RESULTS AND DISCUSSION

Gasifier Temperature

An increase in the water/feed ratio reduces the reactor temperature, thereby requiring a higher oxygen feed rate to reach the typical operating temperature range of the E-Gas™ gasifier—1300 to 1500 °C in the first stage and 1000 to 1050 °C in the second stage [12] (Figure 3). This trend is partly attributed to the fact that a higher moisture content in the slurry increases the energy required for water vaporization, which is supplied by combustion; as a result, more oxygen is needed (i.e., a higher equivalence ratio) [31]. With a water/feed ratio of 0.30, the typical reactor temperatures in both stages were achieved at an equivalence ratio of 0.46.

Figure 3: Gasifier temperature vs ER.



Syngas composition vs ER and water/feed ratio

Figure 3 shows the effect of the equivalence ratio (ER) on the dry-based syngas composition at a water-to-feed ratio of 0.30, a condition under which typical operating temperatures of the gasifier are achieved with a lower oxygen flow rate, compared with the other water-to-feed ratios analyzed. An increase in ER leads to higher

concentrations of H_2 and CO , while CO_2 and CH_4 show the opposite trend [24, 26, 32]. This trend can be attributed to the fact that a higher oxygen feed promotes combustion reactions (Eqs. 1–3), resulting in increased temperature and providing the energy required for the reduction reactions (Eqs. 4–6). Hydrogen reaches a peak value of 0.41 mol% at $ER = 0.43$. Further increases in ER lead to a slight decrease in H_2 concentration in the syngas, which could be attributed to the promotion of the reverse water-gas shift reaction (Eq. 8), favored by the high temperatures within the gasifier [29]. On the other hand, an increase in the water/feed ratio in the slurry decreases CO formation, while the opposite effect is observed for CO_2 (Figure 4). This behavior can be attributed to the higher moisture content in the feed, which promotes the formation of CO_2 and H_2 through the water–gas shift reaction (Eq. 8) [33].

Figure 3: Syngas composition vs ER .

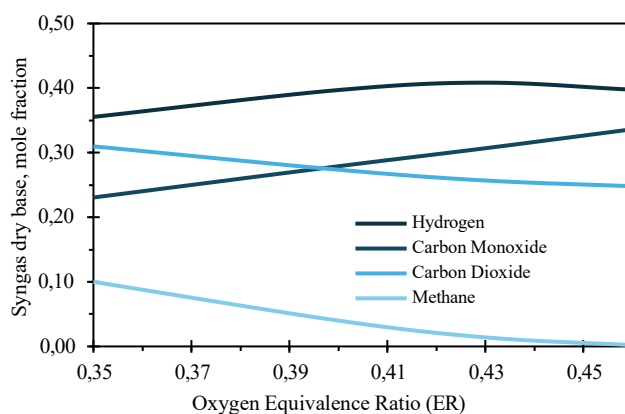
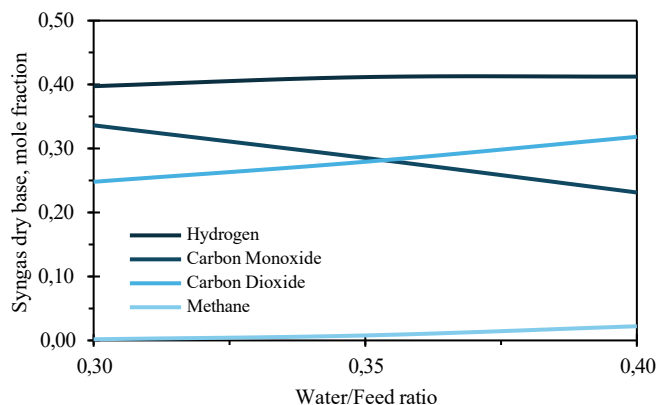


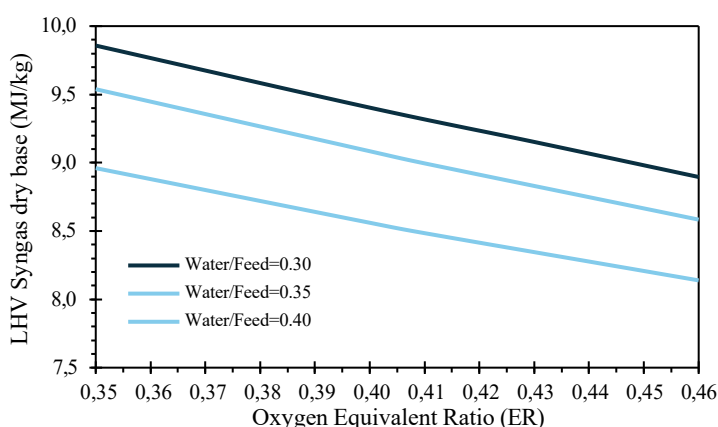
Figure 4: Syngas composition vs water/feed ratio for $ER=0.4C$.



Lower Heating Value (LHV) vs ER and water/feed ratio

The lower heating value (LHV) decreases with increasing water/feed ratio and equivalence ratio (Figure 5). This reduction may be attributed to the promotion of reforming reactions, such as the reverse water–gas shift reaction, driven by the higher gasifier temperatures and increased water content in the feed [34].

Figure 5: ER and water/feed ratio effect on LHV (MJ/kg).

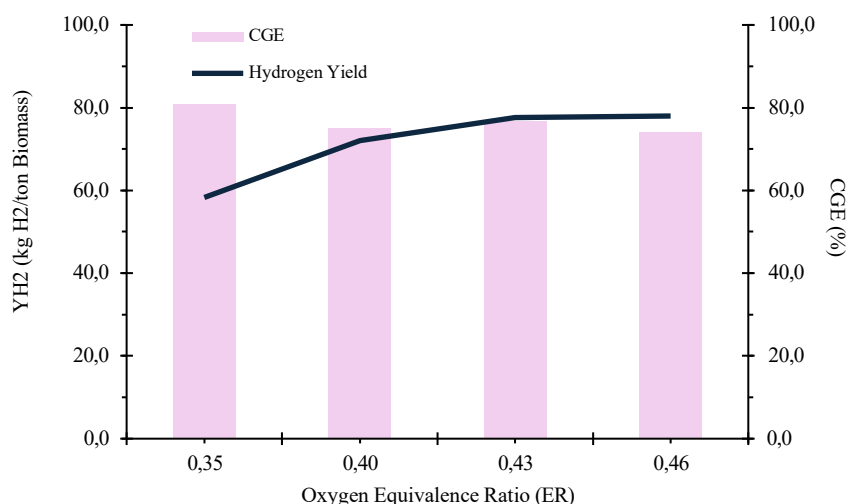


Hydrogen yield and CGE

Hydrogen yield is influenced by the performance of the PSA purification unit, which is determined by its hydrogen recovery rate. In this study, a hydrogen recovery of 80% in the PSA unit was assumed [13], together with a water-to-feed ratio of 0.30, based on the considerations discussed in the previous section. The increase in CO production at higher equivalence ratios (Figure 3) raises the steam demand in the water–gas shift section, increasing both hydrogen production and overall yield (Figure 6), primarily through the water–gas shift reaction (Eq. 8). Under operating conditions of ER = 0.46 and water/feed = 0.30, a hydrogen yield of 78.0 kg H₂ per ton of dry biomass was obtained, which lies within the range of 40–190 kg H₂ per ton of feedstock reported in the literature for thermochemical conversion processes such as gasification, pyrolysis, and reforming [1]. Comparable hydrogen yields have been documented in other biomass gasification studies. For instance, Gubin et al. reported a yield of 87 kg H₂ per ton of dry biomass via air gasification of woody biomass in a dual fluidized-bed gasifier [35]. In another study, Gubin et al. obtained a hydrogen yield of 55.1 kg H₂ per

ton of dry woody chips through air gasification in a downdraft fixed-bed reactor coupled with water–gas shift and PSA purification units at pilot scale [12]. In addition to hydrogen yield, the CGE exhibited only marginal variations at higher equivalence ratios, reaching approximately 74% at an ER of 0.46.

Figure C. Effect of Equivalence Ratio on H_2 Yield, and Cold Gas Efficiency at a Water/Feed ratio of 0.30.



CONCLUSIONS

The potential for hydrogen production from biomass gasification in a two-stage entrained-flow reactor was evaluated using an Aspen Plus V10 model. The parametric analysis showed that increasing the equivalence ratio (0.35–0.46) enhanced hydrogen yield, reaching a maximum of 78.0 kg H_2 per ton of dry biomass at ER = 0.46 and a water/feed ratio of 0.30. Increasing the water/feed ratio from 0.30 to 0.40 decreased reactor temperatures by approximately 292 °C in the first stage and 161 °C in the second at ER = 0.46, contributing to a notable reduction in CO concentration in the syngas. Overall, the entrained-flow gasifier achieved hydrogen yields comparable to those reported for other gasification technologies. Among its main advantages is the potential to simplify downstream gas cleaning due to the low tar concentration in the product gas. However, the need for high-purity oxygen might pose a limitation in practical applications.

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Juan F. Pérez: Writing - Review C Editing, Conceptualization.

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MANAGEMENT TOOL FOR ESTIMATING THE ENERGY POTENTIAL OF MUNICIPAL SOLID WASTE (MSW) THROUGH THERMOCHEMICAL PROCESSES

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ABSTRACT

The efficient management of municipal solid waste (MSW) requires qualified professionals and digital tools that assist decision-makers in selecting the most suitable technological pathway for waste utilization and to determine the amount of energy to be generated through the application of a specific technological route. Many available tools necessitate expertise in programming software or qualified environmental professionals. A simple tool can support municipal managers in decision-making, enabling more municipalities to achieve more efficient utilization of MSW through thermochemical and biochemical pathways, thereby reducing the volume of waste sent to landfills and dumps. This contributes to diversifying the energy matrix, reducing greenhouse gas emissions, and minimizing the risk of soil and water body contamination. The objective of the present study was to develop an easy-to-use and intuitive tool using Microsoft Excel to assist municipal managers in estimating the amount of energy to be generated through the application of mass burning of mixed MSW based on the gravimetric data of their municipal solid waste. The results demonstrated that the tool has a simple, easily applicable, and comprehensible layout, capable of estimating the daily and annual energy generated through mass burning according to different percentages of combustible and/or organic categories present in municipal solid waste (MSW). Moreover, the tool can be applied and adapted to any municipality, respecting the specific characteristics and particularities of each local context.

Keywords: *Municipal Solid Waste; Management toll; Thermochemical process; Energy Recovery, mass burning*

INTRODUCTION

Various governmental directives and policies worldwide have encouraged the energy recovery of several wastes classes, especially MSW [1,2,3]. In Brazil, the preference for

thermochemical or biochemical recovery over landfilling of MSW is promoted by the National Solid Waste Policy (PNRS) [4]. However, landfilling remains the primary method of final disposal of MSW in Brazil [5].

Nevertheless, there is still a shortage of specialized professionals in waste management within municipalities, and the generation and management of MSW should occur effectively in all municipalities, whether small or large, as large quantities of waste are generated daily in all Brazilian municipalities, with an average of 0.98kg/cap.day [5]. However, the lack of a management structure for waste planning greatly hinders its integrated management [6].

Waste management tools can assist decision-makers in determining the best technological pathways and the amount of energy available in waste based on the quantity and type of categories present in MSW. However, many of the tools currently available are difficult to employ, either because they require prior knowledge of programming or because they involve very specific environmental concepts, making them difficult to apply by most municipalities. Since it is crucial for all municipalities to have an understanding of the potential technological pathways and wastes energy potential to meet the goals and targets set by recent policies and directives [2,4,3], the development of a simple and easily applicable tool could effectively contribute to better energy recovery from MSW in different cities.

Current literature features tools that are difficult to apply, requiring either prior programming knowledge or environmental/sanitation professionals to understand technical terms. Simultaneously, there is a significant need for Brazilian municipalities (and others worldwide) to estimate the energy potential of their waste so that informed decisions can be made regarding technological pathways aimed at energy recovery from waste.

Several calculators have been developed worldwide to estimate the energy potential of municipal solid waste (MSW). However, these tools often present specific complexities in data entry for the end user, particularly for municipal managers, who may not possess in-depth knowledge in the energy or environmental field [7,8]. The objective of the present study was to develop an easy-to-use and intuitive tool with

Microsoft Excel to assist municipal managers in estimating the amount of energy to be generated through the application of mass burning of mixed MSW based on the gravimetric data of their municipal solid waste.

METODOLOGY

Using Microsoft Excel, the calculator was programmed through simple calculations entered directly into the cells, as well as by programming other cells using VBA (Visual Basic for Applications) for Windows, due to the need to include various conditions and constraints that could not be addressed using simple cell formulas. The calculation tool named "UFABC 3.0 MSW calculator" was structured by separating the input information and calculations into five groups: Two groups are provided for the user to input data and select configurations of their MSW management process (Groups 1 and 2), and three groups are dedicated to automated calculations performed by the calculator (Groups 3 - 6).

Group 1) Information about MSW: Amount of MSW generated, gravimetric composition.

Group 2) Types of collection (mixed, selective collection for recyclables, and selective collection for organics), mass burning and landfilling process settings, and sorting configurations [9,10,11].

Group 3) Automatic calculations of the quantity of each category present after the sorting processes and in their rejects.

Group 4) Automated calculations of the gravimetric composition of the waste directed to mass burning and landfilling.

Group 5) Automated calculations for the mass burning, such as: lower heating value (LHV); total daily and annual energy generated from MSW mass burning; amount of metals recovered from the ashes; percentage of ash directed to landfilling and mass of waste lost during the combustion process [12,13,14,15].

Group 6) Automated calculations for the landfilling process: estimation of the amount of fuel (methane) or electricity generated (according to the selected configuration) on a daily and annual basis, as well as the amount of methane to be flared per day and per year.

It is important to emphasize that the calculations related to the sorting stage were performed based on efficiency percentages for each type of MSW collected (mixed or recyclables) entering a specific process. Furthermore, the Low Heating Value was estimated using the model developed by Drudi, which calculates the heating value of MSW based on its gravimetric composition (percentages of plastics, paper, organics, etc.). Drudi's model [14] was developed for the city of Santo André (Brazil).

In addition, at the sanitary landfill stage, the calculator enables verification of the MSW composition directed to landfill according to the user's previous selections in the sorting stage. An example of the landfilled waste composition is shown in Table 1. Methane generation in the landfill is calculated using the IPCC's model [16], while the conversion of landfill gas (methane) into electricity is also presented in Table 2. The IPCC model is shown in Equations 1, 2, 3 and 4.

$$Q_{CH_4} = \frac{m_{MSW} * MSW_f * L_0}{\rho_{CH_4}} \quad \text{Equation 1}$$

$$L_0 = MCF * DOC * DOC_f * F * \frac{12}{16} \quad \text{Equation 2}$$

$$DOC = \sum GC * DOC_{region} \quad \text{Equation 3}$$

$$DOC_f = (0.014 * T) * 0.28 \quad \text{Equation 4}$$

Where:

Q_{CH_4} : Annual methane generation volume [m³ CH₄/year]

m_{MSW} : Mass of MSW generated per year [t/year]

MSW_f : Fraction of MSW disposed of in the landfill [%]

ρ_{CH_4} : Methane density [kg/m³]

L_0 : Methane generation potential of MSW [kg CH₄/kg MSW]

MCF : Methane correction factor [%]

DOC : Degradable organic carbon [kg C/kg MSW]

DOC_f : Fraction of degradable organic carbon dissimilated [%]

F : Methane fraction by volume in landfill biogas [%]

$\frac{16}{12}$: Carbon-to-methane conversion factor [kg CH₄/kg C]

GC : Gravimetric composition fraction of the waste category

DOC_{region} : Degradable organic carbon content of the category according to IPCC (1996)

T : Temperature in the anaerobic zone [°C]

Subsequently, the tool was applied using data of MSW from the city of Santo André-SP/Brazil (the amount of MSW generated, the number of inhabitants, and the gravimetric composition of MSW, among other parameters) provided by [17]. By contrast, the data related to sorting and selective collection were assumed, as they were based on a hypothetical scenario.

RESULTS AND DISCUSSION

The developed calculation tool provides the user with an easy-to-use interface in Group 1, where they enter data related to the municipal solid waste (MSW) of their city. In the current study, it was applied the information from the city of Santo André, SP, Brazil.

After the waste data are entered, it is possible to define, in a simplified manner, the types of collection to be considered (mixed, selective collection for recyclables, and selective collection for organics), together with the mass burning and landfilling process settings and the sorting configurations. The configurations were adopted with particular emphasis on the use of MSW for energy generation through the mass burning process. Standard values for sorting process efficiencies were applied, as described in Item 2 – Methodology.

After completing the data entry for Groups 1 and 2, the calculator automatically performed the calculations corresponding to Groups 3, 4, 5, and 6. Group 3 presents the amounts of sorted waste and rejects for each of the three sorting methods (mechanized sorting of mixed waste, mechanized sorting of recyclables, and manual sorting of recyclables). Unlike other calculators available in the literature [7,8], the present tool performs an extremely detailed mass balance, allowing the user to be fully aware of the composition of the waste entering the mass burning reactor as well as the waste entering the sanitary landfill cells (Tabel 1). It is important to highlight that the composition of the landfilled waste includes cells automated through VBA. The use of VBA-automated cells was primarily necessary for mass balance calculations due to the multiple sorting processes and the possibility of selecting different technological routes for each sorted waste fraction and the residues from these processes.

Tabel 2 - Data Group 4: automated calculations of the exact gravimetric compositions of the waste entering the incineration reactor and the sanitary landfill cells in an integrated manner

MSW Category	Composition of waste sent to mass burning (t/day) (%)		Composition of waste sent to landfilling (t/day) (%)	
Food	44.2	23.1	111.2	32.0
Garden C pruning	6.3	3.3	15.7	4.5
Paper C Cardboard	13.8	7.2	40.9	11.8
Plastic film	9.2	4.8	27.1	7.8
Flexible plastic	0.0	0.0	0.0	0.0
Rigid plastic	9.2	4.8	27.1	7.8
Glass	1.2	0.6	3.4	1.0
Ferrous metals	0.8	0.4	2.3	0.7
Non-ferrous metals	0.9	0.5	2.7	0.8
Styrofoam	0.0	0.0	0.0	0.0
Rubber	0.8	0.4	1.2	0.4
Textiles	15.9	8.3	23.9	6.9
Diapers C absorbents	7.0	3.6	10.4	3.0
Wood	2.5	1.3	3.7	1.1
Construction C demolition waste	0.0	0.0	0.0	0.0
Hazardous	0.0	0.0	0.0	0.0
Others	51.9	27.1	77.9	22.4
Incineration ash	27.8	14.5		
Total	191.4	100.0	347.6	100.0

Finally, Data Group 5 displays the automated calculations of energy generated from the mass burning process, while Data Group 6 provides the calculated amounts of energy produced from landfill gas utilization (Table 2). Other data, such as the mass lost by combustion, quantities of metals recovered through mass burning, as well as mass burning ash sent to the sanitary landfill (already accounted for in the landfill composition), are also account.

Table 3 - Data Groups 5 and 6: automated calculations of the total waste sent for mass burning and landfiling, the final energy generated (annually), quantities of metals recovered, and incineration ash sent to the landfill

Mass Burning			Landfilling		
	Value	Unit		Value	Unit
Total mass sent to incineration	347.6	t/day	Total mass sent to sanitary landfill	191.4	t/day
Lower Heating Value (LHV) of all waste sent to incineration	6.1	MJ/kg	Volume of methane (CH ₄) generated naturally by landfill	2,080.2	m ³ CH ₄ /day
Total available electric energy	42,147,349.1	kWh/year	Total available electric energy	1,818,546.1	kWh/year
Bottom ash for reuse	41.7	t/day	Methane to be flared	138,538.2	m ³ CH ₄ /year
Bottom ash (total for landfiling)	27.8	t/day			
Ferrous metals recovered from ash	0.4	t/day			
Non-ferrous metals recovered from ash	0.4	t/day			
Mass lost by combustion	277.3	t/day			

The study conducted by [18] provides estimates of the Lower Heating Value (LHV) of MSW in the municipality of Caieiras/SP, which belongs to the same metropolitan region of São Paulo as the municipality of Santo André. The authors applied several types of models—elemental, proximate, and gravimetric—and obtained, through these approaches, an LHV range between 3.79 and 8.20 J/g of MSW, both with and without the separation of recyclables. The value reported by Dridi's model (6.1 J/g) from the UFABC 3.0 MSW calculator, is very close to the mean between the maximum and

minimum values determined in that study (6.0 J/g), which may suggest robustness in the construction of Dridi's model [14].

Calculators available in the literature, such as [7,8] provide separate areas for user data entry and the presentation of results across different tabs. In contrast, the UFABC 3.0 MSW calculator consolidates all data entry, as well as the adjustment of each technological route configuration, in a single location. It also presents all information related to energy estimation, applied models, and conversion factors in the same place, allowing users to better understand the results and the conditions applied to achieve them.

Furthermore, other calculators in the literature do not determine the gravimetric composition of waste to be sent to landfills and mass burning in such an integrated manner. The gravimetric composition of waste in these processes is specifically determined by the waste and residue destination settings during the initial input phase and is thus fully presented. This feature can greatly assist integrated MSW management in municipal administrations, especially those lacking qualified and specialized personnel in the energy and environmental fields, particularly during pre-project phases and energy estimation stages.

CONCLUSION

The UFABC 3.0 MSW calculator proves to be highly user-friendly (with clear areas for data entry and result visualization), as well as providing direct and informative explanations regarding the values presented. The straightforward approach to using the tool proved effective for calculating the Lower Heating Value (LHV) and the energy generated through the mass burning process of different MSW configurations, as determined by the user through simple settings for collection types and process efficiencies.

The section concerning mass burning, developed using the Drudi model [14] coherently calculated the calorific values based on the input data provided by Orium. This confirms the validity of the model for calculating LHV(w) (lower heating value on a wet basis) for the context of the city of Santo André, as well as for other Brazilian

municipalities with gravimetric composition characteristics similar to those of Santo André.

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DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author(s) used ChatGPT in order to improve readability and language clarity. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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STABILITY AND EFFICIENCY OF AN UPFLOW ANAEROBIC SLUDGE BLANKET (UASB) REACTOR UNDER PROGRESSIVE ORGANIC LOAD OF CORN VINASSE

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ABSTRACT

The *Upflow Anaerobic Sludge Blanket* (UASB) reactor is an efficient process for the removal of organic load and has been employed in the treatment of effluents from ethanol plants. This study aimed to evaluate the stability and efficiency of UASB under progressively increasing organic loads from corn vinasse. The methodology involved monitoring the physicochemical properties: temperature, pH, alkalinity, chemical oxygen demand (COD), and five-day biochemical oxygen demand (BOD₅) - in the reactor operated under different concentrations (Period I = 2.500mg/L; Period II = 5.000mg/L; Period III = 10.000mg/L; Period IV = 20.000mg/L; Period V = 40.000mg/L; and Period VI = 60.000mg/L, Within a period of 225 days. According to the results obtained, the influent exhibited an average temperature of 24.6 °C, while the treated effluent reached 24.8 °C, remaining within the mesophilic range, which promotes microbial growth and process stability. The pH values stayed within the range of 6.5 to 7.1, conditions conducive to methanogenic bacteria. The ratio of partial alkalinity to intermediate alkalinity averaged 0.42; however, this relationship did not adversely affect the treatment process. Removal efficiencies for COD ranged from 34% to 91%. Regarding BOD₅, values varied from 43.42% to 94%. Thus, the UASB reactor demonstrated high efficiency in removing BOD₅ and COD when subjected to a gradual increase in organic load from corn vinasse. Despite the substantial removal of BOD₅, the effluent quality post-treatment remains above legislative limits, indicating the need for additional post-treatment processes.

Keywords: Etanol, flex plant, industrial effluent, corn vinasse, anaerobic treatment.

INTRODUCTION

The demand for ethanol in Brazil has shown significant growth in recent years. To meet this increase, several production plants have undergone a modernization process, resulting in the implementation of the "Flex Plants" concept. These facilities can process sugarcane during the harvest season and corn during the off-season, ensuring greater efficiency and continuity in ethanol production [1].

During the ethanol distillation process, vinasse is produced, and its quantity and composition are influenced by the raw material used (sugarcane or corn) and the production method employed at the plant [2,3].

Most of the available studies address vinasse from sugarcane [4,5]. However, despite its similarity to sugarcane vinasse in terms of high organic load, corn vinasse has some differences, such as a less intense color, a lower concentration of solids and nutrients, and higher acidity [3,6].

In Brazil, vinasse is often discarded raw on the soil to irrigate and fertilize crops [7]. However, the improper use of this practice can lead to environmental problems, such as the contamination of water resources and soil, salinization, nutrient imbalance, and an increase in phytotoxicity and unpleasant odor [8,9].

In this context, due to the high organic matter content in vinasse, anaerobic treatment proves to be particularly attractive, especially when compared to aerobic treatment, which demands a higher operating cost due to high electricity usage and a large production of sludge mass [10].

On the other hand, in anaerobic digestion, a significant portion of the COD can be converted into biogas, in addition to resulting in low sludge production and requiring a smaller input of nutrients for effluent treatment, compared to aerobic processes [11,12].

UASB-type anaerobic reactors are one of the most promising options due to their operational simplicity, increased system stability and flexibility, low cost, and ability to generate biogas as a byproduct—a biofuel produced from a renewable energy source [13,14,15].

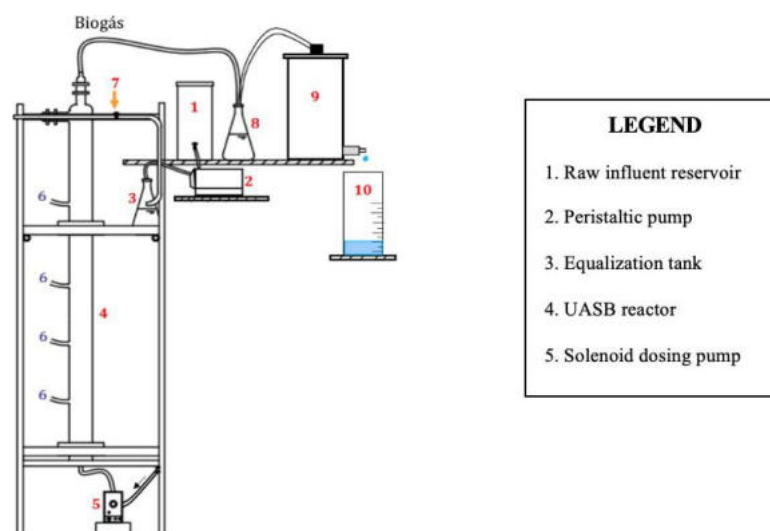
Several studies have investigated the behavior of UASB reactors under different operating conditions, especially concerning the progressive increase of the organic load for the acclimatization and development of the biomass community in the reactor [16,17]. The goal is to develop a sludge blanket adapted to the type of effluent to be treated, which aims to ensure high efficiency in the degradation of organic matter, promoting process stability and the operability of the treatment system [18].

Within this scenario, the aim of this work is to evaluate the performance of a pilot-scale UASB reactor, subjected to a gradual increase in the organic load from corn vinasse. To this end, variables such as the efficiency in removing BOD₅ and COD, as well as the process stability over the operating period, will be analyzed.

MATERIAL AND METHODS

The corn vinasse was collected from a Flex Plant in the State of Mato Grosso, Brazil. The experiment was conducted at the Water and Waste Physicochemical Analysis Laboratory (LAFQAR) of the Federal University of Mato Grosso, located in the municipality of Cuiabá, the capital of Mato Grosso, Brazil. The UASB reactor had a working volume of 0.010 m³, with a circular shape, made of borosilicate glass, measuring 0.10 m in diameter and a total height of 1.83 m (Figure 01).

Figure 01: Schematic of the pilot UASB reactor.



Source: Prepared by the authors (2024)

The reservoir designated for the raw corn vinasse influent had a capacity of 0,010 m³ and was constructed of PVC. The effluent was pumped by a Heidolph peristaltic pump, Model Pump drive PD5002, to an equalization tank.

The equalization tank served functions of flow stabilization, effluent dilution, hydraulic retention time (HRT) control, and volumetric organic load (VOL) control [19]. Subsequently, the effluent was pumped upward to the UASB reactor using an Injetronic dosing pump, Model V-1.5/P4.

In the experiment, the recirculation of effluent in the UASB reactor aimed to improve the degradation of organic matter, increase the hydraulic retention time, stabilize the anaerobic process, optimize sedimentation, and control pH and nutrients. The experiment was conducted at room temperature, without temperature control [20, 21].

Biogas collection was performed from the top of the reactor; the gases then passed through a water seal, which prevented their return to the reactor, avoiding interruption of the digestion process and operational problems [22].

The biogas volume was subsequently quantified using the Mariotte technique, also known as Boyle's law, which consists of measuring the volume of a gas at constant temperature while varying the applied pressure, allowing the determination of the inverse relationship between pressure and volume [23].

The analyzed parameters of the raw and treated effluent included temperature, intermediate alkalinity (IA) and partial alkalinity (PA), pH, chemical oxygen demand (COD), and biochemical oxygen demand over five days (BOD₅) (Table 01) [23].

The system was started up in a closed loop, using inoculated anaerobic sludge (seeding sludge) from the UASB reactor of a Domestic Sewage Treatment Plant. For the start-up, a volume of approximately 10% sludge was dosed relative to the experimental reactor's volume. Over one month, different vinasse COD concentrations (500 mg/L, 1000 mg/L, 1500 mg/L, and 2000 mg/L) were applied to the biomass for acclimatization. After this period, the system began to operate continuously, with its initial phase, called phase 1, at a vinasse concentration of 2,500 mg/L.

Table 01: Parameters, methodology, and equipment

Parameter	Methodology	Equipment
Temperature	Electrometric method.	Portable pH meter Sension+
Intermediate Alkalinity (IA) and Partial Alkalinity (PA)	Potentiometric titration method	Portable pH meter Sension+ Manual titrator
pH	Standard Methods for the Examination of Water and Wastewater, 22nd Edition, 2012. Method 4500 B.	Portable pH Sension+
DBO ₅	Standard Methods for the Examination of Water and Wastewater, 22nd Edition, 2012. Method 5210 B.	BOD ₅ incubator
COD	Standard Methods for the Examination of Water and Wastewater, 22nd Edition, 2012. Method 5220 B.	COD digester

Source: Prepared by the authors (2024).

To evaluate the removal efficiency of BOD₅ and COD, Equation 01 was used:

$$\text{Efficiency (\%)} = (S_0 - S) / S_0 * 100 \quad \text{Eq. 01}$$

Where:

E = removal efficiency

S₀ = initial concentration (mg/L)

S = final concentration (mg/L)

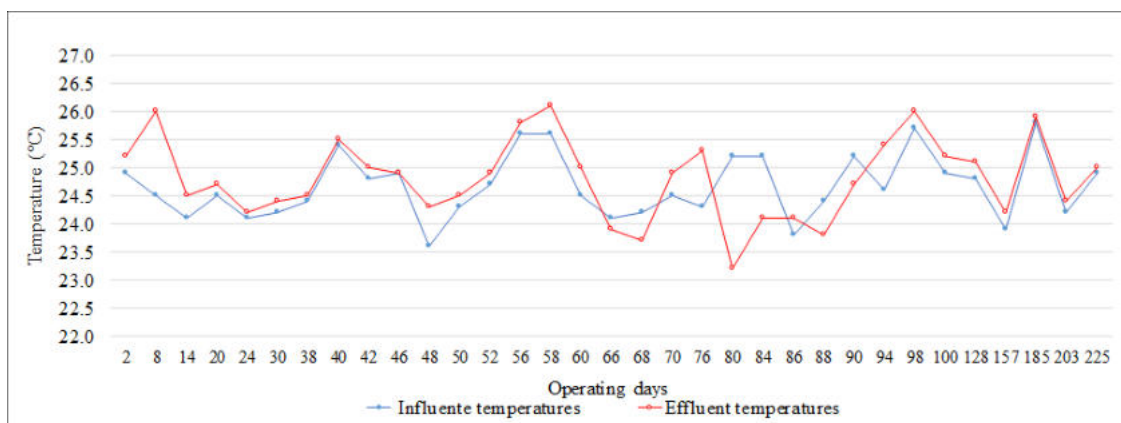
RESULTS AND DISCUSSION

Temperature

Figure 02 shows the temperatures of the influent and treated effluent in the UASB reactor throughout the study. The influent presented an average temperature of 24.6 °C, with a maximum of 25.6 °C and a minimum of 23.6 °C. The average

temperature of the treated effluent was 24.8 °C, with a maximum of 26.1 °C and a minimum of 23.2 °C.

Figure 02: Temperature monitoring of the influent and treated effluent in the UASB reactor.



Source: Prepared by the authors (2024).

The temperature in the UASB reactor remained within the mesophilic range, with gradual variations that ensured system stability, favoring microbial growth and preventing process failure [23]. Temperature not only influences the metabolic activity of microbial communities but also affects biochemical reactions, gas transfer rates, and the characteristics of biological solids. UASB reactors tend to exhibit higher efficiency when operated in warm climate regions [24] .

pH, Intermediate Alkalinity, and Partial Alkalinity

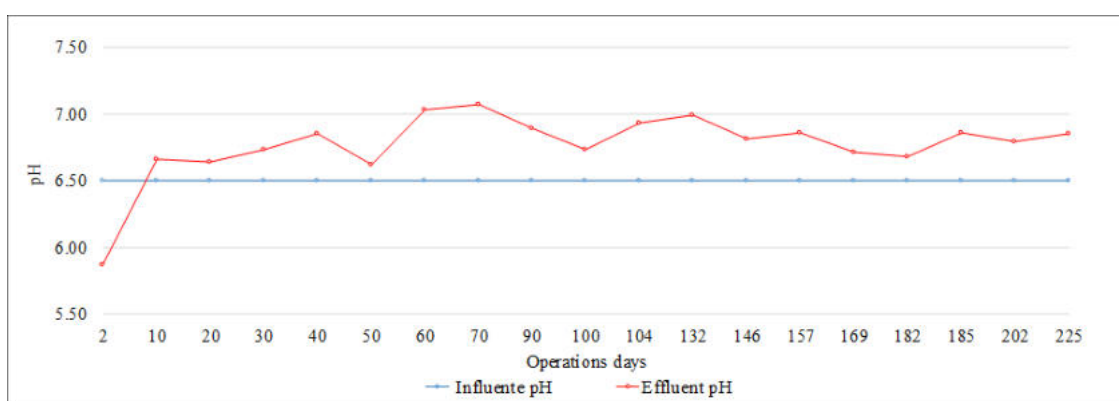
The pH of the raw effluent ranged from 3.5 to 4.3, requiring periodic adjustments using a NaOH solution in the reservoir to maintain the pH and neutralize the acidity. It was then transferred to an equalization tank using a dosing pump [25]. Figure 03 presents the pH variations of the influent and effluent throughout the experiment, remaining within the optimal range for the activity and stability of methanogenic bacteria, between 6.5 and 7.5 [26].

It was observed that the values remained within the recommended range for the growth and maintenance of methanogenic bacteria activity (pH between 6.5 and 7.1). Therefore, pH values close to the neutral range generally do not pose a problem in

anaerobic treatment systems, as the carbonic system, responsible for the buffering capacity of the medium, predominates in these systems.

During monitoring, the pH of the reactor effluent remained consistently higher than that of the influent, demonstrating the presence and effective action of the buffering mechanism provided by alkalinity. This increase in effluent pH indicates that the anaerobic process has a good capacity to maintain chemical conditions favorable to microbial activity, contributing to greater stability of the treatment system. This buffering property is essential because it helps prevent pH drops that could compromise process efficiency, ensuring safer and more reliable operation over time.

Figure 03: pH variation of the influent and effluent during the experiment



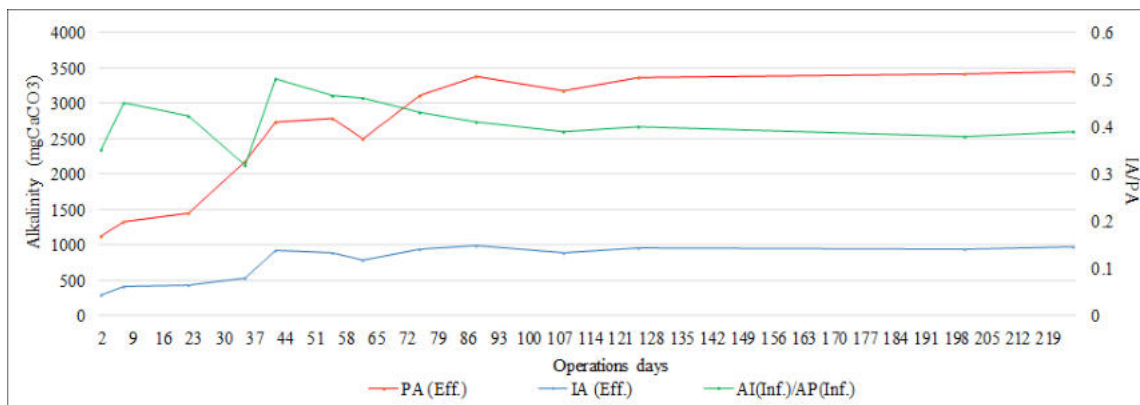
Source: Prepared by the authors (2024)

The effluent showed low variation, demonstrating good buffering capacity, which can be understood as the medium's ability to neutralize acids, or in other words, to resist pH variations. This reveals the system's stability and indicates that it is prone to lower monitoring costs. According to CONAMA Resolution 430 of 2011, for effluent discharge, the pH must be between 5.0 and 9.0 [27].

According to the results, the ratio of Intermediate Alkalinity to Partial Alkalinity (IA/PA) was higher than 0.3 in the treated effluent (Figure 04). According to Ripley, Boyle and Converse [28], values above 0.3 may indicate disturbances in the anaerobic digestion process. However, Foresti [29] states that it is possible to maintain stability in anaerobic digestion even with IA/PA values above 0.3, emphasizing the need for case-

specific evaluations for each reactor and wastewater type. In this study, the UASB reactor showed no signs of physical-chemical or operational imbalances, demonstrating good buffering capacity.

Figure 04: IA/PA Relation



Source: Prepared by the authors (2024)

Regarding the relationship between Partial Alkalinity and Intermediate Alkalinity, the observed values were above 0.3. This ratio is an important indicator of the stability of the anaerobic treatment system, as high values suggest a good buffering capacity of the medium, which helps to neutralize pH variations and maintain an environment favorable for microbiological activities. Although this ratio was above 0.3, which in other circumstances might indicate some concern, in this specific case, it did not negatively affect the reactor's operation. On the contrary, the system remained stable throughout its operation.

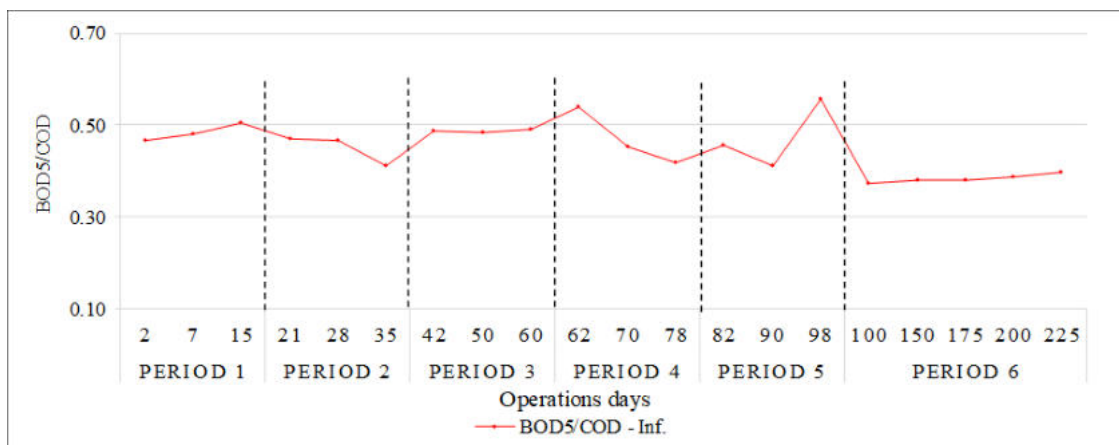
BOD₅/COD Relation

The average BOD₅/COD ratio was 0.54, within the acceptable range (0.4 to 0.6), indicating a predominance of biodegradable matter present in the influent. This characteristic facilitates the biological treatment process of vinasse [30] (Figure 05).

The average BOD₅/COD ratio of approximately 50% indicates a high potential for the biodegradation of organic matter, which facilitates the choice of efficient biological processes. This ratio provides a fundamental metric for sizing and optimizing

treatment systems, ensuring greater efficiency. Furthermore, it highlights the compatibility of corn vinasse with anaerobic treatment technologies.

Figure 05: BOD₅/COD Relation in the influent.



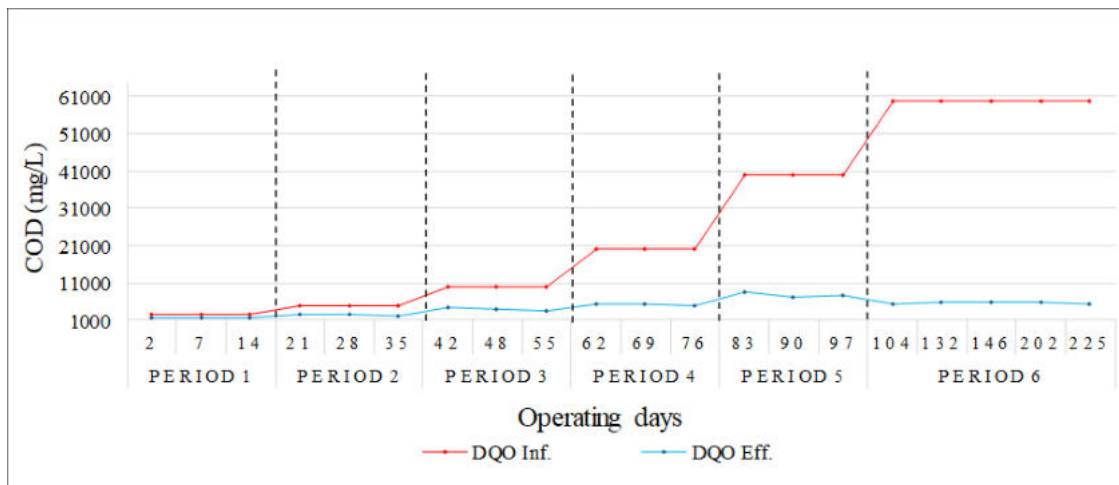
Source: Prepared by the authors (2024)

COD and BOD₅

The UASB reactor showed remarkable efficiency in removing BOD₅ and COD concentrations throughout the entire operational period. This high efficiency was especially evident when the system was subjected to a gradual increase in the corn vinasse load at the end of the 225-day experiment. This indicates that the reactor was capable of effectively handling increments in the substrate load without significant performance loss. The reactor's ability to maintain low BOD₅ and COD levels even with increasing loads suggests a good adaptation of the anaerobic biofilm and stable operation, giving the system important robustness for practical applications in treating liquid waste from alcohol distillation processes, such as corn winemaking.

During the operation of the UASB reactor, the concentration of the vinasse influent was gradually increased. Figure 06 shows the removal efficiencies, which varied as follows: Period I = 34%; Period II = 50%; Period III = 61%; Period IV = 74%; Period V = 81%, and Period VI = 91%. According to the results, it was observed that the reactor's efficiency increased as the applied COD concentrations rose.

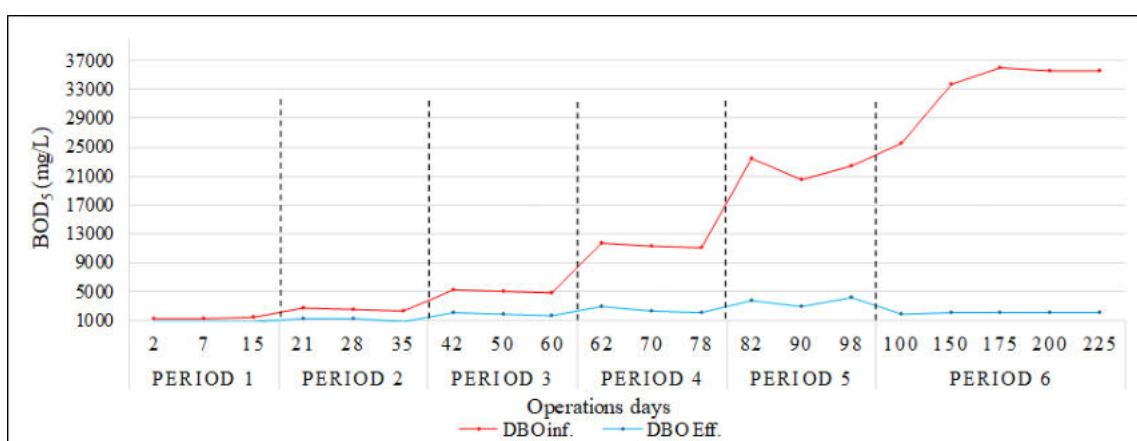
Figure 06: COD of the influent and effluent during the experimental.



Source: Prepared by the authors (2024)

After Period 2, the COD removal efficiencies fell within the range reported by Barros, Duda e Oliveira [10], who operated UASB reactors using sugarcane vinasse and obtained average COD removal efficiencies between 49% and 82%. Similar to COD, the biochemical oxygen demand (BOD₅) removal efficiency of the UASB reactor showed a gradual increase. In all periods, the reactor presented BOD₅ removal efficiencies, Period I = 43%; Period II = 58%; Period III = 68%; Period IV = 81%; Period V = 86%, and Period VI = 94%, which are considered satisfactory according to Chernicharo [22] (Figure 07).

Figure 07: BOD₅ of the influent and effluent during the experimental



Source: Prepared by the authors (2024)

The removal efficiencies of BOD₅ showed variations oscillating between 43.42% and 94%. Thus, the UASB reactor demonstrated the biomass's capacity to adapt to corn

vinasse subjected to a gradual increase in organic load. The BOD₅ values, in turn, are above the limits established by CONAMA Resolution No. 430, regardless of the water body classification or the effluent discharge standard, indicating the need for post-treatment [31]. However, despite the excellent results in organic matter removal, it's important to highlight that the treatment system alone is not sufficient to ensure compliance with environmental standards for effluent discharge into water bodies. Therefore, the installation of an additional post-treatment system is recommended, such as filtration, denitrification, or other polishing processes, which can complement the UASB reactor's efficiency in removing residual contaminants and ensure that the released effluents meet the quality standards required by environmental agencies.

CONCLUSION

The UASB reactor demonstrated high efficiency in removing BOD₅ and COD concentrations when subjected to a gradual increase in the corn vinasse load, especially at the end of the experiment, which was associated with the biomass's acclimatization to the vinasse. This adaptation was fundamental for optimizing the biological degradation processes, improving the system's operational stability. The implementation of progressive feeding strategies allowed for the avoidance of initial overloads, ensuring an efficient response from the UASB reactor. Thus, the study reinforces the viability of using UASB reactors to treat liquid waste from corn ethanol production, promoting environmental sustainability and efficiency in treating this effluent.

The Partial Alkalinity/Intermediate Alkalinity ratio showed values above 0.3, but this did not negatively affect the treatment process. The reactor effluent pH consistently remained higher than that of the influent, demonstrating the buffering capacity of the anaerobic process provided by alkalinity.

It is recommended that, in the future, in-depth studies be conducted to optimize the post-treatment of the UASB reactor. Research in this area can help improve treatment efficiency, ensuring pollutant reduction and compliance with environmental standards. Furthermore, it is essential to investigate the detailed characterization of

corn vinasse, including an analysis of its quantity and quality, to better understand its potential for proper use or disposal.

Another important aspect to explore is the study of the volumetric organic loading rate applied to the UASB reactor. Understanding this variable will allow for better adjustment of operational parameters, increasing the efficiency of the treatment process and promoting more sustainable management of the generated waste. Thus, these future studies can provide valuable information for improving agro-industrial waste treatment and management technologies, contributing to a more sustainable and environmentally responsible sector.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Tadeu José Figueiredo: Writing original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. Aldecy de Almeida Santos: Writing review C editing, Investigation, Formal analysis, Data curation. Álvaro Antonio de Magalhães Gaspar Monteiro: Writing – review C editing, Supervision, Project administration, Funding acquisition,

DECLARATION OF GENERATIVE AI IN SCIENTIFIC WRITING

During the preparation of this work the authors used GPT-4 in order to improve readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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STUDY OF THE FUSIBILITY OF SOLID BIOFUEL ASHES

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ABSTRACT

Energy generation from renewable resources has grown in recent years due to the need to reduce the use of petroleum derivatives for economic and environmental reasons. Solid biofuels have proven to be an alternative for both electricity production and the transportation sector. To efficiently utilize these materials in their various applications, their characteristics must be understood. This study aims to map the melting temperature of ash in biomass samples. The methodology applied was based on the physical-chemical analysis of sugarcane bagasse and wood chips samples, using standardized methods. These materials were selected because they are the most widely used as a sustainable energy source. Ash is a solid residue formed in boilers during the combustion of materials and must have suitable properties, such as a melting temperature compatible with the process. The melting characteristics of ash are directly related to its chemical composition, since the presence of certain elements can impact the melting behavior of materials. A lack of information on this parameter can result in problems such as incrustations and unexpected interruptions in generation unit operations. Despite the importance of this topic, there is still a lack of scientific literature on the fusibility of ash from solid biofuels.

Keywords: Boiler ash; Biomass; Fusibility; Biofuels

INTRODUCTION

In recent decades, global concerns about climate change, volatile oil prices, and the growing risk of fossil fuel shortages have driven the search for energy sources considered clean and renewable [1]. In this context, biomass stands out as a strategic energy resource due to its abundant availability, ability to mitigate greenhouse gas emissions, and flexibility of use in various forms, whether for generating heat, electricity, or producing liquid and gaseous fuels. Driven by international commitments such as the Paris Agreement and the Sustainable Development Goals

(SDGs), solid biomass emerges as a strategic alternative not only because of its widespread availability in different regions of the world but also because of its ability to contribute to reducing greenhouse gas (GHG) emissions compared to traditional fossil fuels. In addition to its potential for environmental mitigation, biomass also plays a key role in diversifying the energy matrix, reducing dependence on petroleum derivatives and increasing energy security in developing countries [2].

The share of biomass in the global energy matrix varies significantly, with industrialized countries accounting for less than 10%, while in developing nations this share can reach 20% to 30%, and even 90% in some countries with a high dependence on renewable sources [3]. Modern technologies for converting biomass have further expanded its use, promoting greater energy efficiency and sustainability. Biomass is characterized by its versatility in energy conversion, and can be used in thermochemical processes (such as combustion, gasification, and pyrolysis) or biochemical processes (fermentation, anaerobic digestion), resulting in electrical or thermal energy, or liquid and gaseous fuels. Furthermore, biomass has the potential to be considered a clean energy source, provided its production and use are linked to sustainable management and replanting practices.

In Brazil, the potential of biomass is especially significant due to the large-scale agricultural production, which generates a variety of agro-industrial wastes that can be used for energy, such as rice husks, coffee bagasse, chestnut husks, corn straw and cobs, orange peel and bagasse, and especially sugarcane bagasse and straw [4]. Among these, sugarcane bagasse represents approximately 73% of the biomass used for energy purposes in the country, followed by firewood, charcoal, and forest residues, which together account for approximately 20% [5].

The use of sugarcane bagasse as an energy source is traditionally intended for the generation of steam and electricity in sugar and ethanol plants, with straw being increasingly used for the same purposes. However, due to transportation costs, these residues are typically consumed near the production sites. The transformation of these residues into pellets, however, opens the possibility of their commercialization on a national and international scale, expanding the use of an abundant resource with high energy potential.

Sugarcane bagasse has traditionally been used to generate the steam needed in sugar and ethanol plants, as well as to generate electricity, and straw has also been used more recently for these purposes. Due to transportation costs, bagasse and straw are primarily used locally and near sugarcane plantations. However, with the processing of these residues into pellets, their use on a national and global scale becomes a possibility, decentralizing and increasing the use of this resource, which is abundant in Brazil and has great energy potential. However, for biomass to be truly competitive, it is essential to understand and control the characteristics of its by-products. Direct combustion of biomass for energy conversion presents operational problems during combustion, which are generally associated with the fusibility of the ash formed during thermochemical conversion, causing various types of technical problems, such as those related to scale or deposits on the internal surfaces of equipment, which can cause unscheduled shutdowns in the production process and also reduce its useful life due to corrosion [6,7].

Among the properties of ash, fusibility is fundamental to the operational performance of boilers, furnaces, and other thermal systems. The formation of slag and scale can cause technical problems, such as:

- Slag formation: Ash melting can lead to the formation of slag, which can accumulate on boiler walls and reduce system efficiency.
- Corrosion: The presence of liquid phases in the ash can increase corrosion of metallic materials used in boilers and other system components.
- Reduced efficiency: Slag formation and corrosion can reduce combustion system efficiency and increase maintenance costs.
- Unscheduled shutdowns for cleaning or corrective maintenance;
- Reduced equipment lifespan

The presence of certain oxides, such as aluminum (Al_2O_3), tends to raise the melting temperature of the ash, while others, such as potassium, sodium, calcium, and magnesium, can increase its fluidity [8]

High calcium (CaO) content generally results in high melting point temperatures.

High silica (SiO_2) content can lead to melting problems, although pure SiO_2 has a very high melting point (1710°C). Interaction with other elements can form a low-melting eutectic.

Alkali metals (K, Na) and chlorine (Cl): These are known to drastically reduce the melting temperature of ash, potentially causing slagging and scale problems at lower temperatures (including below 700°C , depending on the concentration and formation of compounds such as KCl and K_2SO_4).

Despite its relevance, this topic remains underexplored in scientific publications in Brazil, especially when it comes to abundant agroindustrial residues such as sugarcane bagasse and wood chips. Therefore, this study seeks to fill this gap by providing experimental data that aid in the selection and appropriate management of solid biofuels in the energy sector.

MATERIALS AND METHODS

Sampling and preparation of materials

Five different samples of sugarcane bagasse (identified as Samples 1 to 5) and four samples of wood chips (Samples 6 to 9) were collected, supplied by different companies. The samples were obtained on different dates and locations to account for natural variability in the materials, caused by factors such as soil, climate, agricultural management, and storage conditions.

Each sample weighed approximately 350 grams, which was considered sufficient for all planned analyses. Upon receipt, the samples were dried in an oven with air circulation at $105 \pm 5^\circ\text{C}$ until a constant mass was obtained, in accordance with ISO 18134-1:2022, ensuring the elimination of surface moisture and preparing them for grinding.

The samples were then ground in a Willye knife mill until they reached a particle size of 0.595 mm.

Physicochemical Analysis

Elemental and immediate analyses were performed. The applied analyses aimed to characterize the fuels according to their most relevant parameters for use in combustion processes and to evaluate ash behavior. The methods employed were:

- Total moisture content determined based on ISO 18134-1:2022 and ISO 18134-3:2023 standards, aiming to quantify the mass of water present in the sample as received [9].
- Carbon (C), Hydrogen (H), and Nitrogen (N): determined based on ASTM D5373-21 [10], Method A, using an elemental analyzer.
- Oxygen (O): calculated by difference, according to ASTM D3176-24 [11], considering the sum of the other determined elements.
- Volatile matter and fixed carbon: volatile matter was determined according to ASTM D1762-84 (2021) [12]. Fixed carbon was obtained by difference, according to ASTM D3172-13(2021)e1 [13].
- Ash: Ash content was determined based on ASTM E1755-24 [14], by calcining the sample at 575°C, a procedure that allows the quantification of mineral residues remaining after combustion.
- Total sulfur: Determined based on ASTM D4239-18e1 [15], Method A, which allows the identification of the potential for the formation of pollutant gases such as SO₂ and also corrosive compounds in the ash.
- Calorific value (PCS and PCI): The gross calorific value (HHV) was determined by calorimetry (bomb calorimetry), according to ASTM D5865/D5865M-19 [16], on a dry and wet basis. The gross calorific value (LHV) was calculated considering the correction for hydrogen content and moisture content.

Chemical Analysis of Ash

The chemical composition of the ash was determined by inductively coupled plasma optical emission spectrometry (ICP-OES). This method allows for the precise quantification of metal oxides present, the main ones monitored being:

- SiO₂ – Silicon dioxide
- CaO – Calcium oxide
- Al₂O₃ – Aluminum oxide

- Fe_2O_3 – Iron oxide
- K_2O – Potassium oxide
- Na_2O – Sodium oxide

The selection of these oxides is based on the fact that they are primarily responsible for the ash's fusibility properties. Trace elements (such as Cl, Mg, P, or S) may be incorporated in future studies, but in this work, the main components were prioritized.

Determination of ash fusibility.

The fusibility assessment was performed based on ISO 21404/2020 [17].

Ash Preparation.

To prepare the biofuel ash, a sufficient amount of sample to produce 1g of ash was placed in a capsule and spread evenly. The capsule was transferred to an electric muffle furnace at a temperature between 230°C and 250°C, maintaining the temperature at this level for at least 180 minutes to allow volatiles to be released. The furnace temperature was then uniformly increased to 550°C $\pm$ 10°C, maintaining the temperature at this level for at least 120 minutes.

Test Specimen Preparation.

The ash obtained was moistened with ethanol, forming a paste that was inserted and pressed into a compatible mold to form a vertical cylinder with a height and diameter of 3.00 mm to 4.00 mm, with sharp edges. It was removed from the mold and allowed to dry at room temperature.

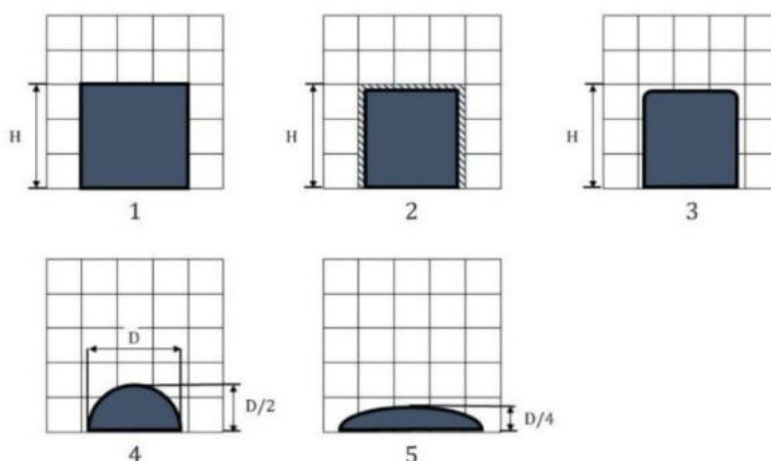
Determination of characteristic temperatures.

After preparation, the specimens were transferred to a furnace support and positioned on a zirconia plate at room temperature. They were heated at a uniform rate of 7°C/min in an oxidizing atmosphere until reaching a final temperature of 1500°C.

For some samples, the characteristic temperatures specified in the standard were not measurable due to the furnace's maximum heating capacity, thus being recorded as above 1500°C (>1500).

The evaluation method consists of visually observing the physical changes in the specimens made with the compacted ash.

Figure 1 – Phases which can occur in the ash melting process [17]



Original shape at reference temperature

SST – Shrinkage Starting Temperature

DT – Deformation Temperature

HT – Hemisphere Temperature

FT – Flow Temperature

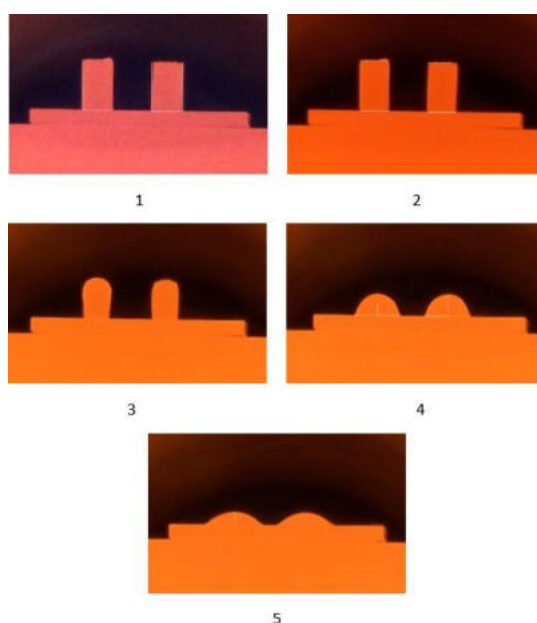
The observed characteristic temperatures were:

- SST - Shrinkage Starting Temperature: decrease in the area of the test specimen (cylinder). The temperature at which carbon dioxide and volatile hydrocarbons are released. In some cases, the start of sintering.
- DT - Deformation Temperature: the temperature at which the first signs of melting appear. Deformation of the edges or expansion of the test specimen, generally changes its cylindrical shape.

- HT - Hemisphere Temperature: the temperature at which the height of the cylinder drops to approximately half, forming a hemisphere.
- FT - Flow Temperature: the temperature at which the ash spreads over the support.

Figure 2 presents resulting from an analysis carried out on biomass, demonstrating the points evaluated.

Figure 2 – Analyzed phases of the ash fusibility process



Original shape at reference temperature

SST – Shrinkage Starting Temperature

DT – Deformation Temperature

HT – Hemisphere Temperature

FT – Flow Temperature

RESULTS AND DISCUSSION

Table 1 present the results obtained for the physical-chemical tests carried out on the sugarcane bagasse samples.

Table 1: Average values and standard deviation of the physical-chemical tests of sugarcane bagasse samples

Analysis	1	2	3	4	5
Total moisture - % mass	23,3	47,1	53,9	-	52,8
Carbon - % mass	47,9	48,6	47,6	49,0	47,4
Hydrogen - % mass	6,06	6,11	6,08	6,25	6,00
Nitrogen - % mass	0,4	0,2	0,2	0,3	0,4
Ash - % mass	2,0 ± 0,5	2,4 ± 0,6	1,8 ± 0,4	2,0 ± 0,5	4,2 ± 0,9

Table 1: Average values and standard deviation of the physical-chemical tests of sugarcane bagasse samples

Analysis	1	2	3	4	5
Volatile matter - % mass	78,6 ± 1,1	82,2 ± 1,1	-	-	-
Fixed carbon - % mass	19,4	15,4	-	-	-
Oxygen - % mass	43,64	42,69	44,32	42,35	42,10
Sulphur - % mass	< 0,1	< 0,1	< 0,1	< 0,1	< 0,1
High heat value (Dry basis)- MJ/kg	19,34 ± 0,11	18,88 ± 0,11	18,94 ± 0,11	18,98 ± 0,11	18,46 ± 0,11
Low heat value (Dry basis)- MJ/kg	18,03	17,56	17,63	17,63	17,17
High heat value (Wet basis)- MJ/kg	14,83	9,99	8,73	-	8,71
Low heat value (Wet basis)- MJ/kg	13,27	8,16	6,83	-	6,83
<i>Ash fusibility:</i>					
SST-°C	930	800	800	815	982
DT - °C	1060	1125	1120	1094	1304
HT - °C	> 1500*	1360	1230	1234	> 1500*
FT - °C	> 1500*	1420	1300	1269	> 1500*

* The furnace temperature capacity (1500 °C) was reached without it being possible to observe the occurrence.

Table 2 present the results obtained for the physical-chemical tests carried out on the Wood Chip samples.

Table 2: Average values and standard deviation of physical-chemical tests on wood chips

Analysis	6	7	8	9
Total moisture - % mass	14,5	16,6	49,9	20,9
Carbon - % mass	47,8	48,0	48,3	47,0
Hydrogen - % mass	6,11	6,15	6,01	6,06
Nitrogen - % mass	0,3	0,2	< 0,1	0,8
Ash - % mass	1,6 ± 0,4	0,5 ± 0,2	1,8 ± 0,4	3,5 ± 0,7
Volatile matter - % mass	81,4 ± 1,1	82,3 ± 1,1	81,1 ± 1,1	-

Fixed carbon - % mass	17,0	17,2	17,1	-
Oxygen - % mass	44,19	45,15	43,89	42,64
Sulphur - % mass	< 0,1	< 0,1	< 0,1	< 0,1
High heat value (Dry basis) - MJ/kg	19,53 ± 0,11	19,54 ± 0,11	19,32 ± 0,11	19,19 ± 0,11
Low heat value (Dry basis) - MJ/kg	18,21	18,21	18,02	17,88
High heat value (Wet basis) - MJ/kg	16,70	16,30	9,68	15,18
Low heat value (Wet basis) - MJ/kg	15,22	14,79	7,83	13,64
<i>Ash fusibility:</i>				
SST - °C	945	995	1210	1145
DT - °C	1265	1290	1330	1260
HT - °C	> 1500*	1335	> 1500*	> 1500*
FT - °C	> 1500*	1370	> 1500*	> 1500*

* The furnace temperature capacity (1500 °C) was reached without it being possible to observe the occurrence.

Figure 1 shows a comparison between the fusibility behavior of the ash in the analyzed samples.

Figure 1 – Ash fusibility

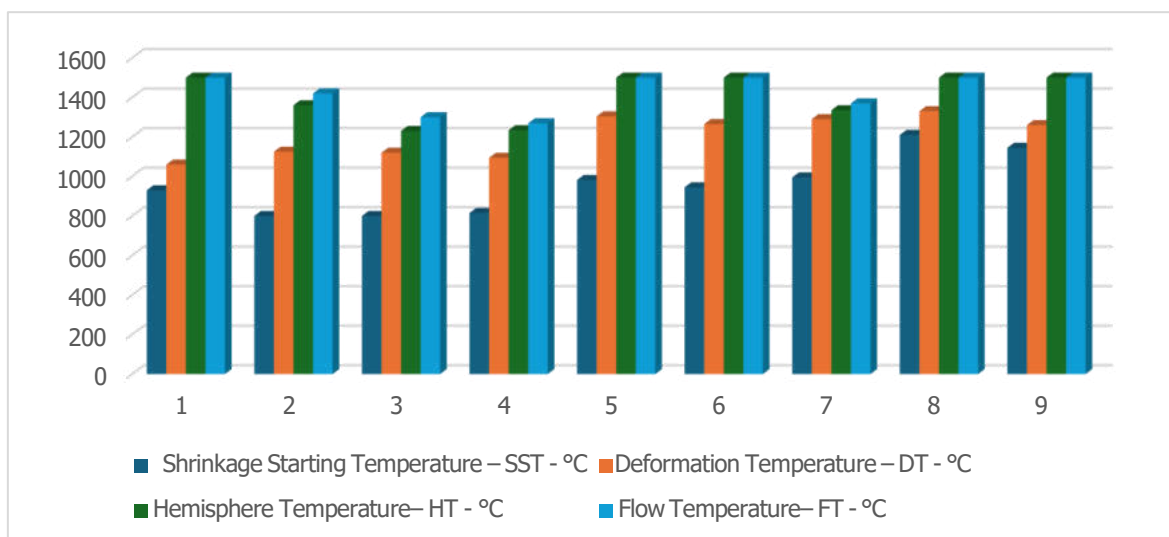


Table 3 presents the results of the chemical analysis of sugarcane bagasse.

Table 3 – Average values and standard deviation of the chemical analysis of sugarcane bagasse

Sample	1	2	3	4	5
Al ₂ O ₃ (%)	0,15 ± 0,03	1,6 ± 0,2	2,5 ± 0,1	3,0 ± 0,3	7,2 ± 1,2
CaO (%)	18 ± 2	3,0 ± 0,4	5,8 ± 0,3	5,2 ± 0,6	2,0 ± 0,3

Fe ₂ O ₃ (%)	Replica 1: 0,38, Replica 2: 0,30	1,4 ± 0,2	2,5 ± 0,1	4,3 ± 0,2	2,9 ± 0,5
K ₂ O (%)	35 ± 4	9,6 ± 1,2	7,1 ± 0,2	27 ± 2	1,6 ± 0,3
NaO ₂ (%)	0,43 ± 0,09	0,22 ± 0,03	0,42 ± 0,02	1,2 ± 0,2	0,065 ± 0,011
SiO ₂ (%)	< 1,3	Replica 1: 100, Replica 2: 82	64 ± 4	25 ± 2	80 ± 13

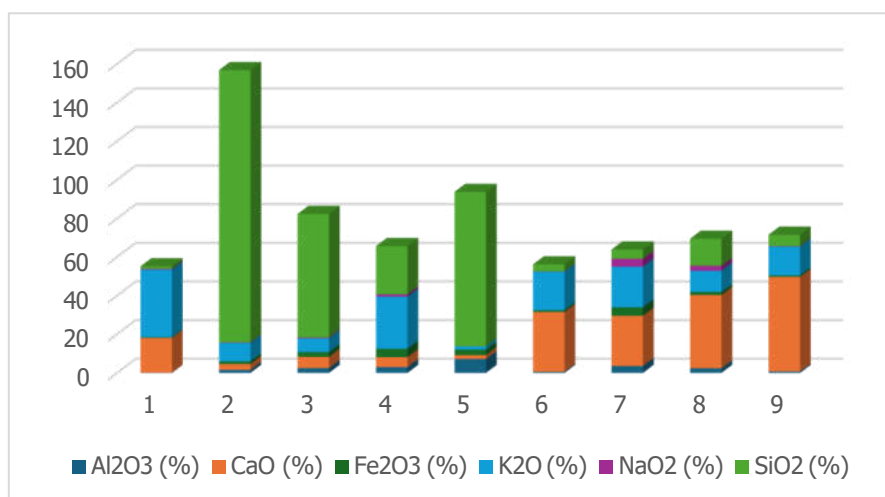
Table 4 presents the results of the chemical analysis of Wood Chips.

Table 4 – Average values and standard deviation of the chemical analysis of wood chips

Sample	6	7	8	9
Al ₂ O ₃ (%)	0,53 ± 0,05	Replica 1: 3,9, Replica 2: 3,3	2,4 ± 0,3	0,73 ± 0,02
CaO (%)	Replica 1: 33, Replica 2: 28	26 ± 4	38 ± 4	49 ± 8
Fe ₂ O ₃ (%)	0,94 ± 0,12	4,4 ± 0,7	1,5 ± 0,3	0,74 ± 0,03
K ₂ O (%)	Replica 1: 21 Replica 2: 18	21 ± 5	11 ± 1	15 ± 2
NaO ₂ (%)	< 0,14	4,1 ± 1,0	2,6 ± 0,2	0,21 ± 0,01
SiO ₂ (%)	3,6 ± 0,1	Replica 1: 5,4, Replica 2: 4,2	14 ± 1	5,9 ± 0,2

Figure 2 presents the composition of the elements in the samples.

Figure 2 – Chemical Analysis



The physicochemical results of the sugarcane bagasse and wood chip samples showed significant variations, reflecting the differences in the composition of the materials and their origins.

The sugarcane bagasse samples presented moisture contents ranging from 23.3% to 53.9%, with total carbon content around 47% to 49% and volatile matter above 78%. The ash content ranged from 1.8% to 4.2%, while the net calorific value on a dry basis ranged from 18.46 to 19.34 MJ/kg. These characteristics confirm the energy potential of bagasse as a solid fuel, but its high moisture content can impair combustion efficiency.

The wood chip samples presented moisture content between 14.5% and 49.9%, similar carbon contents (47% to 48%), ash between 0.5% and 3.5%, and slightly higher calorific value (19.19 to 19.54 MJ/kg).

In general, samples with high SiO_2 and CaO contents showed low fusibility at temperatures above 1500 °C. This is the case for samples 1, 6, 8, and 9, all classified as having low fusibility. The majority presence of SiO_2 (49% in sample 9) and CaO (38% in sample 8) demonstrates that these oxides act as matrix stabilizers, hindering fusion at lower temperatures. This behavior is consistent with the literature, which associates high SiO_2 contents with greater refractoriness of ceramic materials. This indicates high resistance to melting, a desirable characteristic to prevent scale and deposits in boilers. [18]

In contrast, it is observed that sample 3 presented the lowest melting temperature (1300 °C), being classified as having high fusibility. This characteristic can be explained by the balance between an intermediate content of SiO_2 (64%) and the presence of moderate amounts of K_2O (7.1%) and Al_2O_3 (2.5%), which act as fluxing agents.

The influence of K_2O can be better analyzed by comparing samples 1 and 4. Although sample 1 has a higher K_2O content (35%), its fusibility is greater than 1500 °C (low fusibility). On the other hand, sample 4, with a lower K_2O content (27%) but containing Fe_2O_3 (4.3%), is classified as having high fusibility. This demonstrates that the fluxing effect of K_2O can be limited when in excess or when associated with high CaO contents, but is enhanced by the presence of Fe_2O_3 .

Even at low levels, Fe_2O_3 was found to be decisive in reducing fusibility. Sample 7, for example, had a fusibility of 1370°C (medium fusibility), a lower value than samples with similar compositions but without iron. This behavior confirms the literature, which

indicates Fe_2O_3 as one of the main oxides responsible for reducing the melting temperature.

Finally, sample 2, composed almost exclusively of SiO_2 (91%), presented a fusibility of 1420 °C, being classified as medium fusibility. Despite the high concentration of oxide, the K_2O content (9.6%) justifies the reduction in the melting temperature in relation to the samples essentially rich in SiO_2 and CaO .

Low-fusibility samples are recommended for applications where the integrity of equipment's internal surfaces must be preserved, minimizing corrosion and deposits.

This knowledge allows for the optimization of biomass use in energy generation, aiding in the appropriate fuel selection and planning of boiler and thermal system operating conditions, promoting greater process efficiency, safety, and sustainability.

CONCLUSION

The evaluation of the fusibility of the samples allows us to observe a strong correlation between the chemical composition and the melting temperature, highlighting the role of the oxides present as refractory or fluxing agents.

As shown in Figure 1 although some sugarcane bagasse samples (1 to 5) present good thermal performance with deformation temperatures (DT) above 1100°C, the majority present lower hemisphere (HT) and creep (FT) temperatures.

Wood chips (6 to 9), on the other hand, present ash that is more stable and resistant to fusion, with deformation temperatures above 1260°C and, for the most part, presenting hemisphere (HT) and creep (FT) temperatures above 1500°C.

This study demonstrated the strong correlation between the chemical composition of ash and its melting point, which is essential for the proper management and use of biomass as an energy source. It was observed that refractory oxides, such as silica (SiO_2) and calcium (CaO), significantly increase the melting point of ash, providing greater thermal stability, while alkaline oxides (K_2O , Na_2O) and iron (Fe_2O_3) act as

fluxing agents, reducing melting point and increasing the propensity for scale formation and corrosion in equipment.

The detailed characterization of sugarcane bagasse and wood chip samples allowed us to identify their physical, chemical, and thermal properties, highlighting the energy potential of these materials and the challenges associated with their combustion.

The results obtained reinforce the importance of detailed characterization of solid biofuel ash, not only from a laboratory perspective, but also as a tool for industrial management and energy planning.

It became clear that sugarcane bagasse, although abundant and relevant to the Brazilian energy matrix, is more prone to ash fusion at intermediate temperatures, which can compromise boiler operation in the long term due to the risk of scaling, slagging, and corrosion. In contrast, wood chips demonstrated greater thermal stability, making them more suitable for processes that require continuous, safe, and highly efficient operation.

As a scientific contribution, this work expands knowledge on biomass ash fusion in Brazil, a topic still little addressed in the national literature, especially regarding widely available agro-industrial residues. The study reinforces the need to understand the correlation between chemical composition and thermal behavior, providing parameters that can inform both future research and practical decisions in the sugar-energy and forestry sectors.

From an applied perspective, the results presented here can guide fuel selection, blending formulations between different types of biomass, and even the development of additive strategies to reduce operational problems in boilers.

However, the study has some limitations that should be considered. The analysis focused on a limited number of samples and a heating range limited to a maximum of 1500°C, which made it impossible to accurately determine melting temperatures in cases of greater refractoriness. Furthermore, factors such as the specific mineralogy of the silica present, the influence of trace elements (Mg, P, Cl, S), and actual boiler operating conditions were not explored at this stage, which could significantly impact

fusible behavior. Therefore, it is recommended that future research advance in four main directions:

1. Expand the diversity of biomass analyzed, including agricultural and forestry residues relevant to Brazil, such as rice husks, eucalyptus residues, coffee husks, and fruit residues.
2. Investigate the application of mineral additives and ash correction techniques, evaluating their effectiveness in mitigating the effects of fluxing oxides such as K_2O , Na_2O , and Fe_2O_3 .
3. Simulate real industrial conditions, reproducing oxidizing and reducing atmospheres, as well as variable pressures, to approximate laboratory results to operational practice.
4. Analyze the economic and environmental feasibility of adopting fusibility mitigation strategies, integrating technical results with sustainability considerations.

These advances could contribute to the consolidation of biomass as a strategic driver of the Brazilian energy transition, ensuring greater efficiency, safety, and sustainability in the use of solid biofuels.

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SUSTAINABLE BIOENERGY: THE IMPACT OF CARBON CAPTURE AND STORAGE FROM A SOCIO-ENVIRONMENTAL PERSPECTIVE

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ABSTRACT

Over the past five decades, global greenhouse gas (GHG) emissions have increased by approximately 90%, driven predominantly by energy production and consumption. Concurrently, atmospheric CO₂ concentrations have risen by about 50% over the last century, significantly contributing to the intensification of anthropogenic climate change. This scenario of environmental pressure threatens to destabilize the socio-economic system, requiring the public and private sectors to adopt sustainable practices and urgent climate action. Investing in mitigation technologies such as Bioenergy with Carbon Capture and Storage (BECCS) is therefore essential. As well as providing energy, this technology helps to remove CO₂ from the atmosphere, contributing to climate mitigation. This study analyzes BECCS from a socio-environmental perspective, structured into three main dimensions: energy, social, and environmental. The methodology is based on a comprehensive literature review, addressing the technological operation of BECCS, its impacts on food security, and the challenges of CO₂ storage. The critical analysis aims to identify trends and socio-environmental implications associated with the implementation of BECCS.

Keywords: BECCS, Climate Change, Mitigation Technologies, Socio-environmental Impacts.

INTRODUCTION

The effects of climate change are becoming increasingly intense. Over the past 50 years, greenhouse gas emissions have risen by 90%, while atmospheric CO₂ concentration has increased by 50% in the last century, from 290 to 424 ppm [1]. As a result, the current period is considered the warmest in human history, with recorded increases in the global average temperature [1]. Given this scenario, environmental pressure threatens to destabilize the socioeconomic system, making it essential to adopt practices aligned with sustainable development [1, 2].

From this perspective, the implementation of climate actions, along with a large-scale social transformation, is necessary to offset greenhouse gas emissions. Investing in technologies such as bioenergy with carbon capture and storage can contribute to reducing atmospheric carbon levels [3].

Bioenergy with Carbon Capture and Storage (BECCS) has been increasingly recognized as a strategic measure to mitigate climate change [4]. This is because, while providing energy or goods to end users, it also contributes to the removal of carbon dioxide from the atmosphere [4].

Therefore, this study aims to analyze Bioenergy with Carbon Capture and Storage (BECCS) as a technology that contributes to mitigate climate events from a socio-environmental perspective. To this end, the study seeks to understand the technological functioning of BECCS, its potential impacts on food security, considering competition for land and resources, and the challenges associated with the safe storage of captured CO₂. Through this interdisciplinary approach, the objective is to identify trends in the literature and discuss the socio-environmental implications of BECCS implementation.

METHODS

The methodology employed consists of segmenting the study into three areas of knowledge: energy, social, and environmental. Based on this division, a systematic literature review with a qualitative approach was conducted to support the study and to investigate the role of BECCS from a socio-environmental perspective.

Drawing on insights from the scientific sources referenced, the study's analysis was structured around the following key themes: the technological functioning of BECCS and its feasibility as a climate mitigation strategy; potential impacts on food security, considering competition for land and resources; and the challenges associated with the safe storage of captured carbon dioxide.

Accordingly, a critical approach was adopted to identify established trends in the literature and examine the socio-environmental implications of implementing this technology, with an emphasis on social responses and environmental effects.

The main research question guiding this study is: "What are the key contributions, challenges, and social and environmental perspectives related to the use of BECCS technology as a climate change mitigation strategy?"

Based on this central question, five additional specific questions were formulated to support the qualitative development of the topic. Table 1 presents these questions, the keywords used in the search and the Boolean connectors applied.

Table 1: Description of the research questions.

Research Question (RQ)	Keywords	Boolean Connectors
RQ 1 How does the BECCS cycle work?	BECCS; "Carbon Cycle"; CCS.	(BECCS OR "bioenergy with carbon capture and storage" OR Bio-CCS) AND "carbon cycle" AND (CCS OR "carbon capture and storage")
RQ 2 What is the CO ₂ mitigation potential resulting from BECCS implementation?	BECCS; mitigation; "climate change".	(BECCS OR "bioenergy with carbon capture and storage" OR Bio-CCS) AND (mitigation OR "carbon dioxide removal") AND "climate change"
RQ 3 What is the potential for BECCS implementation in Brazil?	BECCS; regulation; "carbon market"; Brazil.	(BECCS OR "bioenergy with carbon capture and storage" OR Bio-CCS) AND (regulation OR law OR legislation) AND "carbon market" AND Brazil.
RQ 4 What are the social and environmental perspectives regarding BECCS?	BECCS; "social perception"; "environmental impact".	(BECCS OR "bioenergy with carbon capture" and storage OR Bio-CCS) AND ("social perception" OR "public acceptance") AND ("environmental impact" OR sustainability)
RQ 5 What impact could BECCS implementation have on food and land competition?	BECCS; "land use"; "food security".	(BECCS OR "bioenergy with carbon capture and storage" OR Bio-CCS) AND ("land use" OR "land competition") AND ("food security" OR agriculture)

Source: Author's elaboration.

The primary databases used for the research were Scopus and Web of Science. Accordingly, the search criteria covered the last decade, from 2015 to 2025, and all

fields of the documents were considered during the search. The types of documents reviewed included primarily research and review articles, books, and book chapters. Studies were selected based on the availability of abstracts and full texts, and on their direct or indirect relevance to BECCS technology. This information is detailed in Table 2.

Table 2: Search criteria used in the review.

Search Criteria	
Databases	Scopus and Web of Science
Search fields	All fields
Document type	Research and review articles, book chapters and books
Date of publication	2015–2025
Language	English and Portuguese
Study criteria	Studies available in full text
Content-based criterion	Studies that directly or indirectly address BECCS technology

Source: Author's elaboration.

Additionally, institutional and legal documents were also used, such as the Brazilian Law No. 13,576/2017, the United Nations Report on Human Rights and the Environment, and a World Bank Report on Climate and Development for Brazil. The purpose of including these official documents is to provide legislative or institutional context.

The exclusion criteria adopted were: duplicate works, abstracts without full-text availability, and studies focused exclusively on technologies unrelated to bioenergy or carbon capture.

RESULTS AND DISCUSSION

Based on the systematic review described in the methodology section, Table 3 presents the number of documents found in the databases for each research question, according to the previously established search criteria.

Table 3: Search results.

Research Question (RQ)	Scopus	Web of Science
RQ 1	23	2.997
RQ 2	253	896
RQ 3	366	28
RQ 4	2	446
RQ 5	16	511

Source: Author's elaboration.

In accordance with the established criteria, 2,659 duplicate publications were excluded. The remaining documents were analyzed according to year of publication, type of document, and, most importantly, the relevance of their content to the main objective of the research. The final sample of the qualitative systematic review comprised 31 publications, distributed as follows: peer-reviewed journal articles ($n = 24$), book chapters or academic books ($n = 4$), and institutional or legal documents ($n = 3$). These studies were published between 2015 and 2025, with a relatively balanced temporal distribution throughout the decade. The classification of these studies is presented in Table 4.

Table 4: Classification of publications by year.

Year	Scientific Articles	Book Chapters/ Books	Institutional/ Legal Documents	Total
2015	1	0	0	1
2016	2	0	0	2
2017	1	0	1	2
2018	2	1	0	3
2019	2	0	1	3
2020	3	1	0	4
2021	2	1	0	3
2022	3	1	0	4
2023	3	0	1	4
2024	3	0	0	3
2025	2	0	0	2
Total	24	4	3	31

Source: Author's elaboration

A growth in scientific production has been observed since 2020, reflecting the increasing academic interest in the topic of BECCS (Bioenergy with Carbon Capture and Storage) and its climatic and socio-environmental implications. The year with the highest number of publications was 2020, totaling four documents, including both scientific articles and book chapters. The years 2022 and 2023 also stood out, each with four publications.

At the beginning of the selected timeframe, between 2015 and 2017, five documents were identified, including the Brazilian legal framework Law No. 13.576/2017, which established the National Biofuels Policy (RenovaBio). More recent documents, published between 2024 and 2025, highlight growing attention to the role of BECCS in the global energy transition and in debates on climate justice.

This variety of sources and publication dates reinforces the interdisciplinary and evolving nature of the topic, enabling a comprehensive analysis from technological, environmental, economic, and social perspectives.

Bioenergy cycle with carbon capture and storage

The BECCS cycle promotes a negative carbon flux to the atmosphere. Its operating principle is based on carbon dioxide removal (CDR) through biological sequestration, which occurs while the biomass is in its growth stage. This biomass can be used either as a fuel or converted into an energy carrier [5]. From a technical perspective, energy crops intended for biofuel production are considered the most suitable biomass for BECCS, as they capture CO₂ during growth and store it in both the soil and biomass, contributing to the reduction or offsetting of greenhouse gas emissions [4].

During the combustion or conversion of biomass, carbon dioxide (CO₂) is released and captured by carbon capture and storage (CCS) technologies. After the capture process, the CO₂ can be stored in underground geological reservoirs, such as saline aquifers, mud basins, unmineable coal seams, and depleted oil and gas fields [3, 6]. Additionally, it can be injected directly into the deep ocean or utilized for other purposes that ensure its long-term storage [4–6].

Alternative carbon retention methods utilize solid biomass residues from BECCS to produce biochar, a product derived from biomass pyrolysis that is characterized by a highly stable aromatic carbon network [7]. Due to this property, biochar can be

considered for carbon sequestration in the soil and for its potential to enhance biomass yield [7].

The main carbon capture techniques are pre-combustion, oxy-fuel combustion, and post-combustion [8]. In pre-combustion, CO₂ is separated from the fuel before combustion; after its conversion into synthesis gas, the CO₂ is captured [4, 8]. In oxy-fuel combustion, nitrogen is removed from the air, and pure oxygen is used in combustion, generating an exhaust stream composed of CO₂ and water, which facilitates CO₂ capture [4, 8]. Finally, post-combustion removes CO₂ from exhaust gases using separation methods such as absorption, adsorption, membranes, cryogenics, and chemical looping [4, 8].

Absorption technology is the most commercially adopted and can be classified as either chemical or physical [9, 10]. Physical absorption requires specific temperature and pressure conditions, while chemical absorption involves solvents such as amines, ammonia solutions, Selexol, Rectisol, and fluorinated solvents [9]. Regarding adsorption, CO₂ is retained through a combination of chemical and physical interactions between the adsorbent surface and the target particles [9, 10].

Membranes, in turn, act as semipermeable barriers capable of capturing carbon dioxide by separating gas stream components based on concentration gradients, electric potential, or pressure [11–13]. From another perspective, cryogenic separation isolates CO₂ through condensation and distillation at low temperatures, ensuring high removal efficiency and producing pure liquid CO₂ for transport and storage [12]. Conversely, chemical looping carbon capture utilizes solid carriers to combust fossil fuels, generating CO₂ and water vapor, which is then condensed to separate the CO₂ [13].

The contribution of BECCS to climate change mitigation

In the context of Brazil, some proposed measures for sustainable development can be found in the Brazil Climate and Development Report (CCDR). One of the key topics in the report focuses on the implementation of emissions trading systems as a means to promote decarbonization and enhance carbon markets [14].

The CCDR suggests that a carbon tax could help reduce greenhouse gas emissions, encourage low-carbon development, and make Brazil's tax system more efficient and

environmentally friendly [14]. Additionally, the report highlights the possibility of reviewing and gradually phasing out subsidies for emission-intensive activities [14].

Given the need to reduce carbon emissions and the potential implementation of a carbon tax, BECCS stands out as a key strategy for climate mitigation and participation in the carbon credit market. Its economic viability depends on the carbon price, as this factor is crucial to making BECCS competitive with fossil fuels [15].

From a Brazilian perspective, it is important to highlight the RenovaBio program, a National Biofuels Policy established by Law No. 13,576/2017 [16]. This policy sets objectives based on decarbonization targets, in compliance with Brazil's commitments under the Paris Agreement, the expansion of biofuels in the energy matrix, and the promotion of energy efficiency and emissions reduction [16, 17].

RenovaBio is also responsible for establishing the Decarbonization Credit (CBio) [16, 17]. The CBio is a financial instrument generated through a registry system that can be requested by biofuel producers or importers, with the number of CBios issued being proportional to the volume of biofuels produced, imported, or sold [16]. Each CBio corresponds to the avoidance of one ton of CO₂ equivalent, and these credits are traded in organized markets, including auctions [16–18].

Based on these concepts, Silveira, Costa, and Santos [18] discussed the relationship between CBios, BECCS, and the Brazilian context. They emphasized the strong potential of BECCS in Brazil due to the well-established ethanol industry, the possibility of low-cost CO₂ capture in ethanol production in the Southeast, and the region's mature pipeline infrastructure. Additionally, the proximity to favorable sedimentary basins further strengthens the country's potential for carbon storage.

Thus, BECCS is regarded as a negative emissions mechanism capable of meeting greenhouse gas reduction targets. However, it still lacks specific policies in Brazil, and as an emerging technology, its adoption is also influenced by economic factors, given the high investment required, leading stakeholders to demand government subsidies [19].

Therefore, this scenario highlights that CBio plays a role in encouraging less polluting technologies and could also promote the development of BECCS by providing price

stability and proper emissions accounting [18]. However, this measure alone is not sufficient, as the country has not yet incorporated BECCS into its climate strategies [18].

The social perspective of BECCS

The benefits of BECCS, as it provides a measure to mitigate emissions across various sectors and reduce atmospheric carbon dioxide concentrations in cases of climate projection exceedance, are essential for fostering a positive social response to this technology. This is because the societal benefits associated with greenhouse gas mitigation indirectly include improved public health by reducing air pollution, as well as the protection of ecosystems and natural resources [4, 20].

According to Fridahl and Lehtveer [21], the implementation of BECCS should be recognized by governments as a strategy capable of driving social change and influencing land-use transformation. However, it is important to highlight the potential challenges faced by developing countries, which tend to be more vulnerable to the impacts of these changes. This could lead to protests and concerns regarding rising food prices and land appropriation due to the lack of adequate regulations.

The public dissemination of BECCS techniques still needs to be widely promoted among stakeholders, including academics, researchers, environmentalists, policymakers, government agencies, industries, and investors, to enhance social acceptance and integration strategies [4]. While the concept of bioenergy is well known in most countries, the understanding of Carbon Capture and Storage (CCS) is not yet widespread [4, 20].

According to the study by Dallo et al. [22] on public perspectives regarding the implementation of carbon capture, transport, utilization, and storage in Switzerland, factors such as trust in responsible institutions, transparency in installation processes, and effective communication are essential for improving community acceptance of this technology. Therefore, the study highlights the importance of communication strategies that rely on credible sources and a people-centered approach, aiming to develop publicly accessible materials tailored to the needs, preferences, and capacities of target audiences, thereby enhancing the learning process about CCS.

From this perspective, academia plays a fundamental role in fostering knowledge, as information tends to be more reliable when developed within these institutions [22]. In some countries, such as China, academic journals, textbooks, and expert lectures are considered the most trustworthy sources when it comes to the topic of CCS. For these specific communities, social media is seen as less reliable and primarily serves as a vehicle for disseminating scientific debates [22].

Therefore, as the population gains access to information about the BECCS cycle and participates in decision-making dialogues regarding the energy sector, it contributes to the process of energy democracy. According to Allen, Lyons, and Stephen [23], energy democracy emphasizes the active involvement of citizens in energy-related decisions, recognizing them as both recipients and key stakeholders in the process.

Socio-environmental challenges of BECCS

It is understood that although BECCS is a decarbonization solution, it can have impacts throughout its entire supply chain, from bioenergy production to CO₂ transport and storage. By affecting land use, water resources, competition with food production, and biodiversity, this technology may present social challenges and raise concerns regarding the sustainability of the process [20].

The expansion of bioenergy production on agricultural land can pose a threat to biodiversity and water resources, with potential impacts on food security [24]. When BECCS relies on first-generation bioenergy, which refers to biomass derived from food crops such as corn, sugarcane, or wheat, it exacerbates social consequences related to land-use pressures and, consequently, increases food insecurity [25, 26].

On the other hand, when BECCS utilizes second-generation bioenergy, which refers to lignocellulosic biomass such as agricultural and forestry residues or non-food crops, it has the potential to reduce competition with food production, although indirect impacts on land use still persist [26].

Regarding land use, a complex relationship is observed between carbon pricing, food prices, and bioenergy expansion. In this context, Muratori et al. [27] highlighted that the value of bioenergy is proportional to the carbon price, meaning that an increase in the

value of this energy input stimulates competition for land use and influences the prices of agricultural products and food.

The study by Kreidenweis et al. [28] indicates that a carbon tax applied to land-based and industrial emissions could more than double corn prices. Furthermore, using an integrated assessment model, the authors found that afforestation measures could lead to a 320% increase in wheat prices by 2095 compared to 2005 levels.

Popp et al. [29] analyzed possible future socioeconomic conditions regarding land management and concluded that mitigation policies, including carbon taxes, changes in agricultural management, increased bioenergy production, and land use for afforestation, could raise food prices by 110% by 2100, using 2005 as a reference year and considering a scenario in which the world follows historical trends with limited social, economic, and technological changes.

Stoy et al. [30] studied BECCS strategies within the context of the Food, Water, Energy, Biodiversity, and Social Systems (FWEBSS) nexus at regional scales, such as the Upper Mississippi River Basin (UMRB). Their findings suggest that a conservative BECCS approach, focused on soil management practices, biological and geological carbon sequestration, reforestation, and the production of perennial bioenergy crops, may be the most viable option for achieving social and environmental objectives. The authors emphasize the importance of a balanced combination of actions, along with the need for new regulatory incentives and policies to ensure the adoption and sustainability of these strategies.

Regarding the technical challenges associated with CCS implementation, it is important to highlight the need for specific sites to ensure safe storage, which often requires transporting CO₂ over long distances [19]. From this perspective, additional challenges arise in ocean and coal seam storage techniques, such as geological uncertainties, risks of CO₂ leakage into potable water aquifers, and the possibility of induced seismic events [6].

Public perception of uncertainties related to CO₂ storage drives the movement known as NIMBY (Not In My Backyard), which refers to public opposition to CCS technology installations near residential areas and communities [31]. Studies indicate that as the

storage site moves closer to urban areas, public approval rates for BECCS and CCS progressively decline [32]. Furthermore, the proximity of gas pipelines to residential areas exerts a negative influence on public acceptance [32].

Proximity to a potential CCS site may lead to lower levels of public acceptance due to two main factors: greater familiarity with the technology, which can heighten concerns, and the perception that the associated risks, such as CO₂ leakage, disproportionately affect the local community, while the benefits of climate change mitigation are shared more widely at the national or global level [31].

Although the relationship between the NIMBY phenomenon and CCS technologies still involves several assumptions about social response, given that CCS plants are still in their early stages, studies indicate that public opposition will mainly be influenced by perceived risks associated with deep geological CO₂ storage, including underground and surface leaks, as well as related safety concerns [33].

Researchers attribute the emergence of this phenomenon to various factors, such as a lack of trust in the government and project stakeholders, unequal access to information, locally focused perspectives, emotional reactions, and concerns about potential risks [34].

As previously mentioned by Dallo et al. [22] in the previous section, Braun [31] also highlights the importance of addressing public concerns through effective communication and engagement strategies to ensure the successful implementation of CCS technologies and mitigate NIMBY opposition.

CONCLUSIONS

Throughout this study, it was observed that BECCS plays a supporting role in climate change mitigation by removing CO₂ from the atmosphere and holding significant potential in the carbon market. During the systematic literature review, a large number of studies related to BECCS were identified. It was observed that, as this mitigation technology matured over the years, the number of research publications increased. However, as research questions became more refined and focused on specific

aspects, the volume of publications declined. Furthermore, based on the inclusion and exclusion criteria applied, it was possible to select the studies most aligned with the research objectives.

In Brazil, the challenges associated with BECCS development stem from the lack of specific policies and high costs, requiring government subsidies for its feasibility. Despite this, it was noted that biofuel policies, such as RenovaBio, can encourage the development of this technology, though they alone are not sufficient, as BECCS has not yet been incorporated into the country's climate strategies.

From a social perspective, the benefits of BECCS are primarily linked to its mitigation potential, generating positive impacts on both society and the environment. On the other hand, this technology faces challenges, such as potential land-use competition between bioenergy crops and food production, which could influence agricultural and food prices. Additionally, the need for secure carbon storage sites may lead to public resistance, intensifying the NIMBY phenomenon, particularly when communities are not adequately informed about the technology.

Finally, it was also concluded that public dissemination of BECCS techniques still needs to be significantly promoted in society to enhance the development of strategies for its implementation.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Beatriz Ribeiro Petrucci Padilha: Writing – original draft, Methodology, Investigation, Conceptualization. Caio Henrique Rufino: Writing – review C editing, Supervision.

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POTENTIAL FOR ENERGY RECOVERY FROM MUNICIPAL SOLID WASTE BY DIRECT COMBUSTION: EFFECT OF IMPROVING SELECTIVE COLLECTION RATES IN THE MUNICIPALITY OF ITAQUAQUECETUBA/SP

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ABSTRACT

This study assessed the impact of increased selective collection on the potential for energy recovery from municipal solid waste (MSW) using mass-burning technology. The study was applied to the municipality of Itaquaquecetuba, located in the São Paulo Metropolitan Region, Brazil. Three scenarios were analyzed: (1) current; (2) current recycling rates in municipalities in the São Paulo Metropolitan Region; and (3) national targets for 2040. Using secondary data on gravimetric composition and average waste generation rates, a mass balance was performed to determine the quantity and composition of wastes destined for Waste to Energy (WtE) plants, for each scenario. As expected, the results indicated increasing selective collection reduces the mass of MSW destined for WtE plants, influencing the heat value and decreasing the energy generated. Annual electricity production ranged from 33,000 MWh (scenario 1) to 53,000 MWh (scenario 3), sufficient to supply the consumption of 13,400 to 21,500 inhabitants, based on an average consumption of 205.5 kWh/inhab/month in São Paulo. Scenario 3 reduced energy recovery by 10.55%. Although selective waste collection partially compromises electricity generation, it extends the useful life of landfills and reinforces sustainability initiatives.

Keywords: Waste to energy, Incineration, MSW, Recycling, Waste Composition.

INTRODUCTION

The generation of municipal solid waste (MSW) is experiencing steady growth, driven by economic development and the consumerist culture of today's society. At the same time, the effects of climate change make the need for a circular economy, combined with sustainable development, increasingly urgent. The United Nations, through the 2030 Agenda, defined 17 Sustainable Development Goals (SDGs) and 169 integrated targets. These goals include diversifying the energy matrix, including clean and renewable sources, as well as reducing waste generation, focusing on reducing it and using environmentally sound technologies for its treatment [1].

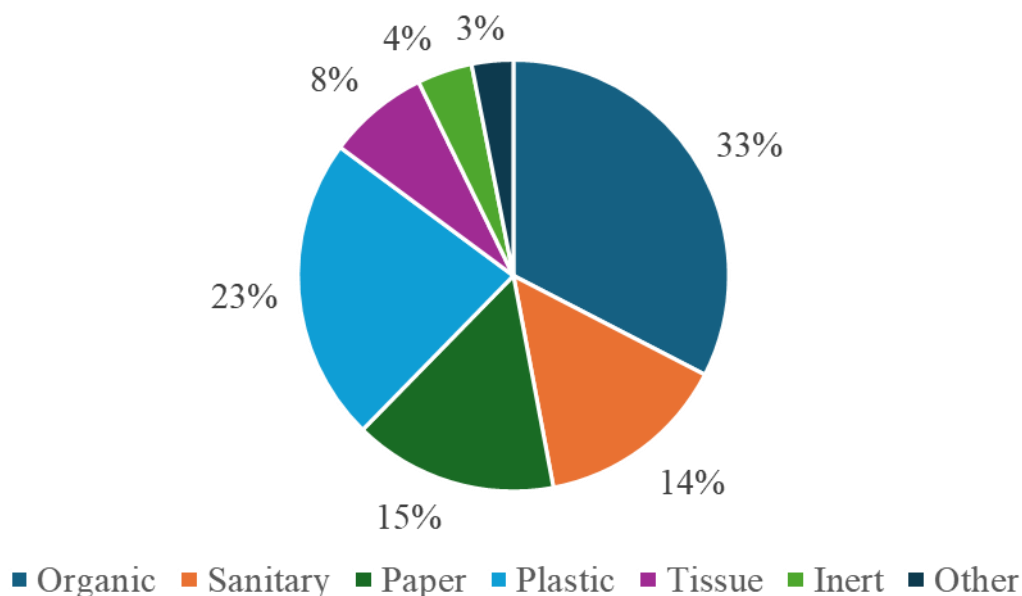
Brazil has an emerging economy that, in 2024, ranked among the 10 largest in the world [2]. With over 200 million inhabitants [3], approximately 81 million tons of urban solid waste were generated in the country in 2023. Of the total generated, it was estimated that approximately 71 million tons were collected, and 40 million tons were disposed of in landfills. This means that almost 36% of the collected waste, as well as the 12% that was not collected, was disposed of in environmentally inappropriate ways, such as controlled landfills or dumps, representing more than 30 million tons [4]. In 2010, Brazil established the PNRS (National Solid Waste Policy) (Law 12,305/2010), which aims to eliminate dumps and controlled landfills, ensuring environmentally sound waste disposal. Inspired by European standards, the PNRS proposes integrated management prioritizing prevention, reduction, reuse, recycling, treatment, and appropriate final disposal [5]. The National Solid Waste Plan (Planares) is a PNRS instrument that defines guidelines, strategies, and goals to improve solid waste management in Brazil. Its latest version, established by Decree No. 11,043 of April 13, 2022, establishes selective collection and energy recovery as strategies to reduce the mass of MSW sent to landfills.

Solid waste management in Brazil is a responsibility of municipalities, which often face financial constraints that hinder investment in technologies for proper management. As a result, there is a trend toward the formation of municipal public consortia [6]. The municipality of Itaquaquecetuba is part of the São Paulo Metropolitan Region, as well as the Mogi das Cruzes microregion, and is a member of CONDEMAT – the Alto Tietê Municipal Development Consortium – an entity responsible for microregional planning and service provision in various areas of municipal development. CONDEMAT is responsible for ensuring the development of the Municipal Solid Waste Plan (PMRS) for the consortium municipalities. However, Itaquaquecetuba has not yet implemented selective collection or treatment initiatives for its waste, which continues to be entirely disposed of in landfills.

The study of the gravimetric composition of MSW in the municipality of Itaquaquecetuba was conducted in 2018, based on an analysis of the waste generated by the 23 collection sectors. The results are presented in Figure 1, where more than 40% of the waste is recyclable, with plastics representing more than 20% [7]. This value is above the 16.8% observed in the national average [4], which reflects the lack of selective collection, so that approximately 48% of the total volume of MSW could

receive another destination, other than sanitary landfills.

Figure 1- Gravimetric composition of municipal solid waste in the municipality of Itaquaquecetuba, in 2018.Fonte: [7]



One possibility for extending the usefull life of landfills is the adoption of solid waste treatment through combustion in Waste to energy plants (WtE), which use the generated thermal energy to convert it into electricity. Waste-to-energy recovery offers the advantages of reducing the mass of waste disposed of in landfills and contributing to the diversification of the energy matrix. The implementation of this technology depends on several factors, which include sensitivity analysis, in addition to economic evaluation and social and environmental impacts. However, all these assessments depend on the sizing of the system to be implemented, which varies according to the quantity and quality of the waste. Designing and sizing these plants requires understanding the characteristics of waste as a fuel, especially its heating value. Therefore, changes in Integrated Solid Waste Management Systems, such as increasing selective collection practices, affect the waste's properties, which must therefore be considered.

The objective of this study was to evaluate the effect of increasing selective collection on the generation of electricity from the direct combustion of municipal solid waste in the municipality of Itaquaquecetuba. This work is in line with PLANARES, which sets

recycling targets until 2040, and analyzes three scenarios, starting from the current one and considering an increase in selective collection of 5 and 20%.

MATERIALS AND METHODS

To develop the scenarios to be analyzed in this work, improvements in selective collection rates were considered, as shown in Table 1.

Table 1- Definition of scenarios based on selective collection rates.

Scenario	Selective Collection rate	Reference
1	0%	Current Scenario
2	5%	Indexes for municipalities from Metropolitan Region of São Paulo
3	20%	PLANARES [8] goals for 2040

Source: Autors (2025)

For each of the proposed scenarios, a mass balance was performed, applying the indexes corresponding to the selective collection rate and sorting efficiency. Based on these results, the new gravimetric compositions of wastes destined for selective collection and for WtE plant were determined. First, selective and undifferentiated collections waste masses were determined, according to Equations (1) and (2).

$$MSW_{und} = MSW_{total} - MSW_{sel} \quad (1)$$

$$MSW_{sel} = SCR \times MSW_{total} \quad (2)$$

Where: MSW_{und} = mass of MSW from undifferentiated collection (t); MSW_{total} = total MSW mass collected (t); MSW_{sel} = mass of MSW from selective collection (t); SCR = Selective collection rate (%)

The index representing the efficiency of the sorting system was applied to wastes from selective collection to determine the recycled waste and rejects masses, according to Equations (3) and (4). For this work, manual sorting was considered,

with an efficiency of 30%.

$$MSW_{rec} = SE \times MSW_{sel} \quad (3)$$

$$MSW_{rej} = MSW_{sel} - MSW_{rec} \quad (4)$$

Where: MSW_{rec} = mass of MSW destined to recycling (t); MSW_{rej} = mass of rejects (t); SE = Sorting system efficiency (%)

The MSW mass destined for the WtE plant (MSW_{wte}) was then determined from Equation (5), as being the sum of the mass originating from the undifferentiated collection and the rejects from the sorting system.

$$MSW_{wte} = MSW_{und} + MSW_{rej} \quad (5)$$

Where: MSW_{wte} = mass of MSW destined to waste to energy plants (t).

For determining the gravimetric composition of wastes destined to WtE plants, annual generation and the initial gravimetric composition (Scenario 1) were used as a basis to determine the total mass of each category in the collected waste mass. Subsequently, based on scenario 1, the recyclables gravimetric composition was determined and used as a standard reference for calculating the mass of each of these fractions in the total allocated to the undifferentiated and selective collection systems. For waste to energy process, it was assumed that the WtE plant can receive waste from two streams: (1) Undifferentiated Collection; (2) Selective Collection, after manual sorting. To estimate the energy generated, a mass burning process followed by conversion to electrical energy was considered. The electrical energy generated was calculated according to Equation (6), proposed by Mamede [9] and described by Dalmo et al. [10]. To estimate the total energy effectively generated in a year ($E_{g, total}$), a reduction factor was considered, that relates the number of hours in which the WtE plant effectively operates to the total number of hours in a year. 8,000 hours of effective plant operation were considered, resulting in a reduction factor of 0.91 (Equation 7).

$$E_g = \left[0,28 \text{ MSW} \right]_{\text{fuel}} \left[\text{LHV} \right]_{\text{total}} E_e \quad (6)$$

$$E_{(g,\text{total})} = 0,91 E_g \quad [\text{MWh}] \quad (7)$$

Where: E_g = Electrical Energy generated [MWh.year⁻¹]; MSW_{fuel} = Total mass of MSW fuel fractions destined for energy recovery plants, per year [t. year⁻¹]; $\text{LHV}_{\text{total}}$ = Lower Heating Value of MSW [GJ/kg]; 0,28 = Unit Conversion Constant [MWh.GJ⁻¹]; E_e = Thermal to electrical energy transformation efficiency

According to Dalmo et al. [10], waste to energy plants thermal efficiency depends on several factors and can vary from 25 to 35%. The Lower Calorific Value was calculated with the model proposed by Drudi et al. [11], which considers the gravimetric composition and moisture content of the different fuel fractions of MSW (Equation 8). The gravimetric composition and moisture content of Itaquaquecetuba's wastes were determined by Toneli et al. (2018).

$$\left[\text{LHV} \right]_{\text{wb}} = \left[(15.42O_r + 19.14S_a + 32.68P_l + 8.33P_a + 21.51T) \cdot (1-W) \right] - (2.442 \cdot W) \quad (8)$$

Where: LHV_{wb} = Lower heating value, wet basis; W = moisture content; O_r = organic fraction, mass concentration; S_a = sanitary fraction, mass concentration; P_l = plastic fraction, mass concentration; P_a = paper fraction, mass concentration; T = Tissue fraction, mass concentration.

According to the proposed scenarios, different efficiency and recycling indexes were considered, which resulted in different values for the variables MSW_{fuel} , Gravimetric Composition and Moisture content, which resulted in different LHV values.

RESULTS AND DISCUSSION

Table 2 presents secondary data regarding waste generation and management in the municipality of Itaquaquecetuba, necessary for calculating mass balances and energy generation.

Table 2- Demographic and waste generation data for the municipality of

Itaquaquecetuba.

Secondary Data	Itaquaquecetuba	Source
Population	369,275	[3]
Annual MSW generation (t. day ⁻¹)	249.76	[12]
MSW generation rate (kg.inhab ⁻¹ .day ⁻¹)	0.675	Calculated

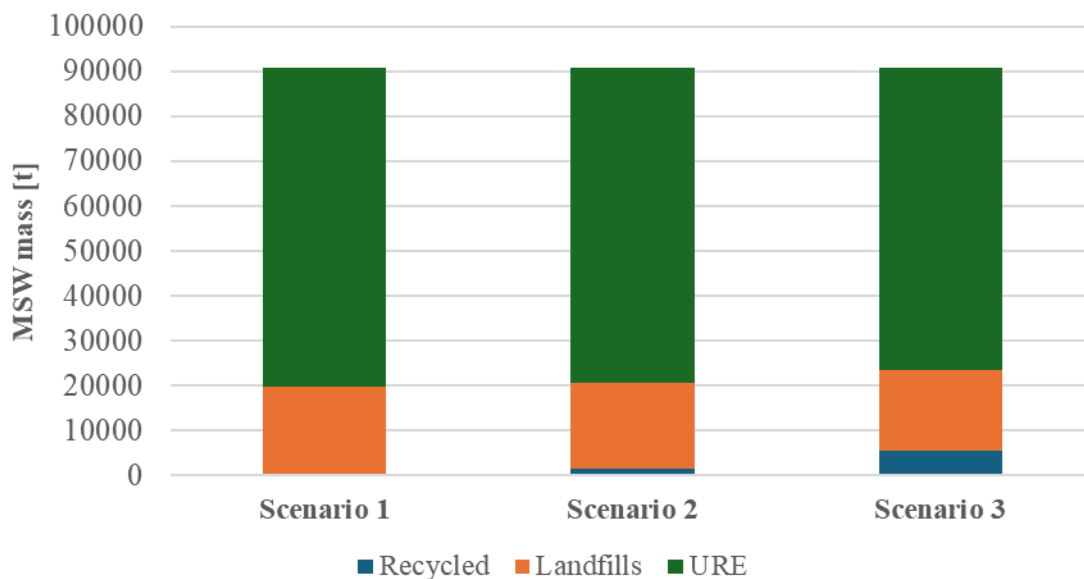
Table 3 presents the results of MSW collecting mass and gravimetric composition from the municipality of Itaquaquecetuba, for each scenario. Figure 2 illustrates, comparatively, the total masses of recycled waste and those destined for the WtE plants and landfills, for each scenario.

Table 3- Gravimetric composition and generated mass of different MSW combustible categories for the municipality of Itaquaquecetuba, within different scenarios.

Category	Scenario 1		Scenario 2		Scenario 3	
	Collected mass [t]	Gravimetric composition [w/w]	Collected mass [t]	Gravimetric composition [w/w]	Collected mass [t]	Gravimetric composition [w/w]
Organic	29,650	33%	29,650	33%	29,650	35%
Sanitary	13,128	14%	13,128	15%	13,128	15%
Plastic	20,743	23%	20,119	22%	18,247	21%
Paper	13,938	15%	13,519	15%	12,261	14%
Tissue	6,914	8%	6,706	7%	6,082	7%
Inert	3,767	4%	3,653	4%	3,313	4%
Other	2,839	3%	2,839	3%	2,839	3%

Source: Authors (2025); [11]

Figure 2- MSW mass destined for recycling, landfills and WtE plants, for different scenarios, with manual sorting at 30% efficiency. Source: Authors (2025)



Data in Table 3 and Figure 2 demonstrate that, as expected, the increase in selective collection rates results in a lower total mass and a lower proportion of recyclables in the composition of waste destined for the WtE plant. On the other hand, it also results in lower total mass destined to landfills, contributing to increasing its useful life.

Table 4 presents the results of the calculations of the electrical energy generated and its representativeness in relation to the municipality's annual consumption, for each scenario.

Table 4- Electrical energy generated [MWh/year] in a WtE plant, based on different selective collection scenarios in the municipality of Itaquaquecetuba, with a manual sorting system (30% efficiency in recovering recyclables).

Scenarios	Selective Collection Rate	Electrical Energy Generated [MWh/year]		% municipality's annual consumption	
		min	max	min	max
1	0%	37,632	52,686	3.64%	5.09%
2	5%	36,757	51,460	3.55%	4.97%
3	20%	33,661	47,125	3.25%	4.55%

Source: Authors

The data in Table 4 demonstrate that if all municipal waste were sent to the WtE plant, it would be possible to generate between 33,000 and 53,000 MWh of energy per year. Considering the average monthly consumption of 205,5 kWh per inhabitant in the state of São Paulo, this amount could meet the energy needs of approximately 13,400 to 21,500 inhabitants [13]. An analysis of the results obtained for scenarios 2 and 3, compared to the baseline scenario, shows that increased recycling rates resulted in progressive reductions in energy recovery through combustion, of 2,32 and 10,55%, respectively. This occurs because the selective collection process, besides reducing the total mass of waste sent to the WtE plant, removes combustible fractions with lower moisture content and higher high heating value.

CONCLUSIONS

Energy recovery from waste in the municipality of Itaquaquecetuba using a combustion treatment system could contribute to generating enough energy to serve up to 21,500 residents. Recyclables separation reduces energy generation by up to 10,55%, according to the rates considered in this study. However, it contributes to the circular economy by increasing recycling,

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