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VALUATION OF RICE STRAW: BIBLIOMETRIC ANALYSIS, SUSTAINABLE USE, PERSPECTIVES AND CHALLENGES

VALORIZAÇÃO DA PALHA DE ARROZ: ANÁLISE BIBLIOMÉTRICA, USO SUSTENTÁVEL, PERSPECTIVAS E DESAFIOS

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RESUMO

A palha de arroz, um subproduto da colheita de arroz, é abundante e tradicionalmente descartada ou queimada, causando impactos ambientais como emissões de gases de efeito estufa. No entanto, avanços tecnológicos destacam seu potencial como alternativa sustentável, especialmente na geração de biogás e energia elétrica no contexto da economia circular. Uma análise bibliométrica foi conduzida para explorar esse potencial, com base em 67 artigos encontrados no período de 2000 a 2024, dos quais 32 foram considerados relevantes. A pesquisa identificou a China, Índia, Indonésia, Bangladesh, Vietnã e Tailândia como os principais países produtores de estudos sobre o tema, refletindo sua alta produção e consumo de arroz. Os resultados confirmam o potencial da palha de arroz na geração de biogás por digestão anaeróbica, embora sua composição lignocelulósica exija estudos adicionais para otimizar seu uso. A pesquisa reforça a relevância desse resíduo no desenvolvimento de estratégias energéticas sustentáveis. Em termos de usos sustentáveis, a palha de arroz, possui grande potencial para aplicações como na produção de energia, biocombustíveis, materiais de construção, biocarvão, plásticos biodegradáveis e na agricultura. Também pode ser utilizado para inovações em nanotecnologia e materiais avançados como o grafeno. No entanto, desafios como os elevados custos logísticos, a necessidade de tecnologias avançadas e a baixa sensibilização dos agricultores limitam a sua adoção em larga escala. Apesar destas barreiras, a palha do arroz apresenta oportunidades valiosas para benefícios ambientais e para a economia circular.

Palavras-Chave: Resíduo agrícola; Biogás; Metano; Valorização de resíduos; Bibliometria.

ABSTRACT

Rice straw, a byproduct of rice harvesting, is abundant and traditionally discarded or burned, causing environmental impacts such as greenhouse gas emissions. However, technological advances highlight its potential as a sustainable alternative, especially in the generation of biogas and electricity in the context of the circular economy. A bibliometric analysis was conducted to explore this potential, based on 67 articles found from 2000 to 2024, of which 32 were considered relevant. The research identified China, India, Indonesia, Bangladesh, Vietnam and Thailand as the main countries producing studies on the topic, reflecting their high production and consumption of rice. The results confirm the potential of rice straw in generating biogas through anaerobic digestion, although its lignocellulosic composition requires additional studies to optimize its use. The research reinforces the relevance of this waste in the development of sustainable energy strategies. In terms of sustainable uses, rice straw has great potential for applications such as energy production, biofuels, construction materials, biochar, biodegradable plastics and agriculture. It can also be used for innovations in nanotechnology and advanced materials such as graphene. However, challenges such as high logistical costs, the need for advanced technologies and low awareness among farmers limit its large-scale adoption. Despite these barriers, rice straw presents valuable opportunities for environmental benefits and the circular economy.

Keywords: Agricultural waste; Biogas; Methane; Waste recovery; Bibliometrics.

INTRODUCTION

Rice is considered a fundamental food in many cultures around the world. It has a long history spanning millennia and continues to play a crucial role in global nutrition, becoming not only a vital grain, but also a symbol of sustenance and prosperity. Given this, the origin of rice is not perfectly known, but theories suggest that this cereal originated in southwest Asia, especially southern China, Indochina, Indonesia and India (DOMENE, 2021). Rice cultivation is extremely important for feeding the population. It is considered one of the foods with the best nutritional balance, accounting for 18% of the calories and 12% of the protein in the population's basic diet, as well as being widely adaptable to different soil and climate conditions and being the species with the greatest potential for increasing production and combating hunger in the world. Thus, in many developing countries, rice is considered the most economically important product, constituting a staple food for billions of people, ensuring the search for new techniques that can increase production (CUNHA, 2021).

Globally, in the 2021/2022 harvest, 166.6 million hectares were cultivated, making rice the third most produced and consumed cereal in the world, behind only corn and wheat (NERY, 2022). It is therefore understood that rice has a good ability to adapt to different climates and soil types. It can be grown in dry ecosystems and flooded areas, which corroborates its important economic role for countries in Asia, Africa and Latin America, especially Brazil (FAGERIA, 2014; NERY, 2022;). However, grain production also leads to the production of large quantities of waste: rice straw. This lignocellulosic biomass can be used for burning, incorporation into animal feed, composting and biofuel production. As a fuel source, it is possible to store and use the gas generated by anaerobic fermentation for heating, lighting and electricity generation. This use stands out as adhering to the sustainable production of biofuels from agricultural waste, where the production of energy/heat may be able to achieve environmental and economic gains. It stands out as a promising area considering the high and growing consumption and production of this cereal, as well as the proper management of this waste for the possible generation of electricity (THOMSEN, 2014). The study aim was to map bibliometric publications related to the potential for generating biogas and methane from rice straw.

THEORETICAL FRAMEWORK

The rice production chain

The rice production chain involves several stages, ranging from the cultivation of rice, through agricultural production, to its processing and marketing. So, highlighting the processing stage of this cereal, it can be seen that, after harvesting, the rice grains are dried to reduce their humidity to levels suitable for storage, followed by husking, which is the stage designed to remove the outer shell and reveal the edible rice grain, finally undergoing polishing, which is characterized by removing the outer film to obtain a more refined white rice, since polished grains are more stable than whole grains when it comes to storage, due to their higher lipid content and enzymatic activities (MULLER, 2022; MUCHLISYIYAH, 2023; MENDES, 2024).

Activities in the rice agro-industry have undergone changes to meet the needs of increasingly demanding and informed consumers. Thus, the greatest advances are focused on good manufacturing practices, such as hazard analysis, control criteria, criteria in the selection and processing of raw materials, traceability, precise storage and diversification of production, which corroborates an adequate food safety management system and is based on controls at various stages of food production (DE OLIVEIRA, 2021).

In Brazil, the main way rice is consumed is in the form of whole grains, including polished rice, brown rice and parboiled rice. As mentioned above, polished rice is obtained by husking and polishing the whole grain using machines that remove part of its outer layers through friction with the grains, which helps to obtain by-products such as the husk, bran, germ and broken grains (BODIE, 2019; DE SOUZA, 2022; COLOMBO, 2023).

Brown rice results from removing only the husk and is rarely consumed in Brazil, although it is richer in nutrients than polished rice because it has a fibrous and fatty covering called bran, which makes it difficult to cook in water. Thus, because it preserves the original constitution of the grain, it has higher concentrations of nutrients, lipids, proteins, vitamins, dietary fibers and minerals (DE OLIVEIRA, 2021). Parboiled rice, on the other hand, can be eaten as a whole grain or polished. It is the result of a hydrothermal process, with the rice still in the husk, which causes partial or total gelatinization of the starch. In relation to milled rice, the parboiling process improves the nutritional quality of the grain, as some of its components are redistributed as a result of the effects of humidity and temperature during the hydrothermal process (DE SOUZA, 2022).

Characteristics of rice straw waste

The external structure of the rice grain is formed by the husk, or straw, which is made up of a set of modified leaves called pálea and grande lema, which constitutes a siliceous and fibrous part inedible to humans, whose main function is to protect the grain from extrinsic factors that are detrimental to its characteristics and quality. However, it is widely used in agricultural systems as food for cattle, sheep, goats and other ruminant animals which, despite having a relatively low nutritional value, can provide some fiber and nutrients for the animals (DE OLIVEIRA, 2021).

The husk is made up of cellulose (37% to 40%), hemicellulose (18% to 24%), lignin (12% to 22%) and other components (17% to 33%) (DE OLIVEIRA, 2021). However, in the rice processing process, the husk is responsible for generating the largest volume of by-products, averaging 22%. Therefore, its composition usually includes protein content ranging from 2% to 2.8%, fat from 0.3% to 0.8%, ash from 13.2% to 21%, fiber from 34.5% to 45.9% and carbohydrates from 22% to 34%. Bran is one of the most nutritious parts of the grain and accounts for approximately 8% of the processing process. The bran, as it is marketed, not only consists of the bran itself, but also the germ, which explains its high nutritional value. The grain, also known as the endosperm, is rich in starch and is one of the most consumed parts, accounting for around 70% of the cereal (DE SOUZA, 2022; NNADIUKWU, 2023).

Waste management in the rice industry

Looking at the rice processing process, there is a large generation of waste, or by-products, which are: rice husks, bran and broken grains, which are called quirera. Among the direct reuses of the waste, we highlight the transformation into oil or feed for the bran, raw material to produce flour and pre-cooked starch for the broken grains and the production of paper or even for use as an energy source (burning) or incorporation into animal feed. Around 20% to 25% of the total weight of paddy rice processed becomes rice straw, which means that for every ton of rice processed, approximately 200 to 250 kilograms of rice straw are generated (LORENZETT, 2012; ESA, 2013; RAMÍREZ, 2024). This process is characterized by the removal of impurities from the rice, which after cleaning is dried and stored in order to be passed through a sieve again to be husked and polished. This generates various residues from impurities from the crop and elements of the cereal itself (HALBERSTADT, 2015).

Rice husks, therefore, represent a problem in the rice industry, especially in relation to the treatment of rice husks and husk ash (when burned) due to the large volume produced and difficulties in their storage and transportation, since most companies are classified as small and do not have adequate processes for the use and disposal of the waste and ash produced, which is generally discarded in wastelands, dumps or thrown into watercourses, corroborating the pollution and contamination of water sources (HALBERSTADT, 2015).

There are various ways of reusing rice husks in the agro-industry, such as using them as a direct fuel by burning them directly in boilers, since they are classified as an excellent source of carbon. The combustion of rice husks in furnaces produces ash as the main residue, which is reused, in most cases, on crops as fertilizer and in the production of cements and mortars, since it cannot be disposed of directly in the environment (SAIDELLES, 2012). Other uses of this waste include: juice processing, where it is used as an auxiliary element in pressing, being mixed evenly into the pulp of the crushed fruit; paper production, since it has 32% cellulose, which makes it viable for use in industry, but 21% lignin is observed, which hinders the manufacturing process, requiring pre-treatment aimed at extracting this lignin; soil conditioner, used as a mixture in the composition of substrates for growing plants and rooting cuttings, as it has properties such as low density, low capacity to retain water, high concentration of macro pores, among others (LORENZETT, 2012).

The potential of rice straw to generate biogas, methane and energy is one of the alternatives for solving this problem and can be effective, since rice straw is an abundant and easily accessible biomass in regions where rice is grown on a large scale. This waste can contribute to the diversification of the energy matrix, reducing dependence on fossil fuels and promoting the transition to more renewable and sustainable sources, also contributing to the circular economy (GRISOLIA, 2022; OLIVEIRA, 2022; JIN, 2023).

Characteristics of rice straw waste

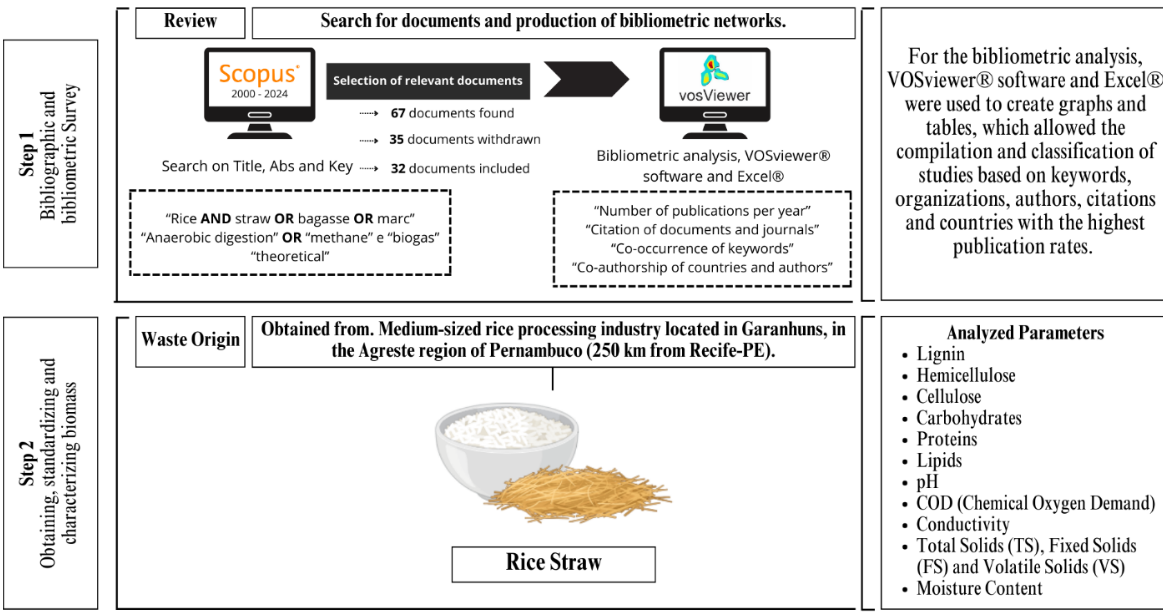
The external structure of the rice grain is formed by the husk, or straw, which is made up of a set of modified leaves called “pálea” and “grande lema”, which constitutes a siliceous and fibrous part that is inedible for humans, whose main function is to protect the grain from extrinsic factors that are harmful to its characteristics and quality.

However, it is widely used in agricultural systems as feed for cattle, sheep, goats and other ruminant animals, and although it has a relatively low nutritional value, it can provide some fiber and nutrients for the animals (FIJALKOWSKI, 2016; PARTAMA, 2019; DE OLIVEIRA, 2021). The husk is made up of cellulose (37% to 40%), hemicellulose (18% to 24%), lignin (12% to 22%) and other components (17% to 33%) (De Oliveira, 2021). However, in the rice processing process, the husk is responsible for generating the largest volume among the by-products obtained, averaging 22%. Therefore, its composition usually includes protein content ranging from 2% to 2.8%, fat from 0.3% to 0.8%, ash from 13.2% to 21%, fiber from 34.5% to 45.9% and carbohydrates from 22% to 34%. Bran is one of the most nutritious parts of grain and accounts for approximately 8% of the processing process. The bran, as it is marketed, not only consists of the bran itself, but also the germ, which explains its high nutritional value. The grain, also known as the endosperm, is rich in starch and is one of the most consumed parts, accounting for around 70% of the cereal (DE SOUZA, 2022).

MATERIAL AND METHODS

The methodology applied in this work followed 3 steps described in the flowchart in Figure 1. In the following subsections, these steps will be described in more detail.

Figure 01: Flowchart of the methodology applied in this work



Source: Authors (2024)

Step 1: Bibliographic and bibliometric survey

For the bibliometric analysis, VOSviewer® software and Excel® were used to create graphs and tables, which allowed the compilation and classification of studies based on keywords, organizations, authors, citations and countries with the highest publication rates. The time frame defined was between 2000 and 2024, resulting in 23 years of research. Figure 01 shows the stages of data collection on the Scopus database and bibliometric analysis. Data collection for bibliometric research was carried out on February 7, 2024, using the Capes Cafe Periodicals Portal, which allows the use of the main academic and research databases, searching for scientific documents on the topic: "Potential for generating biogas and methane through the valorization of rice straw".

Among the available databases, the Scopus platform proved to be the most promising in terms of the number of publications for the selected keywords, which corroborated the generation of a broader database. The search for documents was carried out on the Scopus platform, in English, using selection criteria based on the keywords present in TITLE-ABS-KEY. Three search engines were used for the research: one using "Rice" linked by the Boolean operator "AND" with "straw" with another Boolean operator "OR" with "bagasse" and "marc"; the second search engine is highlighted by "Anaerobic digestion" followed by the Boolean operator "OR" with "methane" and "biogas"; finally the last search engine with "theoretical" in order to direct the research to the theoretical field in order to analyze new calculation models and comparisons.

Step 2: Obtaining, standardizing and characterizing biomass

Obtaining and standardizing

The rice straw samples were obtained from a medium-sized rice processing industry located in Garanhuns, in the Agreste region of Pernambuco. They were gathered in wide mouth 5L polyethylene containers, frozen, and stored (temperature < 0°C) until the analytical characterization tests were conducted according to the project's methodologies and schedule.

The collections were carried out in triplicate, where the raw residue was dried in an oven at (65 ± 2°C) and standardized using a 32 Mesh sieve. The samples were then standardized and stored in the Environmental Sanitation Laboratory (LABSAM/UFRPE) and the Bioproducts and Bioprocesses Laboratory of Biotechnology Center (NUBIOTEC/ UFRPE).

Biomass characterization

The rice straw samples (substrate) were subjected to the following physicochemical analyses described in Table 3 (WHO, 1978; APWA; AWWA; WPCF, 2005; SANTOS, 2019; SILVA et al., 2019). The characterization was carried out in triplicate for each parameter.

Table 1: Parameters, Equipment, and Methods Used in the Physicochemical Characterization of Rice Straw

Parâmetro	Equipamento	Método
pH	pHmetro Digimed DM23	NBR 10006 (ABNT, 2004)

Electrical Conductivity (µs/cm)	Digimed DM32	NBR 10006 (ABNT, 2004)
TS, VS e FS	LUCA Oven - 80/64 and EDG 3000 Muffle Furnace	WHO (1978)
Moisture Content	LUCA Oven - 80/64	WHO (1978)
Fiber Content (Cellulose, Hemicellulose, and Lignin)	Fiber Determinator TE-149 - Tecnal	VAN SOEST (1994)
Protein	Nitrogen Digester (Kjeldahl)	APWA; AWWA; WPCF (2005)
Lipids	Hot Extraction in Soxhlet	APWA; AWWA; WPCF (2005)

Legend: TS = Total Solids; VS = Volatile Solids; FS = Fixed Solids; in case any parameter cannot be obtained due to analytical limitations, literature data will be used, as the objective of this work is to determine the theoretical potential. **Source:** Authors (2023)

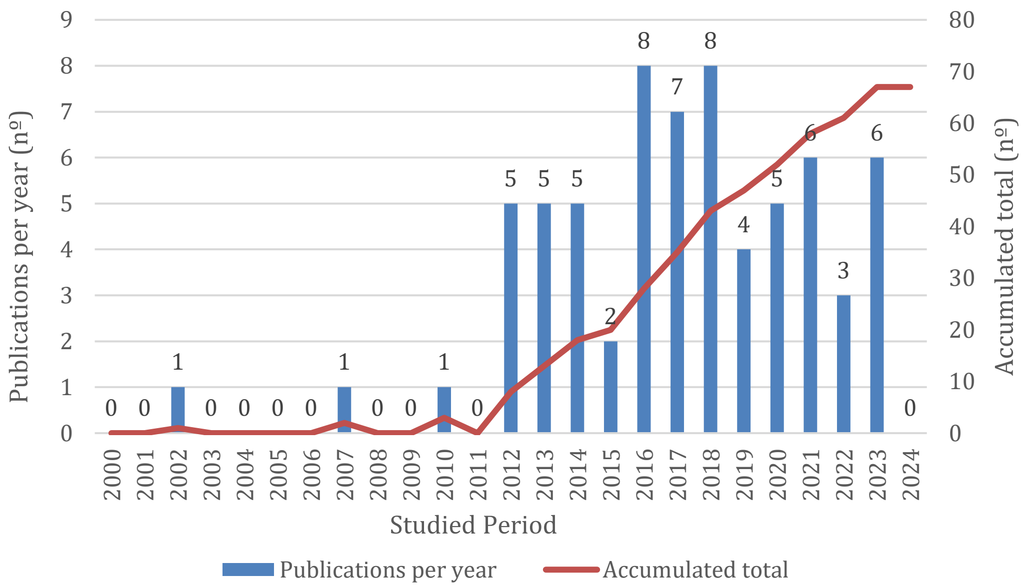
RESULTS AND DISCUSSION

Bibliometric analysis

After applying the methodology described in Figure 01, 32 relevant articles were obtained for the bibliometric analysis focused on the theme. Figure 02 presents the evolution in the number of publications per year and the accumulated totals related to the production of biogas and methane from the valorization of rice straw.

It is noticeable that the interest in the topic between 2000 and 2012 was low, with substantial growth starting in 2012 (Figure 02). The peak in production occurred between 2016 and 2018, with 8 publications each year. The increase in interest is likely related to global policies on waste utilization and valorization, as well as aspects related to climate change, whose interest and application have been growing in practical applications across various sectors.

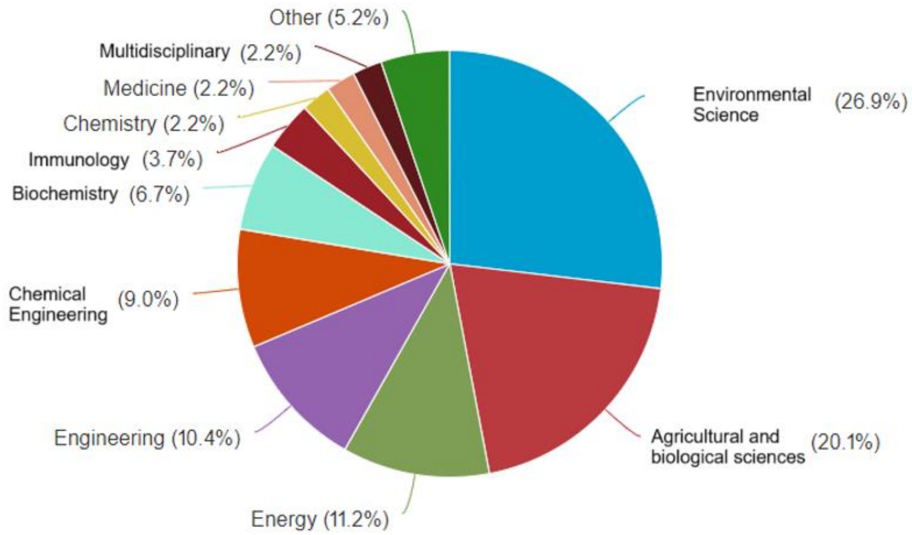
Figure 02: Total number of publications obtained per year and the accumulated total from 2000 to 2024.



Source: Authors (2024)

This observation can be corroborated by analyzing Figure 03, which relates to the division of the thematic areas in focus of the published articles during this period.

Figure 03: Division of thematic areas observed in the articles evaluated (period from 2000 to 2024).



Source: Authors (2024)

The articles related to the chosen topic were primarily focused on the areas of Environmental Science (26.9%) and Agricultural and Biological Sciences (20.1%), together accounting for 47% of the total publications observed. The growing interest reflects concerns regarding better energy utilization of these residues in the past decade, likely driven by economic and

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environmental motivations.

The expansion of studies indicates that the scientific community sees the issue as a real opportunity for gains and advantages from the utilization of this waste for energy purposes, potentially applicable on a larger scale.

Bibliometric citation analysis of documents

32 articles were analyzed and 17 documents were highlighted with at least 10 citations. By observing the bibliometric network, 15 clusters were formed that do not have citation links between them, which supports the idea that the areas of work still have isolated production. Among the 17 documents, the top 5 most cited works from the period 2000 to 2024 were selected to highlight their approach to the main topic (Table 02).

Table 02: Top 5 Most Cited Documents from 2000 to 2024

Ranking	Title	Author/ Year	Number of Citations	Journals	Reference
1º	*Enhanced biogas production from rice straw, triticale straw and softwood spruce by NMMO pretreatment*	Teghammar (2012)	104	*Biomass and Bioenergy*	Teghammar et al. (2012)
2º	*Enhanced methane production from rice straw co-digested with anaerobic sludge from pulp and paper mill treatment process*	Mussoline (2013)	52	*Bioresource Technology*	Mussoline et al. (2013)
3º	*Compositional analysis and projected biofuel potentials from common West African agricultural residues*	Thomsen (2014)	41	*Biomass and Bioenergy*	Thomsen et al. (2014)
4º	*Effects of pretreatments on thickened waste activated sludge and rice straw co-digestion: Experimental and modeling study*	Abudi (2016)	39	*Journal of Environmental Management*	Abudi et al. (2016)
5º	*The relationships among sCOD, VFAs, microbial community, and biogas production during anaerobic digestion of rice straw pretreated with ammonia*	Zuo (2020)	38	*Chinese Journal of Chemical Engineering*	Zuo et al. (2020)

Source: Authors (2024)

The most cited article (104 citations) was by Teghammar et al. (2012), “Enhanced biogas production from rice straw, triticale straw, and softwood spruce by NMMO pretreatment,” published in the journal *Biomass and Bioenergy*. This article discusses the pre-treatment of softwood, rice straw, and triticale straw (a hybrid of rye and wheat) with N-methylmorpholine-N-oxide (NMMO) before anaerobic digestion for biogas production, resulting in methane yields of 400-1200%, reaching 79% of the theoretical yield of 415 Nml CH_4/gVS for rice straw.

The second most cited article (52 citations) was by Mussoline et al. (2013), "Enhanced methane production from rice straw co-digested with anaerobic sludge from pulp and paper mill treatment process," published in *Bioresource Technology*. This article highlights a unique co-digestion strategy to improve methane production and reduce digestion times for agricultural-scale systems, as lignin in rice straw delays the hydrolysis phase, leading to low methane recovery and long digestion periods. The study added pig wastewater and paper mill sludge to enhance methane yields, emphasizing that accelerated hydrolysis of rice straw was directly related to the amount of sludge added.

The third most cited article (41 citations) was by Thomsen et al. (2014), "Compositional analysis and projected biofuel potentials from common West African agricultural residues," published in the same journal as the first article on the list. It focuses on studying the theoretical bioenergy potentials, analyzing the potentials of 13 West African agricultural residues, including rice straw, based on their compositions, and providing a foundation for future biofuel research.

In fourth place (39 citations) was the article "Effects of pretreatments on thickened waste activated sludge and rice straw co-digestion: Experimental and modeling study" by Abudi et al. (2016), published in the *Journal of Environmental Management*. Like Mussoline et al. (2013), it explores the potential of co-digestion, in this case analyzing biogas production from thickened waste activated sludge (TWAS) and rice straw in varying proportions, using the modified Gompertz model to predict biogas yields and assess kinetic parameters.

Finally, in fifth place, with only 1 citation fewer than the previous article (38 citations), was the more recent work, "The relationships among COD, VFAs, microbial community, and biogas production during anaerobic digestion of rice straw pretreated with ammonia," by Zuo et al. (2020), published in the *Chinese Journal of Chemical Engineering*. Despite ranking fifth, it shows promise by investigating the effects of soluble chemical oxygen demand, volatile fatty acids, and microbial communities on biogas production specifically from rice straw, also using the modified Gompertz model, which was the most suitable for the measured methane yields. This study contributes a theoretical basis for improving the efficiency of anaerobic digestion of rice straw.

By reviewing the Top 5, the focus was on the use of pre-treatments and determination of kinetic models, still in laboratory-scale studies, indicating that research is still under development. The barriers to its use are primarily related to the lignocellulosic composition of rice straw, which has low anaerobic biodegradability.

Bibliometric analysis of journals

Among the journals that published the most on the topic, the top 5 with the highest number of publications were selected, accounting for 13 (40.6%) of the 32 selected publications. In Table 03, the ranking of the 5 journals with the most publications and citations is presented. It was observed that the journal *Nongye Goggcheng Xuebao/Transactions of the Chinese Society of Agricultural Engineering* stood out, focusing on scientific publications covering a wide range of topics related to agricultural engineering. This journal is an important research source for professionals involved in the field of agricultural engineering in China and internationally, which once again exemplifies the significance of this topic in the Chinese agricultural economy and the concern with the generation and treatment of waste from rice cultivation, which is widely consumed in the country.

Table 03: Top 5 Journals with the Highest Number of Publications and Citations

Ranking	Journals	Documents	Citations
1º	Nongye Gongcheng Xuebao/Transactions of The Chinese Society of Agricultural Engineering	5	34
2º	Bioresource Technology	3	114
3º	Biomass and Bioenergy	2	145
4º	Nongye Jixie Xuebao/Transactions of The Chinese Society for Agricultural Machinery	2	4
5º	Process Biochemistry	1	41

Source: Authors (2024)

The journals ranked second and third presented a significantly higher number of citations compared to the other journals. These two scientific journals are relevant to the fields of bioenergy, biotechnology, and biological resources. *Bioresource Technology*, with 3 documents and 114 citations, covers a wide range of topics related to the use of biological resources for energy production. *Biomass and Bioenergy*, with 2 documents and 145 citations, focuses specifically on biomass and bioenergy.

Despite having fewer publications, these journals are more widely cited, reflecting their importance as references in the field and as vehicles for scientific dissemination on the studied topic.

In fourth place is *Nongye Jixie Xuebao/Transactions of the Chinese Society for Agricultural Machinery*, with 2 documents and 4 citations. This Chinese scientific journal is dedicated to advancing research and development in agricultural machinery technologies. Its relevance to the topic lies in precision engineering applied to the use of energy from agricultural residues, including rice straw. This journal has a more practical and applied focus compared to the others, which are more experimental and laboratory-scale in nature, with no applications at larger or real-world scales.

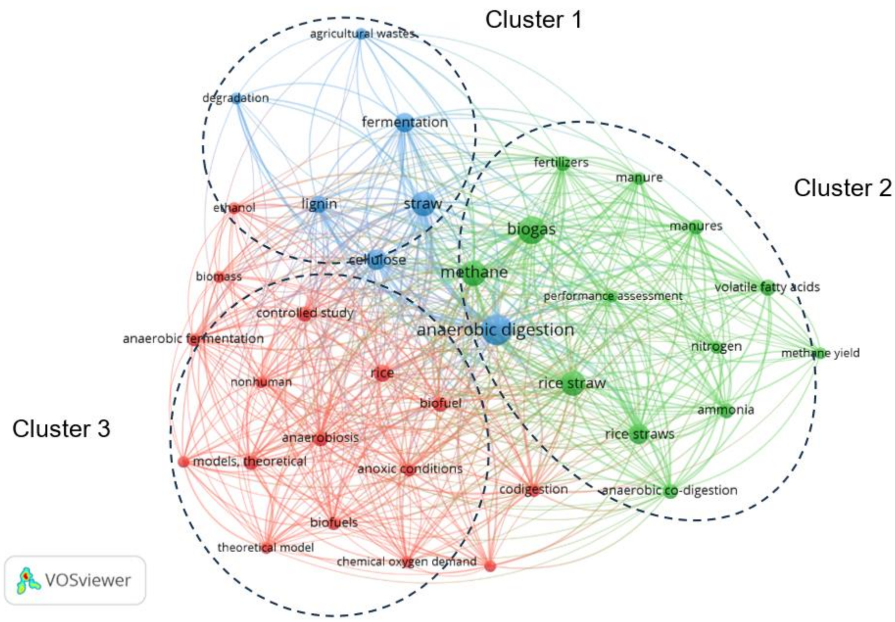
Process Biochemistry, despite having only one document, stands out with a high number of citations (41). This journal is important because it covers a wide range of topics related to applied biochemistry and industrial biochemical processes. Its relevance lies in the optimization of biological systems and large-scale production, especially in relation to bioreactors.

Just as seen in the Top 5 publications, the Top 5 journals show a preponderance of articles based on laboratory-scale contributions, indicating that the field is still in its early stages but with growing interest.

Bibliometric analysis of keyword co-occurrence

It was observed that among the 32 selected articles, the most frequent and strongest keywords were: "anaerobic digestion," with 26 occurrences; "biogas," with 21 occurrences; "methane," with 18 occurrences; and "rice straw," with 17 occurrences. Using the VOSviewer® software, a bibliometric network was created, grouping these keywords into three clusters (Figure 04). Cluster 1, in blue, indicated studies related to the agro-industrial nature and lignocellulosic composition of rice straw in connection with anaerobic digestion. Cluster 2, in green, grouped keywords related to the chemical composition of rice straw in connection with anaerobic digestion, biogas generation, and methane production. Cluster 3, in red, indicated studies focused on theoretical and kinetic modeling of biochemical processes related to the digestion of rice straw. These three clusters have a strong correlation of areas of interest, indicating synergy in this research.

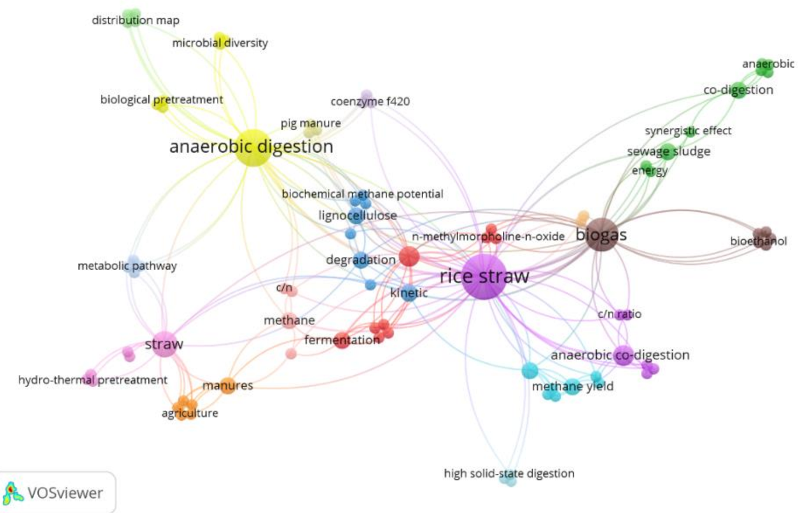
Figure 04: Bibliometric network of the most co-occurring keywords in the selected articles (2000 to 2024).



Source: Authors (2024)

Highlighting also the co-occurrences of keywords from the authors, a bibliometric network was created (Figure 05), where it was observed that the keyword with the highest occurrence and connection with others is "rice straw," with 15 occurrences, followed by "anaerobic digestion," with 10 occurrences, and "biogas," with 8 occurrences. Thus, it is identified that the articles are relevant to the topic, as the pertinent keywords are directly related to the energy potential of rice straw.

Figure 05: Bibliometric network of the most frequently occurring author keywords (from 2000 to 2024).

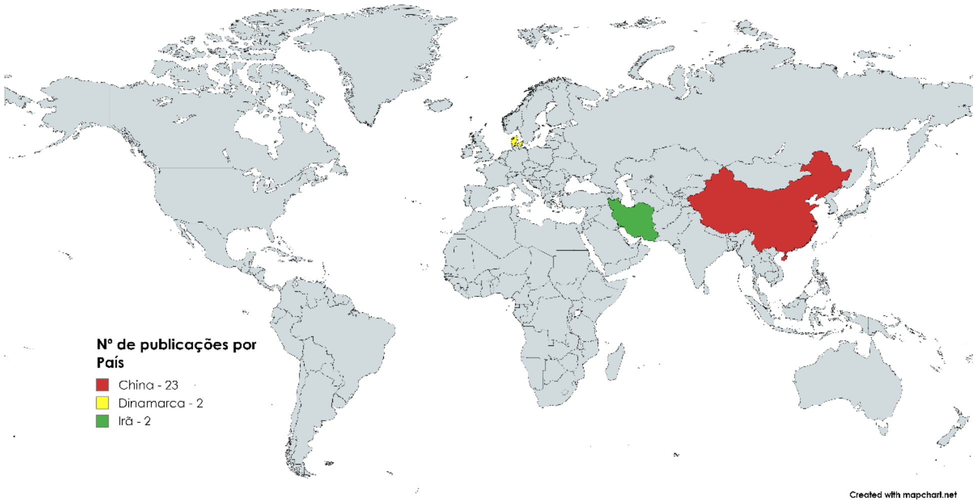


Source: Authors (2024)

Bibliometric analysis of keyword co-occurrence.

Regarding the geographic distribution (Figure 6) of scientific production in terms of authorship and co-authorship, only three countries were prominent: China (23 documents), Denmark (2 documents), and Iran (2 documents). These three countries accounted for 84.4% of the scientific production observed during the period (2000-2024). The prominence of China (71.9%) was expected due to its historical and inseparable connection with rice cultivation; however, Denmark and Iran were not anticipated. These emerging countries stand out in their interest in basic research and sustainable aspects of the energy valorization of this residue.

Figure 06: Number of publications by country.



Source: Authors (2024)

The bibliometric co-authorship network among the authors in these publications is presented in Figure 07. It is clearly divided into 3 clusters: Cluster 1 (red) with 8 authors, with Yuying Deng having the greatest influence; Cluster 2 (green) with 7 authors, with Xualan Chen leading; and Cluster 3 (blue) with Di He as the most prominent co-author. All three authors are Chinese, supporting the previous findings of China's interest and prominence in research related to the focal topic.

Figure 07: Bibliometric research network regarding author co-authorship in the selected articles.

Source: Authors (2024)

Physicochemical characterization of rice straw

Figure 8 presents a record of the raw sample before drying in the oven.

Figure 8: Rice straw sample used in the characterization.

Source: Authors (2024)

Table 04 presents the results of the physicochemical characterization of rice straw. Observing the physicochemical results of the rice straw samples, it is evident that there were no significant variations between them, which supports data uniformity and provides greater certainty regarding the ideal characteristics for efficient biogas production and the applicability of rice straw for this purpose.

Table 04: Caracterização físico-química da palha de arroz

Parameter		**(Results)**
pH		5.82 ± 0.02
Moisture (%)		8.044 ± 0.068
Electrical conductivity (µs/cm)		9.92 ± 0.023
Protein (%)		3.63
Lipids (%)		8.70
Carbohydrate (non-lignocellulosic) (%)		77.20
Solid Series (%)	Total (TS)	100
	Fixed (FS)	10.39 ± 0.14
	Volatile (VS)	89.61 ± 0.14
Fibers (%)	Cellulose	42.25± 1.952
	Hemicellulose	18.52 ± 2.126
	Lignin	14.99 ± 2.885

Source: Authors (2024)

Regarding pH, it can be defined as one of the critical factors influencing biogas production in anaerobic digestion systems, as it plays a crucial role in the stability and efficiency of the process. The ideal pH range for most microorganisms is between 6.5 and 7.5, providing better activity and efficiency in the degradation of organic matter (ANGELIDAKI, 1994).

However, observing the characterization results of rice straw, an average pH of 5.82 was found, which is below the ideal range. Therefore, comparing with the studies highlighted in the literature review, it was noted that in Mussoline et al. (2013), a minimum pH of 5.95 was found between the two samples, also highlighting the co-digestion with anaerobic sludge, which shows that the pH (5.82) found in this study may not be a limiting factor by itself. Furthermore, the study by Abudi et al. (2016) also reported a pH of 6.22, even when rice straw was co-digested with thickened activated sludge (TWAS), demonstrating that the raw residue (even with acidic pH) can still be used.

Rice straw exhibited a low water content in its composition, with an average of only 8.044% by mass. This is explained by the drier appearance of the residue due to the drying process applied to rice after its harvest in the processing industry. After the rice grains are harvested and separated from the straw, they typically undergo several stages, including drying, to reduce moisture content and ensure grain quality and durability. Since rice straw is a byproduct of the processing, it is also exposed to this drying process.

Regarding electrical conductivity, it was observed that it can affect biogas production by anaerobic bacteria in several ways, including its influence on bacterial activity, the redox potential of the system, and nutrient distribution. The obtained result (9.92 µs/cm) is relatively low and may indicate a low concentration of free ions in the solution, which is suitable for optimal conditions for biogas production.

The concentrations of proteins, lipids, and carbohydrates in rice straw indicate that it is predominantly composed of carbohydrates, which account for about 77.20% of its dry mass. The protein content (3.63%) is low, while the lipid content (8.70%) is moderate, especially in comparison to other lignocellulosic materials. These results demonstrate that, in addition to being rich in lignocellulosic material, rice straw also contains fractions of interest, such as carbohydrates and lipids, which can be relevant for bioenergy and biotechnological processes, contributing to the valorization of this biomass.

Regarding the solid series, a volatile solids (VS) percentage of 89.61% was observed, indicating a high amount of potentially biodegradable organic material. Depending on the fiber content (cellulose, hemicellulose, and lignin), the biodegradability of the waste can be more realistically assessed, as part of the carbon may be in a more recalcitrant chemical form. Similarly, a VS percentage of 74% was observed in the study by Teghammar et al. (2012), 88.4% in Mussoline et al. (2013), 79% in Thomsen et al. (2014), 70.37% in Abudi et al. (2016), and 80.82% in Zuo et al. (2020). Therefore, one of the characteristics typically observed in this residue is a relatively high percentage of total volatile solids, which initially makes it favorable for methane production.

Regarding fiber analysis, when compared to the literature, it can be noted that the rice straw presented varied values of cellulose, hemicellulose, and lignin. Regarding cellulose, a higher content was found compared to other studies, except for Zuo (2020), who reported 40.44%, indicating a greater availability of fermentable material, as cellulose is one of the main carbon sources for biogas production. However, the hemicellulose content is among the lowest, similar to Teghammar (2012) with 20% and Thomsen (2014) with 20.4%, indicating that there is less material accessible for anaerobic digestion, as hemicellulose is easier to degrade than cellulose and contributes to biogas production. The lignin content is considerably higher than in Abudi (2016) (6%) and Zuo (2020) (2.17%), but lower than in Teghammar (2012) (19%), suggesting that rice straw has a high level of difficulty in anaerobic digestion, as lignin is the main inhibitor of this process, preventing enzyme access to cellulose and hemicellulose polymers. Thus, although the analyses show a high cellulose content, the high lignification (lignin content) can reduce the efficiency of anaerobic digestion, suggesting the need for pretreatments or co-digestion with other more easily degradable residues to reduce the lignin content and increase biogas production.

Perspectives, challenges and limitations for the more sustainable use of rice straw

From bibliographic and bibliometric research and the characterization of the biomass obtained, we can summarize the perspectives, challenges and limitations for the more sustainable use of rice straw

Perspectives

Rice straw, a by-product resulting from rice harvesting, has great potential for sustainable uses, especially in the context of the circular economy and the mitigation of environmental impacts. Traditionally, it is discarded or burned in the open, contributing to greenhouse gas (GHG) emissions and air pollution. However, technological advances and new approaches are expanding its applications, making it a promising alternative in several sectors.

- **Renewable energy production:** Rice straw can be used as biomass for energy generation. It can be burned in industrial boilers or processed in gasification technologies, transforming agricultural waste into a clean energy source. It is also possible to convert it into biogas through anaerobic digestion, which reduces dependence on fossil fuels.
- **Biofuel production:** Research has explored the conversion of rice straw into bioethanol and biodiesel, using chemical and biotechnological processes, such as hydrolysis and enzymatic fermentation.
- **Manufacturing of construction materials:** Rice straw is rich in silica, an important component for cement production. It can be used in the manufacture of sustainable concrete, bricks and panels for construction, reducing the use of non-renewable resources. Furthermore, the cellulose present in straw can be used to manufacture thermal and acoustic insulation boards.
- **Biochar production:** The carbonization of rice straw generates biochar, a type of charcoal that can be used as a soil conditioner. It improves water and nutrient retention in the soil, in addition to capturing carbon, contributing to the mitigation of climate change.
- **Paper and packaging industry:** Rice straw fiber can be used to manufacture recycled or biodegradable paper, presenting itself as an alternative to conventional paper, which requires cutting down trees.
- **Biodegradable plastics industry:** Combined with natural polymers, rice straw can be used in the production of biodegradable or compostable plastics, reducing the environmental

impact of using conventional plastics.

- **Agricultural use:** Straw can be transformed into organic compost, serving as a natural fertilizer that enriches the soil without the need for chemical inputs. It can also be used as mulch, protecting the soil against erosion and maintaining humidity.
- **Animal food and mushrooms:** Although it has low nutritional value, straw can be used as animal feed or as a substrate for growing mushrooms, such as shiitake and pleurotus.
- **Nanotechnology and new materials:** Research is exploring the use of silica extracted from straw to manufacture silica nanoparticles, applicable in the electronics and advanced materials industries.

Challenges and limitations

Despite the potential, there are challenges to the sustainable use of rice straw:

- **Logistics and transport:** Collecting and transporting straw can be costly due to its low weight and density.
- **Technology:** Many of the applications require advanced technology and significant investments, limiting large-scale implementation.
- **Awareness:** Farmers and companies may not be aware of the potential of rice straw, preferring to dispose of it in a traditional way.

CONCLUSION

Rice straw, a by-product of rice harvesting, offers significant potential for sustainable applications, particularly in energy production through biogas generation. Its increasing relevance stems from the global rise in rice cultivation, especially in countries like China, a major producer and consumer. Biogas production is seen as a viable solution for managing the growing volume of waste, benefiting both small and large-scale producers. The residue's high cellulose and hemicellulose content provides a strong foundation for biogas production, as these structural carbohydrates can be decomposed and converted into methane. However, its lignin content poses a challenge, as this resistant substance limits anaerobic digestion efficiency. To overcome this, pre-treatment techniques are recommended to enhance microbial access to cellulose and hemicellulose, increasing energy yields.

While rice straw has additional applications in biofuels, construction materials, and advanced materials, challenges like logistics, technology costs, and limited awareness hinder broader adoption. Despite these barriers, biomass remains a promising resource for energy valorization, requiring further research to optimize its potential and address its lignocellulosic limitations.

REFERENCES

ABUDI, Z. N. et al. Effects of pretreatments on thickened waste activated sludge and rice straw co-digestion: Experimental and modeling study. **Journal of environmental management**, v. 177, p. 213-222, 2016.

BODIE, Aaron R. et al. Current trends of rice milling byproducts for agricultural applications and alternative food production systems. **Frontiers in Sustainable Food Systems**, v. 3, p. 47, 2019.

COLOMBO, Raffaella et al. Rice Byproduct Compounds: From Green Extraction to Antioxidant Properties. **Antioxidants**, v. 13, n. 1, p. 35, 2023.

CUNHA, D. F. et al. **Bioestimulantes na cultura do arroz inoculado com Pyricularia grisea.** 2021.

DE OLIVEIRA, M.; AMATO, G. W. **Arroz:** tecnologia, processos e usos. Editora Blucher, 2021.

DE SOUZA, S. M.; BASÍLIO, Letícia Silva Pereira; PEREIRA, Joelma. **Grãos de arroz biofortificados:** um referencial teórico. 2022.

DOMENE, S. M. A. et al. Importância nutricional do arroz e do feijão. **Arroz e feijão: tradição e segurança alimentar. Brasília: Editora Embrapa**, p. 147-164, 2021.

EDWIGES, Thiago et al. Influence of chemical composition on biochemical methane potential of fruit and vegetable waste. Waste Management, v. 71, p. 618-625, 2018.

ESA, Norhaizan Mohd; LING, Tan Bee; PENG, Loh Su. By-products of rice processing: An overview of health benefits and applications. **J Rice Res**, v. 1, n. 107, p. 2, 2013.

GRISOLIA, Giulia; FINO, Debora; LUCIA, Umberto. Biomethanation of rice straw: a sustainable perspective for the valorisation of a field residue in the energy sector. **Sustainability**, v. 14, n. 9, p. 5679, 2022.

FAGERIA, N. K.; WANDER, A. E.; SILVA, S. C. Rice (Oryza sativa) cultivation in Brazil. **Indian Journal of Agronomy**, v. 59, n. 3, p. 350-358, 2014.

FIJALKOWSKI, Mateusz et al. Rice husks-structure, composition and possibility of use them at surface treatment. In: **Materials Science Forum**. Trans Tech Publications Ltd, 2016.

HALBERSTADT, K. F. et al. Práticas sustentáveis na destinação dos resíduos resultantes da cadeia produtiva do arroz. **Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental**, p. 298-312, 2015.

JIN, Yunkai et al. Improved bioenergy value of residual rice straw by increased lipid levels from upregulation of fatty acid biosynthesis. **Biotechnology for Biofuels and Bioproducts**, v. 16, n. 1, p. 90, 2023.

LORENZETT, D. B.; NEUHAUS, M; SCHWAB, N. T. Gestão de resíduos e a indústria de beneficiamento de arroz. **Revista Gestão Industrial**, v. 8, n. 1, 2012.

MENDES, K.;**Efeitos de mudanças na política comercial brasileira para a cadeia produtiva do arroz.** 2024.

MUCHLISYIYAH, Jhauharotul et al. Parboiled rice processing method, rice quality, health benefits, environment, and future perspectives: A review. **Agriculture**, v. 13, n. 7, p. 1390, 2023.

MÜLLER, Amanda et al. Rice drying, storage and processing: effects of post-harvest operations on grain quality. **Rice Science**, v. 29, n. 1, p. 16-30, 2022.

MUSSOLINE, et al. "Enhanced Methane Production from Rice Straw Co-Digested with Anaerobic Sludge from Pulp and Paper Mill Treatment Process." **Bioresource Technology**, v. 148, p. 135–143, 2013.

NERY, I. B. D.; CELLA, D. **ARROZ:** uma descrição do mercado. **Revista Interface Tecnológica**, v. 19, n. 2, p. 549-460, 2022.

NNADIUKWU, Uzoamaka C. et al. Phytochemical and Nutrient Composition of Rice Husks. **Tropical Journal of Natural Product Research**, v. 7, n. 2, 2023.

OLIVEIRA, M. P. Pré-tratamento hidrotérmico de cama de aviário sintética a base de palha de arroz para a produção de biogás via digestão anaeróbia. 2022.

PARTAMA, IB Gaga et al. The effect of rice hull in diets on performance, antioxidant capacity and blood chemical profile of bali duck. **International Journal of Poultry Science**, v. 18, n. 2, p. 69-75, 2019.

RAMÍREZ, Angie Tatiana Ortega; TOVAR, Miriam Reyes; SILVA MARRUFO, Oscar. Rice husk reuse as a sustainable energy alternative in Tolima, Colombia. **Scientific Reports**, v. 14, n. 1, p. 10391, 2024.

SAIDELLES, A. P. F. et al. Gestão de resíduos sólidos na indústria de beneficiamento de arroz. **Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental**, p. 904-916, 2012.

TEGHAMMAR, A. et al. Enhanced biogas production from rice straw, triticale straw and softwood spruce by NMMO pretreatment. **Biomass and Bioenergy**, v. 36, p. 116-120, 2012.

THOMSEN, S. T.; KÁDÁR, Z.; SCHMIDT, J. E.. Compositional analysis and projected biofuel potentials from common West African agricultural residues. **Biomass and Bioenergy**, v. 63, p. 210-217, 2014.

ZUO, XIAOYU, et al. "The Relationships among SCOD, VFAs, Microbial Community, and

Biogas Production during Anaerobic Digestion of Rice Straw Pretreated with Ammonia." Chinese Journal of Chemical Engineering, vol. 28, no. 1, Jan. 2020, pp. 286–292.

ZUO, X. et al. The relationships among sCOD, VFAs, microbial community, and biogas production during anaerobic digestion of rice straw pretreated with ammonia. **Chinese Journal of Chemical Engineering**, v. 28, n. 1, p. 286-292, 2020.

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