PRODUCTION ENGINEERING ARCHIVES 2021, 27(2), 130-136

PRODUCTION ENGINEERING ARCHIVES

ISSN 2353-5156 (print)
ISSN2353-7779 (online)

Exist since 4th quarter 2013
Available online at www.pea-journal.eu

Production potential of biodiesel, methane and electricity in the largest steamed rice industry in Rio Grande do Sul, Brazil: case study

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Article history
Received 08.03.2021
Accepted 12.05.2021
Available online 14.06.2021

Keywords
Biodiesel
Bioenergy
Biofuel
Biogas
Rice

Abstract
The potential for energy production from effluents and husks generated in grain processing in the rice parboiling industries in Brazil is capable of promoting energy self-sufficiency in the sector, through the production and use of syngas and biogas. However, the production of methane from residues of the rice parboiling industries is still little explored by academic studies, in general studies on the potential of methane production by this same type of effluent are found in the south of the country, however, the same is not true for the production of biodiesel from rice bran oil. The objective of this study was to determine the production potential of biodiesel, methane and electric energy of the largest parboiled rice industry in Rio Grande do Sul, located in the southern region of the country. According to this study, the rice parboiling industry located in Rio Grande do Sul, Brazil, has a production potential of $1.2 \cdot 10^2$ m^3/day of biodiesel, $2.93 \cdot 10^4$ Nm^3/day of methane and $1.89 \cdot 10^5$ kWh/day of electricity. Despite being a significant and high potential, which may reduce the financial expenses of the industry regarding the purchase of energy from concessionaires, it is not able to promote its energy self-sufficiency. At the same time, it would be necessary to add the energy production potential of the rice husk gasification syngas highlighted in other studies

DOI: 10.30657/pea.2021.27.17 JEL: Q16, L65, M11

1. Introduction

Since the end of the 19th century, oil has been used as the main energy matrix, corresponding to 33.3% of global energy consumption (Jiang et al., 2017; Varão et al., 2017). The depletion of fossil fuels and the increase in the price of crude oil makes the search for new energy sources an emergency, thus the development of clean and renewable energies also represents the possibility of reducing the emission of (Jiang et al., 2017).

The use of bioenergy provides a better balance for the biogeochemical cycle of carbon, as it allows the recycling of sources of biological origin through the production of energy and the consumption of carbon resulting from photosynthesis (Creutzig et al., 2015; Gil de los Santos et al., 2012; González-González et al., 2018). Its sources are in the form of biomass from crops and agricultural waste, solid urban waste and effluents with a high content of organic matter. In this context, the development and use of biomass for energy generation allowing the reduction of greenhouse gases (Macek, 2019).

Brazil is the ninth largest rice producer in the world, in the 2018/2019 harvest the country produced around 10.45 million tons of rice. Most of the Brazilian rice production is concentrated in the southern region of the country, mainly in the state of Rio Grande do Sul. The state is responsible for more than 70% of the national production. In addition to being a major grain exporter, the country is also a major consumer. The grain is part of the Brazilian diet, having its consumption per capita at about 25 kg/year (Queiroz et al., 2007; Spinosa et al., 2016) . Of all the rice consumed in the country, about 25% is of the parboiled type (Paraginski et al., 2014). The processing of parboiled rice involves a grain soaking unit, where the main generation of effluent in the sector occurs.

The processing of rice involves several processes (Tutak et al., 2020, Ulewicz et al. 2021). In general, the main productive cost of the rice industries is the consumption of electricity, which can exceed 40% of the total, so that it has a great influence on the profitability of the industries that develop such activity (Macek et al., 2020). Among the processes of industrial processing of the grain, the ones that have the greatest influence on the demand for electric energy are the debarking, which represents 52% of the demand, followed by the parboiling stage, with 28% of the general consumption.

Another cost to the rice processing is that it increases the amount of carbon dioxide in the atmosphere.

According to the classification of EPE, the rice processing industries are classified as Food and Beverage Industries, this category is responsible for 9% of the final energy consumption of the national industrial sector, being that in the South region, as in RS, consumption is even higher, where the manufacture of food products is responsible for the highest consumption of electricity, 23.4%.

The state of Rio Grande do Sul has a developed industrial sector, occupying the 3rd national position and representing 27.5% of the state's economy, one of its main branches being the agro-industry. In 2017, the industrial sector was responsible for the highest consumption of electricity in the state (EPE, 2018). In general, industries have suffered in the last decade a significant increase in their production costs due to the use of electricity.

Nadaleti (Nadaleti, 2019) shows that the potential for energy production from effluents and husks generated in grain processing in the rice parboiling industries in Brazil can promote energy self-sufficiency in the sector, through the production and use of methane and biodiesel. Thus, highlight the relevance of the study of the application of residues, such as husk and grain bran, and effluents from rice processing in the production of biofuels as a source of clean and renewable energy.

Methane production from residues from the rice parboiling industries is still little explored by academic studies. In addition, it has studies on the potential of methane production by this same type of effluent in the southern region of the country (Nadaleti, 2019) and in the city of Pelotas, located in the state of Rio Grande do Sul (Rodrigues Silveira et al., 2019), however, the same does not occur regarding the production of biodiesel from rice bran oil.

To produce biodiesel, the technique generally applied on industrial scales is that of transesterification of oils extracted from biomass to obtain fatty acids, this process guarantees oil characteristics similar to those of diesel oil. Anaerobic digestion, on the other hand, is a valuable source of bioenergy capable of offering a competitive solution in relation to the global dependence on fossil fuels by producing methane-rich biogas from effluents with a high load of organic matter (González-González et al., 2018).

Considering Rio Grande do Sul the Brazilian state responsible for the largest national production of rice, the state becomes attractive from the scientific point of view in relation to conducting research that explores the production of biofuels and bioenergy. Based on the above, the objective of this study was to determine the production potential of biodiesel, methane and electric energy of the largest parboiled rice industry in Rio Grande do Sul, located in the southern region of the country.

2. Some aspects of methane and biodiesel production

Biodiesel

The use of rice bran in the production of biodiesel does not represent a new occupation and use of the land, since the bran is already generated on a large scale in the country during the processing of the grain. This possibility stands out for promoting the diversification of the sources of the bioenergetic matrix and relieving the occupation and use of the soil for soy planting in the country.

Rice oil is obtained from the grain bran, such bran is considered an agricultural residue from the stages of husking and polishing the grain, which, in general, is intended for the production of animal feed. Bran contains 15 to 23% oil (Sinha et al., 2008; Zullaikah et al., 2005) consisting of about 68 to 71% triacylglycerols, 2 to 3% diglycerols, 5 to 6% monoglycerols and 2 to 3% of free fatty acids.

Due to enzymatic systems present in the bran, triglycerides are rapidly hydrolyzed, increasing the acidity content. Thus, the feasibility of extracting oil for refining for human consumption occurs only when the acidity content is reduced (Evangelista, 2012). In a study by Zullaikah et al. (Zullaikah et al., 2005), at zero storage time the percentage of free fatty acids in rice bran was above the pre-established by ANVISA ("ANVISA – Agência Nacional de Vigilância Sanitária. Resolução no 482, de 1999. Regulamento Técnico, no196-E, Brasília: Diário Oficial da União.," n.d.). On the other hand, according to Sinha, these characteristics ensure that rice bran vegetable oil produces biodiesel with excellent physical and chemical properties (Sinha et al., 2008).

Nadaleti (Nadaleti, 2019) obtained an average production potential of $1.7 \cdot 10^4$ Nm^3/day of methane and $5.95 \cdot 10^4$ kW/day of electric energy when estimating the biofuel production potential in the parboiled rice industry in throughout Rio Grande do Sul, during the study of this author the state had a total of 34 parboiled rice industries.

Methane

In terms of experimental studies on the production of biogas and methane from the anaerobic digestion of the effluent from rice parboiling, studies by Nadaleti et al. (Nadaleti et al., 2018), the ideal temperature for biogas production via anaerobic digestion in a batch of effluent and anaerobic sludge from the UASB at the Effluent Treatment plant for the production of parboiled rice is 35°C, the authors obtained a production of

5,198 dm³ of biogas over a period of 276 hours. Lourenço (Lourenço et al., 2019) carried out studies on the co-digestion of effluent and sludge from the UTE of the ETE of the parboiling of rice and fruit peels in batches at 35°C, the authors obtained 11,730 dm³ of biogas during 168 hours of codigestion with orange peel and 8,490 dm³ with banana peel. Nadaleti et al. (Nadaleti et al., 2019) studied co-management with effluent from a dairy industry, also in batch and at 35°C, for 252 hours and obtained a total production of 1,500 dm³ of methane. Reactors of 2,150 dm³ in volume and 30% headspace were used for all the studies mentioned.

The critical point for the generation of effluents in a parboiled rice industry occurs in the flooding stage, as it uses a large volume of water that in turn retains grain properties during the bath, and for each kilo of parboiled rice is generated from 2 to 4 dm³ of effluent (Gil de los Santos et al., 2012). The effluent generated is characterized by high loads of organic substances and nutrients, such as nitrogen and phosphorus (Faria et al., 2006; Queiroz et al., 2007), which, when disposed in water bodies without proper treatment, can lead to the eutrophication process (Faria et al., 2006; Okunuki et al., 2004) Bastos et al. (Bastos et al., 2010) report that the variability in the characterization of the effluent from rice parboiling results from seasonal aspects related to grain production, so that different studies present effluents from the same industrial sector with high variation in their characterization. Such variation can influence the production yield of biogas and methane during the anaerobic digestion of the effluent, since the microorganisms that act in the process require physical-chemical conditions according to their specificities. According to Khalid et al. (Khalid et al., 2011)] the ideal pH for the development of methanogenic bacteria is found in neutrality. For the C/N ratio, it was indicated that anaerobic digesters should be operated with a C/N ratio between 20 and 30.

Silveira et al. (Rodrigues Silveira et al., 2019), Evaluated the potential of methane production from the digestion of rice effluent by parboiled by three different methodologies, Metcalf Eddy (Tchobanoglous et al., 2002), Speece (Speece, 1996) and UNFCCC ("UNFCCC, Approved Methodologies for Small Scale CDM Project Activities. Type Ill, AMS lll.H Methane recovery in wastewater treatment, Version 16.0, 2012.," n.d.). According to the author, the UNFCCC method resulted in less methane generation potential. The maximum mass production capacity of methane adopted by the method is equal to 0.25 kg of methane produced per kg of COD removed. In addition, the method considers reducing factors linked to uncertainties, establishing a more conservative format in relation to the others. Metcalf & Eddy and Speece use a theoretical position for the relationship between the production of methane and COD removed. For this quantification, Speece also considers the ideal temperature and pressure conditions for the reactors.

Silveira et al. (Rodrigues Silveira et al., 2019) studied the potential for energy production from synthesis gas and methane in the rice industries of Pelotas and region, a city located in the south of Rio Grande do Sul, the author determined a potential of $3.01 \cdot 10^4$ kWh/day of electric energy for methane and $1.23 \cdot 10^6$ kWh/day of electric energy for syngas. The study also addressed the energy balance of the industries, based on the chemical energy necessary for the parboiling of the grain, so that the sector's energy self-sufficiency was obtained. However, the author points out that such self-sufficiency only occurs with exploring the energetic potential of syngas together of biogas.

A mixture of rapeseed oil and alcohols can also be used for the production of biodiesel. By pressing rapeseed oil from one ton of grain, we are able to obtain 400 liters of rapeseed oil. The average yield of rapeseed per hectare is 2500 kg of grain. Therefore, we need 5 ha of land to obtain 5000 liters of rapeseed oil. Using straw and cakes after pressing rapeseed oil, we get 5000 kg of biomass from 1 ha. One ton of biomass will yield 220 liters of alcohol. To obtain 5000 liters of alcohol, we need 4.55 ha of arable land.

To sum up, in order to obtain 10,000 liters of rapeseed oil mixed with alcohol, we need 5 ha of agricultural land.

Table 1. Fuel consumption for the production of 12,500 kg of rape and 22,750 kg of straw

Type of activity	**Consumption of fuel (mixture) l**
Stubble	63
Tillage	110
Cultivation	104
Seeds	29
Fertilizing	42
Protective treatments	42
Harvesting seeds	104
Commuting	33

The consumption of the oil-alcohol mixture, as it was noticed during the tests on the dynamometer, is higher by about 10%. The energy value of mixing oil with alcohols is at the level of diesel fuel. An energy value of 36 MJ / l was adopted for the calculations. The energy value of the fuel used (Ezon) is:

Ezon = 36 MJ / l * 494 l = 17784 MJ

The following were also used in the production of rapeseed: Table2.

In addition to having high-performance biomethane or biodiesel production technologies, an investor introducing a new technological solution to his company should take into account the local public mood. Mental limitations of the population are often a problem that prevents the effective application of new solutions. More on this can be found in the work (Ingaldi and Klimecka-Tatar, 2020).

Table 2. Consumption of materials in the production of rapeseed:

Type of material	**Consumption kg**	**Conversion factor MJ / kg**	**Energy value of MJ**

Nitrogen fertilizers	1400	20	28000
Phosphorus fertilizers	570	7	3990
Potash fertilizers	630	5	3150
Chemical plant protection products	15	150	2250
Sum			37390

3. Material and methods

The quantification of the potential of rice bran oil production was carried out based on data from the literature (Sinha et al., 2008; Zullaikah et al., 2005) and on the operating licenses of the rice industries of Rio Grande do Sul granted by the State Foundation for Environmental Protection. The potential for biodiesel production from such oil, was calculated based on results obtained in pre-existing studies regarding the efficiency of the methyl transesterification of vegetable oil (Lourenço et al., 2019).

From the data obtained in the operating licenses of the rice industries of Rio Grande do Sul granted by the State Foundation for Environmental Protection, UNFCCC ("UNFCCC, Approved Methodologies for Small Scale CDM Project Activities. Type Ill, AMS lll.H Methane recovery in wastewater treatment, Version 16.0, 2012," n.d.) methodology was applied to calculate the methane generation potential. The characterization of the effluent applied in the methodology was based on the results obtained by Lourenço (Lourenço et al., 2019):

$$Q_{CH4} = Q_{ef} \cdot COD_{ef} \cdot Bo_{CH4} \cdot MCF \cdot CFU \cdot \eta \cdot COD \quad (1)$$

where:
Q_{CH4}: amount of methane (kg CH_4 h^{-1});
Q_{ef} : effluent flow (m^3 h^{-1});
COD_{ef} : COD of the effluent (kg DQO m^{-3});
Bo_{CH4}: maximum capacity for mass methane production (kg CH_4 (kg DQO)$^{-1}$), equal to 0.25;
MCF: methane correction factor, referring to anaerobic reactors, UASB reactors and fixed bed reactors, equal to 0.8.
CFU : correction factor due to uncertainty, equal to 0.9;
$\eta \cdot$ COD : COD removal efficiency for UASB reactors, equal to 0.7.

In order to determine the energy potential of Rio Grande do Sul from biodiesel from rice bran vegetable oil and methane from the rice parboiling industries, the theoretical PCI of both biofuels 51.55 MJ m^{-3} for methane (Rodrigues Silveira et al., 2019) and 55.77 MJ m^{-3} for biodiesel (Lourenço et al., 2019). Thus, the potential for producing electric and thermal energy from biofuels, methane and biodiesel, were calculated based on equations of Nadaleti (Nadaleti, 2019):

$$CE = Q_{av.} \cdot LCV \quad (2)$$

where:
CE_{CH4}: chemical energy production (MJ/day);
$Q_{av.\ CH4}$: volume of fuel (m^3/day);
LCV_{CH4}: lower calorific value of biofuel (MJ m^{-3}).

$$E = CE \cdot \eta M \cdot C \quad (3)$$

where:
E: energy (kW/day);
ηM: engine efficiency (%), equal to 85 for thermal energy and 45 for electrical energy for the CHP engine powered by methane (Jiang et al., 2017) 80 for thermal energy and 20 for electric energy for the mCHP engine powered by biodiesel (Lourenço, 2020);
C: conversion from MJ to kWh, equal to 0.2778.

Table 3. Industry data and potential for production of biodiesel, methane and electricity.

Crude rice (ton/day)	$5.92 \cdot 10^3$
Bran (ton/day)	$5.86 \cdot 10^2$
Oil (m^3/day)	$1.21 \cdot 10^2$
Wastewater (m^3/day)	$1.78 \cdot 10^4$
Biodiesel (m^3/day)	**$1.20 \cdot 10^2$**
Methane (Nm^3/day)	**$2.93 \cdot 10^4$**
Energy (kWh/day)	**$1.89 \cdot 10^5$**

4. Discussion

According to the data collected by this study, the largest parboiled rice industry located in Rio Grande do Sul produces a total of $5.92 \cdot 10^3$ ton/day of rice, so that it has a potential to generate $1.89 \cdot 10^5$ kWh/day of electric energy through the burning of $1.20 \cdot 10^2$ m^3/day of biodiesel and $2.93 \cdot 10^4$ Nm^3/day of methane to be produced through grain bran and parboiling effluent.

When considering the chemical energy required for $1.06 \cdot 10^3$ MJ/ton grain parboiling determined by Nadaleti and that a Rice Bran Oil Extraction System has a demand of $3.70 \cdot 10^2$ MJ/ton ("Sistema Granjatec de Extração de Óleo de Farelo de Arroz - Extração de Óleo e Produção de Farelo," n.d.), the energy use of only the biofuels covered in the present study is not able to promote the self-sufficiency of the industry (Table 2):

Table 4. Energy balance of the industry considering the production of biofuels and bioenergy.

Energy demand (MJ/day)	**$6.49 \cdot 10^6$**
Biodiesel potential (MJ/day)	$4.65 \cdot 10^4$
Methane potential (MJ/day)	$4.35 \cdot 10^6$
Total energy potential (MJ/day)	**$4.40 \cdot 10^6$**

In addition to ensuring greater energy security for the sector, the objective of using all available energy sources in waste and effluents would allow the cycle of waste-to-energy technology to be concluded. In this context, there is still the possibility to explore the potential for energy production from synthesis gas in the gasification of rice husks, contributing to the diversification of the state's industrial energy matrix, increasing the gains from the sale of surplus energy and reducing negative environmental impacts.

The waste-to-energy technology presents itself as a potentially sustainable and environmentally friendly solution to deal with the growing generation of waste in general, offering the possibility of ecologically correct and economically viable energy generated by biological and thermal processes responsible for extraction of energy stored in waste streams (Rajaeifar et al., 2019). The use of waste in energy technologies, such as the production of biogas and biodiesel, is one of the best options to meet the global demand for energy. Biogas is often presented as the best alternative due to its diversity of energy applications (Khalil et al., 2019). The energy recovery of these residues and effluents, which represent environmental liabilities when not properly treated, allows to maintain or even reduce the waste's carbon cycle and reduce the emission of greenhouse gases. Thus, while non-renewable energy elevates the world's environmental degradation, renewable energy helps to reduce and control it when replacing fossil energies (Sharif et al., 2019). In addition to reducing environmental liabilities, the use of these residues for energy generation can reduce industry expenses or promote revenue generation. to the environmentally appropriate final disposal.

However, it is important to note that the production of 10 kg of biodiesel generates about 1 kg of glycerol (Papanikolaou et al., 2017), thus, the supply of glycerol grows linearly with the increase in the production of biofuel. In 2017 alone, Brazil achieved a production of more than 4 million cubic meters of biodiesel ("ANP - Agência Nacional do Petróleo, Gás Natural e Biocombustíveis. Anuário Estatístico 2018," n.d.), that is, a generation of more than 400 thousand tons of glycerol. It is predicted that in 2021 the global production of biodiesel will generate 3 million tons of glycerol (Koutinas et al., 2014).

The high production of biofuel caused the price of this by-product to fall, weakening its market. Currently, glycerol is subjected to separation and purification processes to obtain the glycerin to be marketed, with low added value, for the cosmetic and cleaning chemical industries (Almeida et al., 2018). Bearing in mind that the industrial sector uses only glycerin, unrefined glycerol is characterized as an environmental liability.

Since glycerol is a stable compound consisting of three hydroxyl functional groups with hydrophilic and hygroscopic properties, it is able to raise the potential in numerous applications, that is, its molecular structure and physicochemical properties give the compound multifunctionality (Okoye and Hameed, 2016). The chemical composition of glycerol varies according to the catalyst and efficiency of transesterification, however the efficiency in the recovery of biodiesel and the presence of impurities in the raw material can also influence its composition of the crude glycerol fraction (Yang et al., 2012). According to Hansen et al. (Hansen et al., 2009), the chemical compositions of crude glycerol from different producers vary between 38% and 96% in the glycerin content.

The use of a co-substrate such as glycerol in anaerobic digestion can facilitate the process of producing biogas and methane, since the by-product of biodiesel production can act as a carbon source for several microorganisms in the process and thus promote the necessary balance of the ratio C/N of the middle. The application of glycerol as a co-substrate for the anaerobic digestion of starch effluent is capable of promoting 94% greater production when compared to the anaerobic digestion of the same effluent without the addition of glycerol and a 46% increase in methane production with the addition of glycerol to the anaerobic digestion process. However, glycerol can be toxic to the anaerobic digestion process, and it is essential to determine the support limit for the medium. It was found found that the addition of 3% glycerol in the anaerobic digestion of starch is capable of generating a drop in the production of biogas, since its addition confers toxicity to the medium, while the addition of 2% promotes growth in the production of biofuel.

5. Conclusion

According to this study, the rice parboiling industry located in Rio Grande do Sul, Brazil, has a production potential of $1.20 \cdot 10^2$ m^3/day of biodiesel, $2.93 \cdot 10^4$ Nm^3/day of methane and $1.89 \cdot 10^5$ kWh/day of electricity. Despite being a significant and high potential, which may reduce the financial expenses of the industry regarding the purchase of energy from concessionaires, it is not able to promote its energy self-sufficiency. At the same time, it would be necessary to add the energy production potential of the rice husk gasification syngas highlighted in other studies.

In this context, the sector would guarantee its self-sufficiency and explore new sources of energy from its waste and effluents, in order to reduce its financial expenses, mitigate its negative environmental impacts and promote the diversification of the state's industrial energy matrix through technology waste-to-energy, with high utilization of its residues and effluents for energy purposes. In addition, the energy recovery of these residues and effluents makes it possible to maintain or even reduce the emission of greenhouse gases, considering the replacement of fossil fuels with biofuels.

The importance of exploring new applications for the glycerol generated in the production of biodiesel stands out for future studies, mainly in the feasibility of its use for anaerobic co-digestion with the effluent, in order to increase the production of biogas and consequently the energy potential of sector.

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巴西南里奥格兰德州最大的蒸米产业中生物柴油，甲烷和电力的生产潜力：案例研究

關鍵詞
生物柴油
生物能源
生物燃料
沼气
米

摘要
巴西稻米煮制行业在谷物加工过程中产生的废水和果壳产生的能源潜力，可以通过生产和使用合成气和沼气来促进该行业的能源自给自足。但是，学术研究仍未从稻米煮沸工业的残余物中生产甲烷，在该国南部发现了关于这种类型废水的甲烷生产潜力的一般研究。用米糠油生产生物柴油并非如此。这项研究的目的是确定位于该国南部地区的南里奥格兰德州最大的半熟大米产业的生物柴油，甲烷和电能的生产潜力。根据这项研究，位于巴西南里奥格兰德州的大米煮饭产业的生物柴油生产潜力为 1.2·102 立方米/天，甲烷的生产潜力为 2.93·104 Nm3 /天 电力为 1.89·105 千瓦时/天。尽管潜力巨大且潜力巨大，这可能会减少从特许经营商购买能源方面的行业财务支出，但它无法促进其能源自给自足。同时，有必要增加其他研究中强调的稻壳气化合成气的能源生产潜力。