Environmental, field and impurity factors to increase the agricultural performance of Brazilian and Australian sugarcane mills

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Received: 24 October 2020 / Accepted: 27 April 2021 / Published online: 15 May 2021
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Abstract

This study aims to identify explanatory factors to increase the agricultural performance of Brazilian and Australian sugarcane mills. The relevance of Brazil and Australia for the sugar industry motivated the development this study based on the most important factors in both countries responsible for increasing the efficiency in sugarcane production. Thus, this study is designed to assess the hypothesis that there are a few explanatory variables that are deeply responsible for the agricultural efficiency in the sugar-energy sector. As a specific objective, it proposes a DEA (Data Envelopment Analysis) model that seeks to optimize the production of Total Recoverable Sugar (TRS) by planted area, and simultaneously, minimizes mineral and vegetable impurities. The sample consists of 82 observations from 32 sugarcane mills. An agricultural efficiency study was performed using the two-stage DEA, in which the evaluated mills according to the level of efficiency in the proposed model. Then, a Multiple Linear Regression Analysis was performed to identify the variables with the greatest influence on the performance of the mills in terms of efficiency. The results revealed six relevant variables for increasing the agricultural performance in the production of sugarcane: rainfall (mm weekly), chopped cane delivery (%), delivery time (h), borer (%), air humidity (%), and rods in raw wine ($\times 10^5/\text{mL}$). Finally, semi-structured interviews with Brazilian and Australian experts in the sugar-energy sector allowed the identification of five other relevant complementary factors that were unavailable in the database: genetic variety, agricultural cultivation activities, edaphoclimatic factors, renewal of sugarcane fields and irrigation system. The results of this study were grouped into the dimensions of environment, yield, and impurities, providing quantification and better understanding of the identified explanatory factors and the agricultural performance in terms of production efficiency, offering fundamental information that enables managers to make decisions and prioritize the aspects that contribute more significantly to the increase in agricultural productivity of the planted area.

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Graphic abstract

Keywords Bioenergy companies · Agroindustrial best practices · Efficiency · Two-stage DEA · Renewable energy

Introduction

The use of renewable energies and clean energy technologies is a prominent mechanism to sever the long-standing link between fuel pollution, carbon emissions (CO_2), and economic growth (Ike et al. 2020). Nie et al. (2019) affirm that renewable energies will play an intimate and critical role in energy supply and carbon mitigation around the world in the future.

Corroborating this statement, Maroušek et al. (2020) states that the participation of renewable energies has grown at an accelerated rate in recent years in many countries around the world, which leads to the need to develop efficient production techniques, with economic viability and that does not bring aggressions to the environment (sustainable production). According to Machová and Jaromír (2018), a balanced and sustainable development of agriculture is essential, since it aims to meet basic human needs.

Among the various types of renewable energy available, the energy from sugarcane production has great potential, and it is an appropriate alternative to fossil fuels (Parsae et al., 2019). Global sugarcane production in 2018 was record-breaking, at 1.9 billion tons of sugarcane, in approximately 100 countries (Faostat 2020).

Rabbani et al. (2020) state that bioethanol has played a key role in recent years as an alternative energy in the transport sector with multiple advantages over conventional fuels. This is because of the increase in global energy demand and environmental concerns, which have led to a tendency of replacing fossil fuels with clean and renewable fuels, such as bioethanol.

Therefore, in recent years, many emerging countries are rising up the ranks through innovation, particularly in the renewable energy and biofuels sector, surpassing developed countries once considered technology leaders (Samant et al. 2020). Emerging countries depend on energy-intensive sectors, such as construction, mining, and manufacturing, for economic growth and industrialization, as they experience rapid population growth, changes in lifestyle, and urbanization (Adedoyin et al. 2020).

Also, the rapid advancement of data communication technology has shaped the materialization of the network realm typified by the ubiquitous integration of intelligent technologies (Kliestik et al. 2020). This phenomenon has also been verified in the sugar cane industry, through the integration of communication between the field and the industry, contributing to greater integration of activities and increased operational efficiency (Marin et al. 2019).

The development of these sectors creates a growing demand for energy consumption, presenting serious climate changes and concerns about global warming, directing efforts towards the development of energy from renewable raw materials, such as hydro, wind, solar and biomass (Meza-Palacios et al. 2019).

Brazil and Australia are some of the world's largest sugarcane producers (Faostat 2020). In the 2017/2018 harvesting season, the total volume of sugarcane harvested across Australia was 31,472,101 tonnes, produced over 2,100 km on the east coast of Australia, for a total of 360,127 hectares of planted area (Canegrowers 2020). Australian producers are recognized as one of the most technologically advanced and world leaders in their agricultural practices, enabling a high quality product, which puts them in a situation capable of dealing with the challenges of the current market (QSL 2020). In addition to the globally recognized quality of sugar, one of the differentials of the sugarcane industry in Australia are some production practices that increase productivity and at the same time reduce environmental impacts (Renouf et al. 2013).

Regarding the Brazilian industry, about 13.2% of Brazil's total energy consumption is from renewable energy, making it one of the highest consumers of renewable energy in the world. In this category, sugarcane energy contributes 18.8% (OECD/Food and Agriculture Organization of the United Nations, 2015), as it is one of the most produced agricultural crops in the country. In recent years, the planted area of sugarcane increased from 7,086,851 hectares in the 2007/2008 harvest to 10,229,881 hectares in the 2017/2018 harvest (União and DA CANA-DE-AÇÚCAR - UNICA 2020).

Currently, Brazil has the largest area of sugarcane cultivation in the world and it is the second largest producer of ethanol. The historic increase in the cultivation of sugarcane is the result of public policies stimulating the production of ethanol-based on sugarcane to increase energy security, promote rural development, and reduce dependence on fossil fuels (Duden et al. 2020). Because of the growing domestic and international demand, Brazilian ethanol production is expected to increase from 35.6 billion liters in the 2019/2020 harvest to 54.2 billion liters in 2030 (Van Der Hilst et al. 2018). The 2019/2020 harvest achieved the highest ethanol production in history, even with a 1.7% reduction in the total planted area.

Therefore, it is clear that sugarcane is important for both the food and energy sectors, with its cultivation requiring continuous development in Brazil. The supply of raw material will depend on climatic conditions, which will determine the productivity of the crop and the investments to expand ethanol production capacity, which should increase the flexibility of the production units. The supply of corn ethanol is expected to grow (União and DA CANA-DE-AÇÚCAR - UNICA 2020) and with the expected positive start of

RenovaBio, as Brazil has one of the largest and most successful biofuel programs in the world (Gerardi et al. 2017).

Thus, according to Scherer and Porsse (2017), the identification of relevant characteristics in the agricultural development process is essential, together with strategy formulation to increase the productivity of the sector, which eventually leads to the optimization of the factors of production, helping economic development.

According to Gerardi et al. (2017), such development is important because of the challenges in the sector with falling prices of sugar globally and the increasing cost of production, which is compromising the margins of producers and causing the indebtedness of industrial units. Because of these factors, annual productivity in Brazil is falling in recent years, which can be attributed to the postponing of replanting, and consequently, fewer harvests (Marin et al. 2019).

Besides these reported problems, as documented by Lau et al. (2020), the world is struggling with the coronavirus outbreak (COVID-19), which has turned into a global pandemic afflicting most countries and threatening the health of millions. The paralysis of economic activity worldwide has drastically reduced the demand for oil derivatives, causing prices to drop sharply to unprecedented levels. This reduction in commodity prices is pushing ethanol prices downwards, which directly impacts the results and profitability of the sugar-energy sector.

Due to the importance of increasing productivity, the number of studies using mathematical models to measure efficiency is increasing with the objective of maximizing agricultural production (Carvajal et al 2019).

The literature emphasizes the importance of food production and the existence of renewable energies to meet the growing demand globally, and the possible contribution of sugarcane production. This study has the specific objective of proposing a model for increasing agricultural efficiency that increases the production of this crop from the available planted area, which means better use of the territory available for the production of sugarcane in the world.

This present study uses mathematical techniques from a database of Brazilian mills, over five harvest seasons, for an integrated evaluation of several variables belonging to the sugarcane production process, which are often analyzed individually. Thus, this study has the main objective of identifying explanatory factors to increase the agricultural performance of Brazilian and Australian sugarcane mills. Therefore, it is necessary to evaluate the agricultural efficiency of mills in sugarcane production, identification of influence factors in terms of agricultural efficiency, identification of benchmark values for the variables, and the determination of the potential to increase financial gains by increasing efficiency. Thus, this study is designed to assess the hypothesis that there are a few explanatory variables that

are deeply responsible for the agricultural efficiency in the sugar-energy sector.

Material and methods

This study has a quantitative and a qualitative part. In the quantitative part, it applies the DEA technique to categorize and classify Brazilian mills in terms of agricultural efficiency, followed by an analysis of the variables that impact this classification. In the qualitative part, it identifies other variables that are relevant to the study.

Quantitative stage

The database used contains information from mills that together produced a total of 4.16 million tons of sugar in the 2016/2017 harvest, which represents approximately 10.75% of the total quantity produced in Brazil in the same harvest.

The database is confidential, as it was developed by a company specializing in consulting services for sugarcane mills. The researchers obtained access to the information for academic purposes after signing a data confidentiality agreement.

Initially, the information was compiled from 38 mills from the 2012/2013 to the 2016/2017 harvests, with each mill having 168 variables that were measured throughout the sugar and ethanol production process. These variables were analyzed individually and they were selected for the quantitative stage of the research.

The quantitative analysis started with the descriptive statistics of the available database, which allowed an overview of the availability and characterization of the data. Then, to identify the key factors to prioritize in terms of efficiency in sugar-energy production, the DEA technique was used to identify the efficient sugarcane mills in Brazil, according to the proposed model. The DEA technique was applied using the software *Performance Improvement Management Software* (PIM-DEA)®.

A fundamental step in the application of the DEA is the development of the model by identifying the input and output

variables associated with the evaluated units (Kaab et al. 2019). In other words, it is essential that the variables used are capable of satisfactorily representing the efficiency of the chosen decision-making units.

Mehdiloo and Podinovski (2019) discuss the problems arising from the choice of inputs or outputs that do not satisfactorily represent the proposed efficiency concept, and the mathematical influence of redundant variables that ultimately overlap. Considering the importance of choosing variables that satisfactorily represent the concept of efficiency presented by Farrell (1957), the selection of the variables was based on the theoretical framework, and it was subsequently validated by conducting semi-structured interviews with industry experts in Brazil.

Figure 1 shows the DEA model proposed in this research, in which the Decision Making Units (DMUs) are represented by sugarcane mills and the four variables in the model are organized in one input variable and three output variables, two of which are undesirable, represented in the model in as fractions (1/variable).

For the definition of the parameters of the proposed DEA model, we used the BCC model (variable return of scale) with an orientation to output, as the goal of sugarcane producers is to maximize productivity with the minimization of mineral and vegetable impurities, given the availability of the planted area available in the harvest.

The formulation of the model can be represented as follows:

$$\text{Max } h_o = \sum_{i=1}^n v_i X_{io} + v_0 \quad (1)$$

$$\text{Subject to restrictions} \quad \sum_{r=1}^m u_r Y_{ro} = 1 \quad (2)$$

$$\begin{aligned} \sum_{r=1}^m u_r Y_{rj} &\leq \sum_{i=1}^n v_i X_{ij} + v_0 \\ u_r, v_i &\geq 0 \\ j &= 1, \dots, s \\ r &= 1, \dots, m \\ i &= 1, \dots, n \end{aligned} \quad (3)$$

Fig. 1 DEA model developed for this study

Table 1 provides a breakdown of the four variables used in the proposed efficiency model, with the respective descriptions of the concepts for each and the primary authors who provided the theoretical framework that justifies the choice of variables.

As the DEA model assumes the absence of missing data, the study excludes 52 sugarcane mills from the database, which did not have data reported in relation to at least one of the four variables of the model.

As the efficiency of a DMU is defined by the ratio of multiple inputs and multiple outputs, the objective of each DMU is to use the minimum of inputs to produce the highest possible value of outputs (Tran et al., 2019). However, the DEA mathematical formulation allows the use of undesirable output variables, as foreseen by Song et al. (2020), who developed a model to simultaneously maximize a desirable output and minimize an undesirable output.

Thus, a data transformation technique called Multiplicative Inverse (MLT) was used, initially suggested by Golany and Roll (1989). Afzalinejad (2020) present efficiency analysis studies that used the multiplicative inverse technique for undesirable output adjustments in Data Envelopment Analysis models. This approach incorporates each undesirable output as a desirable output through the following mathematical adjustment (Eq. 4):

$$f_i^k(U) = \frac{1}{u_i^k} \quad (4)$$

Therefore, as detailed in mathematical terms, the data referring to the mineral impurity and vegetable impurity variables were subtracted by 1 in the proposed model, because they are undesirable output variables.

Although the DEA is a widely used technique, primarily in operations research, it may present some type of bias due to the lack of statistical assumptions (Odeck, 2009). To correct this bias and create confidence intervals for the scores, this study uses the Bootstrap model proposed by Simar and

Wilson (1998), which comprises a technique based on the idea of repeated simulations with the intention of approximating the original distribution of the data.

The results show that some of the independent variables selected to perform the two-stage DEA had missing data, which the mills had not completed. Thus, this study used the Missing Data Imputation technique, which is a statistical technique that allows missing data to be completed, whether they are quantitative, categorical, ordinal or nominal, allowing the analysis of all study variables (Schafer 1997).

This study used the *Statistical Package for Social Sciences*® (SPSS) to analyze the database in relation to the characteristics of randomness of the sample and the absence pattern. It found that the absence of data was of the type Missing Completely at Random (MCAR), that is, the absence is totally random, which is favorable for the application of the multiple imputation technique with the non-monotonic absence pattern (without the repetition of the absence pattern).

With these behaviors verified, following the guidelines of Schafer (1997) for the variables with up to 5% of missing data, a unique imputation was performed by filling in the missing data with the mean value for a given variable. For variables with more than 5% of missing data, the multiple imputation technique was performed (Table 2).

After the imputation of data in the DEA Bootstrap model, the second stage of quantitative analysis began, with Despotis and Smirlis (2002) and Zhu (2003) discussing the basic models of Data Envelopment Analysis and its extensions to deal with multistage models.

This relationship can be represented by Eq. (5), which verifies that the independent variables influence the dependent variable.

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_i x_i + r_i \quad (5)$$

Kaffash et al. (2019) analyzed 132 studies that used the DEA to evaluate efficiency between 1993 and 2018, and the

Table 1 Details of the variables used in the DEA model

Variable type	Variable name	Variable definition	Theoretical framework
Input— x_1	Planted Area (ha)	Represents the total area, measured in hectares, used to plant sugarcane for a DMU in a harvest	(Nothard et al. 2019; Carvajal et al. 2019; Marin et al. 2019)
Output 1— y_1 (Desirable)	TRS (tons)	The Total Recoverable Sugar, measured in tons, represents the capacity of sugarcane to be converted into sugar or alcohol through the production process	(Nothard et al. 2019; Carvajal et al. 2019; Marin et al. 2019)
Output 2— y_2 (Undesirable)	$\frac{1}{\text{Mineral Impurities}}$ (tons)	Impurities such as dirt, stones and gravels introduced by mechanized harvesting, compromising the production of ethanol and sugar	(Fernandes 2011; Lemos et al. 2019; Meghana and Shastri 2020)
Output 3— y_3 (Undesirable)	$\frac{1}{\text{Vegetable Impurities}}$ (tons)	Impurities such as green and dry leaves, stem, weeds, and roots introduced by mechanized harvesting, compromising sugarcane crushing	(Fernandes 2011; Lemos et al. 2019; Meghana and Shastri 2020)

Table 2 Imputation techniques used for regression analysis variables

Final product	Processes	Indicators	Imputation technique
Sugar and ethanol	Industry	Location (State)	Multiple Imputation
		Size (s/m/l)	Multiple imputation
	Field	Rainfall (mm/week)	Multiple imputation
		Maximum Temperature of Environment (°C)	Unique imputation
		Minimum Temperature of Environment (°C)	Unique imputation
		Relative humidity (%)	Unique imputation
		Dextran (mg/L Brix)	Unique imputation
		Sugarcane Borer (%)	Unique imputation
	Raw material	Chopped cane delivery (%)	Multiple imputation
	Juice extraction	Filter cake (kg)	Multiple imputation
Ethanol	Mud	Rods $\times 10^5$ /mL	Multiple imputation

two-stage DEA technique was the dominant approach used when it was necessary to explore the influence of independent variables on efficiency, represented by the DEA score.

The analysis of the quartiles of the DEA scores allows a preliminary assessment of the independent variables to provide additional information to the two-stage DEA analysis. This analysis allows an additional verification of the behavior of each of the independent variables of the second stage, and consequently, a discussion of possible results in terms of the explanatory capacity of each variable, seeking to verify any significant statistical differences between the DMUs of the upper quartile and the DMUs of the lower quartile.

To perform this verification, this study used three statistical tests. For variables that with a normal distribution, the One-Way ANOVA test of difference of means (parametric test) was used. For variables with non-normal distribution, the Mann–Whitney non-parametric test was used. Finally, to verify the normality of the distributions, the Kruskal–Wallis test was used. All the statistical tests mentioned in this stage of the research were performed using the *Statistical Package for Social Sciences*® (SPSS).

The main variables of the production process were identified to perform the multiple linear regression analysis, enabling this study to proceed with the qualitative analysis of the research.

Qualitative stage

The qualitative stage was developed from the selected variables using the two-stage DEA (multiple linear regression analysis) and the quartile analysis. In the qualitative stage of the research, four interviews were conducted with experts in the sugar-energy sector: two with Brazilian experts and two with Australian experts.

The experts made important comments regarding the explanatory variables found in the quantitative stage, and above all, identified new relevant variables that contribute to efficiency according to the model proposed in this study.

Thus, the experts contribute by commenting on new variables to maximize the production of Total Recoverable Sugar (TRS) by planted area and minimize mineral and vegetable impurities, as some important variables may not be available in the database, and they were not identified in the quantitative stage.

As mentioned in detail, this study uses an approach with quantitative and qualitative characteristics, so that the results found in the DEA analysis and in the various statistical analyses allow greater depth in the qualitative study.

Figure 2 represents a summary of the proposed methodology.

Results

The results of this study are in two stages. The first stage consists of the results of the quantitative model and the second stage consists of the results of qualitative research with experts in the sugar-energy sector.

Quantitative results

The quantitative stage of the research consists of several stages and activities that were developed sequentially because of the interdependence of the process. Regarding the distribution of data on the planted area, the production of TRS, mineral impurities and vegetable impurities of the sugarcane mills in Brazil, Table 3 presents the average, minimum, maximum, and variability values of the variables that compose the DEA model proposed in this research to evaluate the agricultural efficiency in sugarcane production.

Note that the participating mills have an average sugarcane plantation area of 26,477.86 hectares and generate 419,426.64 tons of TRS. This means that the average value of TRS production per hectare corresponds to 15.84 tons/ha. Another important aspect is the standard deviation of the TRS production, which is significant because the

Fig. 2 Summary of the research methodological procedures **Table 3** Descriptive analysis of the variables of the DEA model

Variables	N	Minimum	Maximum	Average	Standard deviation	Variance
Planted area (ha)	82	11,403.28	146,779.18	43,470.59	26,477.86	701,077,112.02
TRS (ton)	82	127,350.42	958,594.43	419,423.64	209,978.77	44,091,082,850.30
Mineral impurity (ton)	82	8.18	181.76	46.60	32.48	1,054.65
Vegetable impurity (ton)	82	1.33	16.47	5.60	3.04	9.23

database used contains data from mills of different sizes. The mill with the lowest TRS production is responsible for 127,350.42 tons, while the mill responsible for the highest production accounts for 958,594.43 tons.

Table 4 presents the panel with the DEA scores for each sugarcane mill evaluated in this research over the five crops studied. This study evaluated 38 mills, totaling 82 observations, over five harvests (2012–2013 to 2016–2017).

As mentioned, the DEA analysis can measure the distance from the DMUs to the efficient frontier; therefore, it is possible to measure the increase in output necessary for each DMU to become efficient. This measurement is called slack, and it represents the potential gain of each unit to become as efficient as are the efficient units on the production frontier.

In the sugar-energy sector, which works with a large amount of raw materials and significant volumes of products (sugar and ethanol), small percentage losses may represent significant economic returns (Fernandes 2011). Even though the available database does not contain financial or economic information, based on the average price of the TRS in each harvesting season applied to the potential operation gain identified using DEA, it was possible to measure the estimated amount of additional revenue that the sugarcane mills could have obtained due to an increase in efficiency

level. Therefore, Table 5 represents the potential gain in the production of TRS based on the situation in which all 82 mills in the sample were at the efficiency frontier, that is, in case they had the maximum level of efficiency.

The sum of each DMU per harvest was obtained by multiplying the potential gain (in tons of TRS) by the adjusted average value of the TRS in each harvest. It provided the total value of the potential financial gain for the hypothetical case of all 82 DMUs with the same level of performance as units that were initially classified as efficient. When converting the TRS production in the DMUs analyzed to monetary values, the potential for financial gain per harvest is verified, as inefficient DMUs can increase TRS production from the available planted area. Consequently, the total potential increase in the harvests analyzed is of US\$ 609,062,496.93 which corresponds to an average value of US\$ 7,427,591.42 per mill.

In the last harvest season available in the database (2016/2017), there was a potential increase in TRS production of 1,248,048.04 tons due to inefficiency (considering all available sugarcane mills), which in monetary terms corresponds to a loss of US\$ 8,167,847.37 per mill.

These results presented in Table 5 are able to provide economic evidence to the impact of enhancing the operational

Table 4 Unbalanced panel of DEA scores

Mills	12/13	13/14	14/15	15/16	16/17	Mills	12/13	13/14	14/15	15/16	16/17
1	74.56	77.76	72.61	94.13	72.10	20					72.03
2		90.87				21					99.26
3					98.69	22	66.85				
4					100.00	23	85.12	80.04			
5	80.23	89.36	86.68	83.05	90.70	24				72.25	71.71
6	71.79	72.39	75.59	100.00		25	81.89	77.80	79.91		
7	88.08	94.31	80.70	81.83		26					72.37
8	97.11	87.18	89.74		82.85	27					100.00
9			69.42			28		95.95	90.17		
10		96.42				29			83.45		
11	79.12	96.62				30	87.47	91.17			
12	68.26	67.77				31	67.11	77.16	64.99		
13	85.83	82.91				32				68.59	
14	68.27	77.71				33	84.92	95.53	99.12	84.66	95.30
15	81.65	84.43				34	98.62	100.00	100.00	95.31	98.33
16					75.77	35		87.00	88.35	87.66	89.40
17	63.15	66.06		76.31	89.68	36					78.68
18					100.00	37		77.35			
19					93.00	38		87.00	88.35	87.66	89.40

Table 5 Total potential gain per harvest

Harvest	N	Harvest adjustment (US\$/kg TRS)	Potential gain (ton TRS)	Financial gain (US\$)
2012/2013	18	0.0859*	1,785,449.70	153,483,748.72*
2013/2014	22	0.0831*	1,573,379.86	130,790,776.72*
2014/2015	13	0.0866*	997,541.38	86,387,083.50*
2015/2016	10	0.1009*	824,324.26	83,211,787.11*
2016/2017	19	0.1243*	1,248,048.04	155,189,100.82*

*Exchange rate US\$ 1 = R\$ 5.50 (Brazilian currency)

efficiency in the production of sugarcane. It is observed, therefore, that increasing the yield and better using the available planted area may generate significant financial gains for both the mill and the sugarcane grower. Furthermore, it is clear that the discussion provided in this research may also allow for a better financial and economic outputs for the sugar-energy sector.

Last but not least, for the purpose of this research, the increase in financial gains in a productive unit must consider several factors, as for optimal performance levels, the agricultural area must focus its efforts on the productivity of sugarcane, measured in TRS (ton), use of inputs to improve production and mechanized harvesting, minimizing vegetable and mineral impurities, given the available area for planting.

Table 6 also represents the potential increase in TRS if all mills performed according the efficiency frontier, organized all 82 observation in quartiles. While the group represented by the upper quartile has the potential to increase efficiency

by only 2%, the group of mills represented by the lower quartile shows a potential increase of 44%, which in raw numbers corresponds to an increase of 2,834,557.19 tons of TRS.

Note that the group of six mills classified as efficient do not have potential for improvement, as they are already on the frontier, and therefore, represent the benchmark in terms of efficiency for the other mills in the sample.

Through this technique, it is possible to measure the potential production of the inefficient mills if they achieved the same level of performance as the efficient mills.

Regarding the quartiles analysis, it is necessary to evaluate the difference in the results found in each quartile for each variable. To analyze this difference, this study used the One-Way ANOVA Test for variables with normal distribution and the Mann–Whitney Test for variables with non-normal distribution, which will evaluate the differences in the medians of the distribution. The normality tests showed two variables with statistically different medians of the

Table 6 Total TRS increase potential per quartile

Mills	N	Total TRS production (ton)	Potential total TRS production (ton)	Potential increase in Total TRS (ton)	Equivalent percentage (%)
Upper Quartile	20	10,413,087.08	10,664,519.94	251,432.86	02
2nd Quartile	21	9,334,787.49	10,600,549.49	1,265,762.00	14
3rd Quartile	21	8,189,241.49	10,266,232.68	2,076,991.19	25
Lower Quartile	20	6,455,622.71	9,290,179.90	2,834,557.19	44
Total	82	34,392,738.77	40,821,482.01	6,428,743.24	19

quartiles: chopped cane delivery and rods in raw wine. Just as the variables identified in the regression analysis, these two independent variables are also relevant in explaining a possible difference in performance between the 82 sugarcane mills studied.

According to Zhu (2003), the two-stage DEA technique consists of regression analysis to evaluate the impact of independent variables (external factors) on the performance (efficiency) of the DMUs found through the DEA.

The Multiple Linear Regression Analysis presents a correlation between variables of 0.556 (R) and also the proposed model is able to explain 31.3% (R^2) of the variation in the dependent variable through the 12 independent variables. Proceeding with the analysis of the Multiple Linear Regression, the hypothesis that the adjustment of the proposed model is equal to the adjustment of the model without the predictors. As the p -value is equal to 0.007, it is possible to reject the null hypothesis, which means that the variables in the proposed model can significantly explain the variations and possible predictions in relation to the dependent variable, represented by the DEA score.

Table 7 shows the coefficients of the regression model, from which the independent variables are analyzed individually. The variables with the greatest explanatory capacity in the proposed model are as follows: rainfall (millimeters per week), chopped cane delivery (%), cane delivery time (hours), air humidity (%) and borer (%). These four variables have a significant influence on agricultural efficiency in sugarcane production.

Still, the multicollinearity seeks to evaluate the existence of a high correlation between independent variables. The statistics of the VIF Test show a lack of multicollinearity, which is one of the assumptions of the Multiple Linear Regression Analysis.

Therefore, the Multiple Linear Regression Analysis identified the following relevant variables to explain the difference in efficiency among the 82 mills that were part of this study: rainfall (mm/week), chopped cane delivery (%), sugarcane delivery time (h), air humidity (%) and borer (%). The borer variable, significant at 11% level, was included as relevant due to its p -value close to 10%, but also because of the considerations of the experts, who

Table 7 Coefficients of the Multiple Linear Regression Analysis

Model	Unstandardized coeff		Standardized coeff Beta	Sig	Collinear statistics	
	B	Standard error			Tolerance	VIF
Constant	17.958	22.74		0.432		
Rainfall (mm/week)	− 0.203	0.092	− 2.44	0.030*	0.831	1.204
Chopped cane delivery (%)	0.414	0.116	0.405	0.001*	0.783	1.277
Sugarcane delivery time (h)	0.101	0.041	0.304	0.016*	0.660	1.516
Maximum Temperature (°C)	0.194	0.301	0.068	0.522	0.901	1.110
Minimum Temperature (°C)	0.641	0.705	0.112	0.366	0.656	1.525
Air humidity (%)	0.273	0.14	0.262	0.055**	0.555	1.801
Borer (%)	− 1.156	0.708	− 0.183	0.107***	0.792	1.262
Rods in raw wine ($\times 10^5$ /mL)	0	0	− 0.132	0.213	0.904	1.106
Dextran (mg/L)	− 0.008	0.048	− 0.020	0.866	0.686	1.457
Size (s/m/l)	− 0.149	2.531	− 0.007	0.953	0.644	1.553
Location (State)	− 1.004	0.695	− 0.174	0.153	0.690	1.450
Filter cake (kg)	0.092	0.12	0.093	0.442	0.688	1.454

*Significant at 5% level

**Significant at 10% level

***Significant at 11% level

pointed this pest as one of the most important in the Brazilian sugarcane production.

Among the relevant variables, rainfall (mm/week) and borer (%) presented negative value of Beta, which means that an increase in the value of these variables has a negative impact on the DEA score of the analyzed sugarcane mill. In other words, an increase in the value of these variables negatively impacts the efficiency of the analyzed DMUs. On the other hand, the variables chopped cane delivery (%), sugarcane delivery time (h) and air humidity (%) have positive value of Beta, which means that an increase in their values impacts the efficiency of the respective DMUs. It is important to highlight the relevance of the variables chopped cane delivery (%), sugarcane delivery time (h), since they are both relevant at 2% level of significance, with Beta of 0.405 and 0.304, respectively. These results show that, according to the proposed efficiency methods, these variables are responsible for a relevant influence in the efficiency performance of the sugarcane production activity.

Finally, Table 8 presents a summary of the quantitative results, indicating the variables with the greatest influence on agricultural efficiency according to the quantitative methods used. These were classified according to their influence on the yield of the field (increase in Total TRS per planted area) or influence on mineral and vegetable impurities.

The Multiple Linear Regression Analysis, quartile analysis, and Mann–Whitney test (Table 8), helped find the most important variables for the development of the agricultural process in the sugar-energy sector. It is now necessary to undertake a bibliographic investigation of these variables to verify their relevance in published studies.

Table 8 Summary of the results of the quantitative stage

Variables	Normal distribution	Regression analysis	ANOVA/Mann–Whitney quartile analysis
Rainfall (mm/week)	Yes	*	
Chopped cane delivery (%)	No	**	X
Sugarcane delivery time (h)	No	*	
Air humidity (%)	No	*	
Borer (%)	No	***	
Rods in raw wine ($\times 10^5$ / ml)	No		X

*Significant at 5% level

**Significant at 10% level

***Significant at 11% level

Relevant indicators pointed out by the experts

From the results observed in the quantitative stage of the research, it was necessary to assess the procedures carried out by the parties involved, which enable the superior performance of some mills in relation to their peers. Therefore, in the qualitative stage of this research, four interviews were carried out with experts from sugar-energy sector. The interviews were conducted with two Brazilian experts and also with two Australian experts. The aim of the qualitative study is to evaluate other factors that may influence agricultural efficiency in the production of sugarcane. As variáveis identificadas através dos especialistas trazem uma grande contribuição para os resultados práticos deste estudo, pois elas não estavam disponíveis na base de dados disponível, utilizada para os estudos quantitativos, apesar de se mostrarem relevantes na literatura e nas entrevistas.

The first interview was conducted with a Brazilian executive of a consulting organization that serves sugarcane mills throughout Brazil and Latin America. The second interview was conducted with a Brazilian executive of an organization that represents sugarcane producers, assisting them in agricultural activities. Then, the third interview was conducted with an Australian researcher specialized in the harvesting process of sugarcane. Finally, the fourth interview was conducted with an Australian consultant that provides consulting services for sugarcane growers throughout Australia.

According to the experts, the management of sugarcane production varies according to the climatic conditions of its production region. Some planted areas historically have more or less rainfall in different periods throughout the year. It is necessary to consider this factor when analyzing the impact of rainfall in relation to TRS production. It is also necessary to consider the historical behavior of the region, because it influences the decisions of the producers.

In terms of variable rainfall, regarding the variables of the efficiency model, rainfall is directly linked to vegetable impurities. When harvesting wet cane, the level of vegetable impurities brought to the mill increases. Rain during the planting period contributes to budding and vigorous growth. Rain during the harvest period contributes to the development of sugarcane. Both aspects are important and complementary for the maximization of productivity.

As for the variable chopped cane delivery (%), it is a fresher cane with a higher percentage of sugar, although it also brings some challenges that influence the proposed model, such as the removal of stubbles and the greater volume of mineral and vegetable impurities. The trampling of the harvester influences the value of Total TRS produced in chopped cane harvested using harvesters, as this impairs plant growth, thereby, decreasing productivity in the subsequent harvest.

According to experts, the benefit of a shorter cane delivery time (hours) is the crushing of a fresher cane and, consequently, with less contamination. Two aspects influence the decrease in TRS as follows: increase in the time between the harvest, and the crushing of the sugarcane. The first is the consumption of sugar by bacteria. The second is the inversion of the sugar that happens during this interval (sucrose that turns into glucose and fructose). This has a negative impact on the TRS value obtained in the measurement performed at the mill.

The variable Air Humidity (%) has a strong relationship with rain. Regions with less water stress tend to favor the planting and development of sugarcane, producing higher concentrations of TRS. Therefore, a more humid environment tends to have higher levels of rainfall and greater abundance of water, which favors cane production.

The variable Borer (%), according to interviews with experts, denotes a pest that directly affects not only the productivity of the cane field, but also the capacity of the industrial unit to extract juice. Thus, controlling borers must be a priority for any sugarcane producer. The most frequently used methods for borer control in Brazil are biological, cultural, and chemical.

The variable Rods in Raw Wine ($\times 10^5/\text{mL}$) is a consequence from contamination in sugarcane that is measured in the industry. It is a consequence of the contamination problem verified in the field. Regarding the activities developed in the production of sugarcane, this variable must be related to the increase in contamination from the greater exposure of chopped cane in relation to the whole cane. Thus, to minimize contamination in the field, the chopped cane must be processed as quickly as possible, as it has a lot of exposed area, which can cause greater contamination, affecting the value of Total TRS produced.

Besides confirming the variables from the quantitative process, the experts added four variables to the agricultural production process that were not present in the database of this study, but which, in any case, must be considered for increasing the theoretical and practical basis of this study.

Table 9 presents the main contributions of each interview regarding the indicators that have an impact on the proposed efficiency model.

Besides the importance of variables from the quantitative analysis, the experts stressed the importance of agricultural cultivation activities, such as cultivation methods, which are essential for the good development of sugarcane (Bigott et al. 2019). Some of these activities are the renewal of the cane field for continuous productivity and high conversion into total TRS (Oliveira et al. 2011). There are edaphoclimatic factors, such as soil type and climate in line with sugar-energy production (Pongpat et al. 2017). Also, the genetic variety of sugarcane is considered, where the search for better productivity reflects the better choice (Amaral

et al. 2019). And finally, the irrigation systems used for sugarcane production, which may increase the performance of sugarcane farms that lack the adequate conditions regarding natural and ecological resources (Ullah et al. 2019).

Some indicators were not identified during particular interviews due to the particularities of each country. Rods in raw wine and sugarcane borer were not found during the interviews in Australia, while the indicator irrigation system was not found in Brazil.

To facilitate an understanding of all the influencing factors for the agriculture performance of Brazilian and Australian sugar-energy sector found in the study, and their contributions to the sugarcane production process, they were grouped into variables related to the environment, yield, and impurities of the process presented in Fig. 3.

These variables were divided into three major areas within the sugar-energy production. The “Environment” contains rainfall, air humidity and edaphoclimatic factors as uncontrollable factors, requiring adaptation. “Yield” contains chopped cane delivery, delivery time, sugarcane borer, agricultural cultivation activities, sugarcane field renewal, genetic variety of sugarcane and irrigation systems, as they are directly linked to agricultural production. Finally, “Impurities”, which negatively affect production, and are represented by the factor rods in raw wine, which is a result of the accumulation of impurities in ethanol production, highlighted as bottlenecks in sugarcane production, which mostly come from mechanized harvesting that, as highlighted by experts, must be efficiently carried out by the agricultural area of the mill.

Discussion

From the evaluation of the performance of these mills according to the proposed model, through the Multiple Linear Regression Analysis, it was possible to identify the variables that explain part of the performance difference between the studied mills, and they are classified in three major areas: environment, yield, and impurities, which will be discussed respectively by topics.

Environment

The variables that compose this group are rain (mm/week) and air humidity (%), as sugarcane production systems around the world are exposed to uncertainties associated with variations in rain, which influence agricultural productivity (An-Vo et al. 2019). Pongpat et al. (2017) corroborate this statement specifically regarding the production of sugarcane, affirming that the adequate supply of water is fundamental for the satisfactory growth of this crop. According to Zacura Filho and Piccirilli (2012), the three main

Table 9 Indicators found with theoretical framework and the opinion of experts

Relevant variables	Brazilian experts		Australian experts	
	Expert 1	Expert 2	Expert 3	Expert 4
Rainfall (mm weekly)	Long drought impairs sugarcane growth and sugar concentration	High rainfall influences the amount of TRS in sugarcane	The amount of water at the right times is fundamental to the quality of sugar cane	Each region has different rainfall rates. It is essential to take this aspect into account for increasing productivity
Chopped cane delivery (%)	Chopped cane is fresher and has a higher percentage of sugar	The technological advancement of these aspects allows a gain in yield with the increase in the percentage of delivery chopped cane	Current harvesting technology enables time and efficiency gains in the sugarcane production process	The mechanization of sugar cane is a very advanced and mature process in Australia, which allows for gains in productivity and scale. In addition to gaining access to information that enables better management
Sugarcane delivery time (h)	Faster cane delivery contributes to fresher cane crushing	Crushing in less time generates gains in the extraction of sugarcane juice	It allows less contamination and gains in the quality of the sugar cane produced	An efficient logistic system allows a better use of the CCS of the harvested sugar cane
Air humidity (%)	Humid environments favor sugarcane planting and development	Higher humidity allows a greater amount of TRS from sugarcane	Air humidity allows for gains in productivity. They are more favorable environments for the production of sugar cane	It favors yield in the sprouting of sugar cane. Humid environments are positive for an increase in CCS
Rods in raw wine ($\times 10^5/\text{mL}$)	Variable related to contamination of sugarcane in the field and contamination in industrial processes	A shorter time between harvest and crushing minimizes the chances of contamination of the raw material	–	–
Borer (%)	It has an impact on sugarcane productivity and juice extraction capacity	It must be controlled through cultural, biological, or chemical control	–	–
Agricultural cultivation activities	Cultivation methods that involve fundamental activities for the production of sugarcane, such as planting operations, physical–chemical analysis of the soil, maturing and application of fertilizers	Activities related to percentage of chopped cane delivery and cane delivery time. The operation of a harvester is a step of fundamental importance for the efficient production of sugarcane	There are activities related to the management (operation) of sugarcane cultivation and which contribute to the gain in quality of the culture and increase in productivity	Activities related to the planting of sugar cane that guarantee a healthy plantation and rich in CCS
Sugarcane field renewal	The capacity of the producer to renew the cane field reflects in the productivity. It is a financial decision	The decision demands assertive cash flow management and allows great productivity gains if done correctly	Sugarcane renewal is an important stage in the sugarcane production cycle and contributes to productivity	There are several variables related to the sugarcane renewal process. The way the grower develops this process directly influences productivity and CCS
Edaphoclimatic factors	Cultivation methods and genetic variety of sugarcane must be in line with the type of soil and the climate. This variable is related to rain, air humidity, and temperature	Agricultural cultivation activities must be in line with soil and climate characteristics	Each region has distinct soil and climate characteristics. Sugarcane production must adapt to these characteristics in order to maximize productivity	Edaphoclimatic factors are decisive in the quality of sugarcane. Constant monitoring and adjustment is essential to maximize production

Table 9 (continued)

Relevant variables	Brazilian experts		Australian experts	
	Expert 1	Expert 2	Expert 3	Expert 4
Genetic variety of sugarcane	There are several genetic varieties and the choice depends on some factors such as the type of soil and climate	The decision aims to minimize the proliferation of pests and maximize the productivity of the cane field	The choice of the genetic variety of the planted sugarcane is crucial for productivity	The appropriate genetic variety contributes to combating pests and must be adapted to the region's soil and climate conditions for greater production efficiency
Irrigation system	-	-	Failure to perform irrigation when needed leads to serious productivity problems in the field. Thus, the lack of water supply at the right time ends up harming the growth of sugarcane and, consequently, the yield in the ratoon cane	When natural resources are not sufficient to supply the amount of water needed for sugarcane production, the implementation of irrigation systems is essential to guarantee a high performance in sugarcane production

characteristics that favor the production of sugarcane are soils with great depth to allow the root system to explore a high volume of organic matter, water sufficiency with good infiltration capacity for water absorption, and less sandy soil to avoid the loss of nutrients through leaching.

Yield

The second major area consists of the variables of chopped cane delivery (%) and cane delivery time (h) linked to the harvest; and the borer variable (%), representing the management of agricultural pesticides. Manual harvesting and mechanized harvesting are currently used in the sugarcane harvest (Pongpat et al. 2017).

A sugarcane harvest front is made of a team that operates machinery and equipment with prior planning (Pongpat et al. 2017). It includes sugarcane harvesters, transshipments (which accompany the harvesters to load the raw material) and the team that provides fuel supply, maintenance equipment, support for emergency services (fire) and trucks for transporting the harvested sugarcane to the mill (Junqueira and Morabito 2019).

For optimal percentage of chopped cane delivery, the mechanized harvesting requires specialized labor, as rain is an important factor (Carvajal et al. 2019), which determines the harvesting process. The cutting height of the blades can prevent the loss of 1.9 and 12.5 tons per hectare of cane in the soil (Pongpat et al. 2017). It is crucial to minimize the loss of cane in the field (Patane et al. 2019), which is under the control of the harvester operators. An increase in the speed of the harvester extractors increases the loss of sugarcane (Nothard et al. 2019). Traffic control is important (Braunack and McGarry 2006), as it reduces soil handling through zero tillage (Hogarth 2017).

The sugarcane delivery time (h) requires that the activities of harvesting and transporting the sugarcane to the industrial unit are made of complex logistical operations (Junqueira and Morabito 2019), with the transport of sugarcane being one important element of the production system (Masoud et al. 2012). It requires planning to ensure efficient logistical activities (Zacura Filho and Piccirilli, 2012), because it is necessary to minimize the time between harvesting and processing at the mill (Junqueira and Morabito 2019), as the sugarcane harvested mechanically must be transported to the mills within a maximum of 24 h (Pongpat et al. 2017).

A third variable in the yield area is the borer (%). This insect causes the most damage to sugarcane crops in Brazil (Zacura Filho and Piccirilli 2012). Brazilian productivity is significantly affected by the attacks of this insect (Peñaflor and Bento 2019), which prevents cane growth, significantly influences the weight of the blades, and in more severe cases, can lead to dryness and plant death (Huang et al. 2018). Zacura Filho and Piccirilli (2012) state that the best

Fig. 3 Division of variables according to the sugarcane production process

way to fight the borer in Brazilian fields is biological control, using *Cotesia flavipes*, which are parasitic flies that are usually produced in the laboratories of sugarcane mills. In Brazil, approximately 3.3 million hectares are treated with *Cotesia flavipes* to contain the advance of the borer in the cane fields (Parra 2014).

Finally, with regard to the increase in yield, there are several practices and activities that can be highlighted for each of the variables found. A process that deserves to be highlighted are the carbon sequestration methods, whose evidence suggests the ability to significantly improve the quality of the soil, providing increased productivity (Maroušek et al. 2019).

Impurities

Traditionally, the main objective of the cultivation of sugarcane is the production of sugar, and it currently meets 80% of the global demand for sugar. This production process generates large quantities of solid residues, such as mineral and vegetable impurities, bagasse, filter cakes, and vinasse that are generated after harvest (Meghana and Shastri 2020).

Mineral and vegetable impurities significantly affect the production of sugar and ethanol (Lemos et al. 2019), as the conditions of each stage of the production process must be monitored and controlled to avoid favoring the selection and development of microorganisms that cause undesirable changes to the final product (Duarte et al. 2019).

The rods in raw wine ($\times 10^5/\text{ml}$) is a bacterium that consumes part of the juice extracted from the raw material, producing toxic metabolites that inhibit yeast, with the variety *Saccharomyces cerevisiae* being the most used

in Brazil (Carvalho-neto et al., 2015), favoring flocculation and causing a drop in ethanol production (Silva et al. 2017).

According to Narendranath et al. (2003), the contamination of bacteria can lead to losses of 1.5 to 5% in ethanol productivity, depending on fermentation conditions, because of the metabolic change in sucrose, as the contamination of cane must by yeast and bacteria can be related to environmental factors and practices applied to the raw material (Brexó and Sant'Ana AS 2017).

Benchmarks

The quantitative character of the analysis identifies the results achieved by the most efficient mills for each of the variables identified as relevant to agricultural efficiency. This analysis creates benchmarks, which refer to the results obtained by efficient mills, and consequently, serve as reference values for mills that seek to increase efficiency.

Table 10 presents the benchmark values. They show that the approximate value of rainfall in the group of efficient mills was 20.18 mm weekly, while the percentage of chopped cane delivery is above 99%. The efficient mills deliver cane in less than 10 h. The air humidity, measured in percentage, is above 65.26%. Finally, the percentage of borer in the cane field is below 2.58%, while the concentration of rods in the raw wine is below $47.14 \times 10^5/\text{mL}$ for the group of efficient mills in the database.

The benchmark values represent results that are significantly higher than the results corresponding to the medians, as the medians consider the entire universe of mills, which also includes those with low efficiency.

Table 10 Explanatory factors identified in the study

Variables	DEA Model	Two-stage DEA	Brazilian experts	Australian experts	Benchmark	Medians
Total TRS (ton)	X		X	X		
1/mineral impurities (ton)	X		X	X		
1/vegetable impurities (ton)	X		X	X		
Planted area (ha)	X		X	X		
Chopped cane delivery (%)		X	X	X	99%	96,47%
Rainfall (mm weekly)		X	X	X	Average of 20,18 mm weekly	23,48 mm weekly
Sugarcane delivery time (h)		X	X	X	Up to 10 h	12,50 h
Air humidity (%)		X	X	X	Above 65,26%	65,67%
Borer (%)		X	X		Below 2,58%	2,75%
Rods in raw wine (10 ⁵ /mL)		X	X		Below 47,14 × 10 ⁵ /ml	123,31 × 10 ⁵ /ml
Genetic variety of sugarcane		Δ	X	X	Δ	Δ
Agricultural cultivation activities		Δ	X	X	Δ	Δ
Edaphoclimatic factors		Δ	X	X	Δ	Δ
Sugarcane renewal		Δ	X	X	Δ	Δ
Irrigation system		Δ		X	Δ	Δ

X–Variables analyzed in each phase

Δ–Variables identified in the qualitative stage

Therefore, these results correspond to the values that producers and sugarcane mills should pursue, according to the results in the analysis of the quantitative studies.

All the explanatory factors presented in Table 10 are corroborated through the extensive literature available on each of the variables analyzed, which presents the authors who contributed to the theoretical framework in analyzing the relationship between each of these factors in relation to the efficiency in production of sugarcane.

From the operational point of view, the results presented may be applied to other countries, whose agriculture is an important commercial activity, especially through the production of sugarcane. However, as highlighted by Maroušek et al. (2015), it is essential to consider that different countries have different decision-making processes, as well as different values and laws in relation to land use. Therefore, such particularities must be taken into account when generalizing the results present in this research.

Moreover, competitiveness is an important element in the sugar cane industry, due to the high demand for derivative products and the high competitiveness among several countries around the world. In this way, the various players interact and move at all times through the adoption of new practices, innovations and technologies. In addition, each country adopts programs that aim to boost the efficiency and economic viability of the industry. In Brazil, the most recent program launched was RenovaBio, which aims to increase ethanol production and consumption. This program aimed to help the country to reduce greenhouse gas emissions and to contribute economically to the development of the ethanol

industry by creating a new product, the decarbonization credit called CBio (Gonçalves et al 2021).

Meanwhile, in Australia, mechanisms are implemented that reward efficient farmers (in terms of reducing indirect costs) and penalize inefficient farmers by implementing a program of good management practices aimed at greater sustainability combined with economic and financial gains (Deane et al. 2018).

These results helped identify key factors for developing the efficiency of the agricultural and industrial processes of sugarcane production, through multiple sources of evidence: they were identified in the literature, validated statistically through a mathematical model of efficiency analysis and finally validated by experts in the Brazilian sugar-energy sector.

Conclusions

Taking into account the increase in global demand for renewable energies, the role of sugarcane as an important source of food and bioenergy worldwide and the restrictions on available land for sugarcane production, higher efficiency is paramount to increase productivity with sustainability. Therefore, this study provides important guidance for sugarcane growers and professional from the sugar-energy sector to increase the productivity of sugarcane per planted area. Thus, this study identified and analyzed the main variables that influence the agricultural efficiency of sugarcane mills. It analyzed data from 82 mills over five harvests and used it

to develop a DEA model to evaluate agricultural efficiency in sugarcane production.

Initially, the proposed efficiency model was developed to increase productivity with the best possible use of the areas available for planting sugarcane in Brazil with minimal mineral and vegetable impurities. This model undertook the Second Stage using the Multiple Linear Regression Analysis, identifying six explanatory variables that influence the performance of the sugarcane production: chopped cane delivery (%), rainfall (mm weekly), sugarcane delivery time (h), air humidity (%), sugarcane borer (%), rods in raw wine ($10^5/\text{mL}$).

The results suggest that practices related to these six variables positively influence the increase in TRS per planted area and the reduction of mineral and vegetable impurities that, as verified in the theoretical review, largely favor the performance of the industrial activities of the sugarcane mills. Also, benchmark values have been proposed that should be pursued by producers and mills that seek agricultural efficiency according to the proposed model. It is also possible to verify possible financial gains from an eventual increase in efficiency per planted area based on the difference in performance of the mills analyzed in the research.

Finally, the study identified complementary variables corroborated by the literature, with two experts from the Brazil and two experts from Australia, all professional from the sugar-energy sector, who made important contributions on other important variables for the agricultural efficiency, identifying five relevant qualitative variables that were not available at the database: genetic variety of sugarcane, agricultural cultivation activities, edaphoclimatic factors, sugarcane renewal and irrigation system.

This study provides quantification and better understanding of each of the variables, the interdependence and complementarily relationships established between them, and also the cause-and-effect relationships between the identified explanatory factors and the agricultural performance in terms of production efficiency.

Therefore, the research hypothesis was confirmed, through the identification of these explanatory variables that influence the agricultural performance of sugarcane plants. Thus, the present study fills an important gap by compiling in a single research several complementary and related variables that aim to increase the efficiency in the production of sugarcane. Also, a unique result is the verification of variables identified through studies in Australia to complement the quantitative findings identified in Brazil, which confers greater coverage of the results and the possibility of greater applicability in other countries growing sugarcane.

Finally, executives, managers, and consultants in the sugar-energy sector should evaluate the ten variables found in this study to improve the production of sugarcane, as there is evidence that these variables are fundamental for

the improvement of agricultural efficiency in sugarcane production in Brazil, which must be considered with the current production models, where it is necessary to reduce greenhouse gas (GHG) emissions, use the available land with more efficiency, and increase the alternative sources to fossil fuel.

As a limitation of the study carried out to date, we have the restrictions of the database, which although it has a large volume of data, does not represent the totality of the plants that are part of the sugarcane industry in Brazil and does not have all the information that make up sugarcane production activities, especially economic and financial information. Still, the lack of individual data on the performance of the production of sugarcane in Australia, which makes a quantitative analysis of mills or producers impeding.

For future studies, the quantitative variables could be further explored through case studies and the qualitative variables should be measured in quantitative terms.

Acknowledgements This study was supported by funding from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES). We are also very grateful to Dr. Malcolm Wegener, from The University of Queensland for the support provided for all the activities developed in Australia.

Funding This study was supported by funding from Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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