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Energy analysis of ethanol from sugarcane irrigated with treated domestic sewage[1]

Análise energética do etanol obtido da cana-de-açúcar irrigada com esgoto doméstico tratado

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ABSTRACT - Using energy balance methodology, this study compared the sustainability of ethanol synthesis from sugarcane irrigated with different replacement levels based on the evaporation estimated in a Class A pan (ECA), using treated domestic sewage effluent and groundwater as the water source, in Aquiraz, in the State of Ceará. The adopted statistical design was of randomised blocks in split plots, with four replications. Two water sources (treated sewage effluent and groundwater) were evaluated in the plots, and five irrigation levels (50, 75, 100, 125 and 150% of the ECA) were evaluated in the split plots. Irrigation with treated domestic sewage effluent results in greater energy expenditure. The irrigation depth relative to 150% of the ECA expends the most energy, irrespective of the water source. Irrigation with treated domestic sewage effluent gives a higher energy yield (368.9 GJ ha^{-1}) through the application of a depth of 781.4 mm, while for irrigation with groundwater, 937.6 mm (150% of the ECA) is the best recommended depth for obtaining the highest energy yield (276.9 GJ ha^{-1}). Domestic sewage effluent gives the best energy return, and its use in systems of crop-production is viable.

Key words: Reuse of water. Energy balance. *Saccharum officinarum* L..

RESUMO - Avaliou-se, comparativamente, através da metodologia do balanço energético, a sustentabilidade da síntese do etanol da cana-de-açúcar, irrigada com diferentes níveis de reposição da evaporação estimada no tanque Classe "A" - ECA, utilizando como fontes hídricas: efluente de esgoto doméstico tratado e água subterrânea, em Aquiraz, Ceará. O delineamento estatístico adotado foi em blocos casualizados, em parcelas subdivididas, com quatro repetições. Nas parcelas, avaliaram-se duas fontes hídricas (efluente de esgoto doméstico tratado e água subterrânea) e nas subparcelas avaliaram-se cinco diferentes níveis de irrigação (50; 75; 100; 125 e 150% da ECA). A irrigação com efluente de esgoto doméstico tratado resulta em maior dispêndio energético. A lâmina de irrigação referente a 150% da ECA é a que mais despende energia, independente da fonte hídrica. A irrigação com efluente de esgoto doméstico tratado proporciona maior rendimento energético (368,9 GJ ha^{-1}), mediante a aplicação de uma lâmina equivalente a 781,4 mm, enquanto na irrigação com água de poço freático, a lâmina de 937,6 mm (150% da ECA) é a mais recomendada para a obtenção do maior rendimento energético (276,9 GJ ha^{-1}). O efluente de esgoto doméstico apresenta a melhor rentabilidade energética, sendo viável sua utilização no sistema de produção da cultura.

Palavras-chave: Reúso de água. Balanço de energia. *Saccharum officinarum* L..

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INTRODUCTION

The current increased demand for energy has driven the development of research into more-efficient systems and technologies, and the diversification of energy sources, to the detriment of traditional sources derived from petroleum, with a special focus on sources of clean and renewable energy (CHEL; KAUSHIK, 2011). In this context, in recent years, a number of countries, notably those that make up the European Union, plus the United States, motivated by the incessant search for environmental sustainability, have adopted policies to encourage the production and consumption of biofuels (MASIERO; LOPES, 2008).

Ethanol, a product of the fermentation of sugarcane juice, can be considered the only fuel capable of meeting the growing world demand for low-cost, low-polluting renewable energy (SANTOS *et al*., 2012).

Brazil is one of the countries that most encourages and invests in biofuel production. Brazilian exports of ethanol increased until 2008, after that, there was a yearly drop in exports, and by the first five months of 2017, the country had already imported one billion litres of ethanol (NOVACANA, 2017). Among the various factors associated with the reduction in exports and even the importation of ethanol by Brazil, the climate (the amount and distribution of rainfall) and domestic consumption stand out (BITTENCOURT; FONTES; CAMPOS, 2012).

The main criticisms currently directed at the production of biofuels are related to their reduced energy balance in relation to fossil sources. For each unit of energy invested in the production of ethanol obtained from beet (Europe) or from Maize (United States), the energy return is 2.0 and 1.6 respectively; whereas for ethanol from sugarcane the balance varies from 8.3 to 10.2 (PEZZO; AMARAL, 2007), considered by Goldemberg (2009) to be the best commercial option among biofuels. Vieira (2007), evaluating the energy balance of sugarcane, from the preparation of the soil to the fifth cut, found an energy balance of 1:20 and 1:15, for sugarcane harvested both after burning the straw and when raw, respectively.

Despite its favourable energy balance, the sustainability of sugarcane ethanol has been questioned, mainly due to the excessive water requirement of cultivating sugarcane under an irrigation regime. It is therefore common to find research directed towards quantifying a rational irrigation depth for crop production (CARVALHO *et al*., 2009; NOGUEIRA *et al*., 2016; SILVA *et al*., 2011; SILVA *et al*., 2015).

In this respect, the reuse of water in the production of sugarcane is a reality. The factories use the vinasse, a residue from the fermentation of sugarcane juice, for fertirrigation of the crop (BARBOSA *et al*., 2013). However, recent research has focused on the effects of using treated domestic sewage in sugarcane irrigation (DEON *et al*., 2010; FREITAS *et al*., 2013). So, in addition to being an alternative source of water, there is also the possibility of the partial replacement of commercial synthetic fertilisers in crop production.

In view of the above, the aim of this study was to compare the energy-balance sustainability of sugarcane ethanol under two water sources and different irrigation levels.

MATERIAL AND METHODS

The present study was carried out between 2010 and 2011 with a crop of sugarcane at the Centre for Research into the Treatment and Reuse of Wastewater, maintained by the Companhia de Água e Esgoto do Estado do Ceará (CAGECE) and the Federal University of Ceará, located in the town of Aquiraz, in the Metropolitan Area of Fortaleza.

The present research used an experimental design of randomised blocks with split plots. The plots consisted of two types of irrigation water: GW - groundwater from a well; and E - treated domestic sewage effluent from treatment processes in the domestic sewage stabilisation ponds of the municipality of Aquiraz, in Ceará. Physicochemical analysis of the groundwater and the sewage effluent was carried out at the Environmental Engineering Laboratory (LABOSAN) of the Universidade Federal do Ceará. The results are shown in Table 1.

The effects of five different irrigation depths were evaluated in the split plots, based on the evaporation from a Class A pan - (ECA) installed in the immediate vicinity of the experimental area. The irrigation depths corresponded to: D1, irrigation depth relative to 50% of the ECA; D2, irrigation depth relative to 75% of the ECA; D3, irrigation depth relative to 100% of the ECA; D4, irrigation depth relative to 125% of the ECA and D5, irrigation depth relative to 150%.

A drip irrigation system was used in the experiment. Katif self-compensating drippers, with a mean flow rate of 3.75 L h^{-1}, at a working pressure of 100 kPa, were spaced 0.5 m apart along the row, with one dripper for every two plants. During the crop cycle, the application uniformity of the irrigation system was evaluated at 60-day intervals. At the fourth evaluation, Christiansen's uniformity coefficient (CUC) was 64%, considered poor according to the Mantovani classification (2002), and the system was cleaned with 10% hypochlorite. A second evaluation was then carried out, in which uniformity had increased to 92%.

Table 1 - Physicochemical parameters of the groundwater and treated domestic sewage effluent

Type of water	pH[1]	EC	Na^+	Ca^{2+}	Mg^{2+}	K^+	Cl^-	NH_4^+	P	TS	TSS	TDS
		dS m^{-1}	mg L^{-1}									
Groundwater	6.0	2.08	19.2	16.0	16.2	10.1	37.7	0.0	0.2	219.3	6.8	212.5
Sewage	7.8	7.27	53.7	45.4	28.0	26.2	92.5	7.7	12.8	520.6	15.2	505.4

[1]pH in water (1:2.5); EC - electrical conductivity; TS - total solids; TSS - total suspended solids; TDS - total dissolved solids

To evaluate the sustainability of the sugarcane ethanol, the energy balance was determined; this establishes the ratio between the total energy contained in the ethanol (output) and the total energy invested in the entire production process (Input or Expenditure), including the agricultural and industrial stages.

In view of the complexity of determining the energy consumed in the entire agricultural production process, a table of mean values for energy expenditure is used in Brazil. For some factors therefore, tabulated values from earlier studies were used for each unit of input used in production.

Energy components

To estimate the energy expended in constructing the ponds, the project description for the Aquiraz sewage treatment plant (STP) was used (Table 2).

The energy composition of the stabilisation ponds (Table 3) was estimated from the materials and respective operations employed in constructing the treatment system.

A Composite Budget Pricing Table (TCPO 10) was used to estimate the machines and operating times involved in the earthwork activities and mechanical compaction, dumping (5 km) and excavation, loading, transportion and spreading of 200 to 100 m, painting, earthworks and concreting.

To calculate the energy expended on labour, the hourly workload was recorded for each operation as per TCPO 10, and multiplied by the energy coefficient of 4.39 MJ $hour^{-1}$ man^{-1}, as adopted by Souza *et al*. (2009).

From the total estimated energy expended on pond construction of 493,977 GJ, the working life of the ponds of 30 years, and the estimated effluent flow rate in 2011 of approximately 60.44 L s^{-1}, an energy expenditure relative to 1 L of treated domestic sewage of 0.000166 MJ L^{-1} was determined.

In order for the agricultural operations to approach the reality of sugarcane producers in Brazil, data relative to agricultural operations and energy expenditure employed by Soares *et al*. (2009) were used in this research, as shown in Table 4.

The energy expended on labour was the same as estimated by Vieira (2007) of 4.06 MJ ha^{-1}, 225.48 MJ ha^{-1}, 395.72 MJ ha^{-1} and 360.64 for preparing the area, planting, cropping treatments and harvesting respectively, giving a total of 985.9 MJ ha^{-1}.

For the energy expended on planting material (seed cane), this study employed the same value as used by Soares *et al*. (2009), who considered 2,000 kg of cane setts ha^{-1} and an expenditure of 252.2 MJ ha^{-1}, taking into account that 12,000 kg of setts ha^{-1} are required, but that these will last for 6 cycles.

As adopted by Silva and Freitas (2008) and Freitas *et al*. (2013), the energy expended by the fertiliser, nitrogen, phosphorus and potassium was approximately 67.0 MJ kg^{-1}, 17.25 MJ kg^{-1} and 13.54 MJ kg^{-1} respectively. For the micronutrient, a value of 5.40 MJ kg^{-1} was used, as adopted by Souza *et al*. (2008) and Chechetto, Siqueira and Gamero (2010). In the present study, 150 kg ha^{-1} N were used, 100 kg ha^{-1} P, 120 kg ha^{-1} K and 41.67 kg ha^{-1} micronutrients.

Table 2 - Dimensions of the stabilisation ponds of the sewage treatment plant - STP

Pond	Depth (m)	Floor dimensions (m)
Anaerobic	3.00	86.70 x 40.70
Facultative	1.50	192.70 x 95.50
Maturation	1.50	154.00 x 72.00
Maturation	1.50	153.70 x 71.70

The energy expended by the localised irrigation system was 4,159 MJ ha^{-1}, as suggested by Frigo *et al*. (2008).

Transportation was estimated for trucks with trailers (road train), with a capacity to transport 58 Mg. The composition of the freight vehicle was considered to

Table 3 - Estimated energy input components for the construction of the sewage treatment plant - STP

Pre-treatment	Unit	Quantity	Energy Expenditure (MJ)
Manual cleaning	m^2	324.00	8.69
Manual excavation of the trench, to 1.5 m	m^3	85.11	1,952.77
Manual trench earthworks	m^3	59.38	1,362.42
Earthworks and mechanical finishing	m^3	264.79	8,299.12
Ready-mix concrete	m^3	5.60	637.40
Reinforced concrete	m^3	15.80	39,700.01
Mortar 1:3	m^3	46.44	87.63
Whitewash, 3 coats	m^2	37.34	129.72
Solid-brick masonry	m^2	34.77	1,050.05
Plain cement floor, T = 0.02 m	m^3	1.35	0.10
Cement and coarse sand plastering 1:3	m^2	24.34	45.43
Subtotal energy expenditure			53,273.36
Stabilisation ponds (Anaerobic, Facul., Mat.. 1 and Mat. 2)			
Manual excavation, to 1.5 m	m^3	301.05	3,872.32
Manual cleaning	m^2	180,236.36	4,834.66
Dumping, MTD 5 km	m^3	5,142.18	984,465.08
Earthworks and mechanical finishing	m^3	168,452.30	
Motor grader 95 kw	H	842.26	768,869.36
Irrigation truck 97 kw	H	1,684.52	1,741,361.77
Tyred tractor 59 kw (MF 3060)	H	1,684.52	927,718.94
Soil compactor 75-97 kw	H	842.26	969,150.22
Disc harrow	H	1,684.52	63,079.49
Tyred compactor 92 - 108 kw	H	842.26	798,432.23
Jobber	H	2,526.78	12,103.30
Excavation, loading, transportion and spreading from 200 to 100 m	m^3	16,558.00	
Bulldozer 140 hp PD 140	H	331.16	366,354.76
Tyred loader 170 hp	H	331.16	361,786.63
Dump truck	H	993.48	1,027,001.76
Asphalt mantle 3 mm*	m^2	8,389.00	427,839.00
Reinforced concrete	m^3	56.36	141,613.46
Mortar	m^3	0.83	1.56
PVC tubing, J.E DN 200 mm	M	347.42	354,368.40
PVC tubing, J.E DN 300 mm	M	226.18	493,977.12
Subtotal energy expenditure			9,446,830.05
Total energy expenditure			9,500.103.41

Source Tavares (2006)

Table 4 - Energy consumption, in the form of diesel fuel, in agricultural operations for the renovation and maintenance of the sugarcane plantation during a sugarcane production cycle in Brazil

Agricultural operation	Equipment	MJ ha^{-1}
Application of limestone	MF 290	161.00
Incorporation of plant residue	Valmet 1280	330.40
Heavy ploughing I	CAT D6	665.70
Subsoiling	CAT D6	1,070.40
Heavy ploughing II	CAT D6	646.10
Heavy ploughing III	CAT D6	646.10
Harrowing	CAT D6	246.40
Furrowing	MF 660	435.90
Distribution of cane setts	MF 275	199.50
Closing grooves and application of insecticides	MF 275	91.00
Application of herbicides	Ford 4610	57.90
Weeding between rows	Valmet 880	182.40
Mechanised harvesting*		1,900.8
Total		6,633.60

Source: Soares *et al*. (2009); Salla *et al*. (2009)

be: a tractor unit, Mercedes-Bens Axor 2644, with a weight of 10.3 Mg and power output of 428 hp; and a trailer (dolly coupling), with a weight of 13.35 Mg, as used by Carreira (2010). According to the latter author, the energy coefficient of this vehicle composition is approximately 68.47 Mg km L^{-1}.

To estimate the indirect energy expenditure on transportation (truck and trailer manufacture), the Macedonio and Picchioni methodology (1985) was used. Accordingly, for the tractor unit (self-propelled), the value adopted was 69,830 MJ kg^{-1}; for the non-self-propelled trailers, the value was 57,200 MJ kg^{-1}. The working life of the composition was 500,000 km, as used by Carreira (2010). The energy coefficient of diesel fuel is equal to 11,400 kcal of energy per litre of diesel (PIMENTEL; PATZEK, 2005).

A distance of 18.20 km was considered for the location of the experimental unit and the factory. Table 5 shows the expenditure, considered fixed, and estimated in this study for the production of 1 hectare of sugarcane.

Energy expenditure related to obtaining (the catchment of groundwater and treated sewage water with a 5 hp motor pumping system) and applying irrigation depths relative to treatments D1 = 312.60, D2 = 468.80, D3 = 625.10, D4 = 781.40 and D5 = 937.70 mm, using a 5 hp motor pump assembly (Table 6).

For industrial processing, an energy coefficient of approximately 32.84 MJ was used for every 1 Mg of processed stalks, as estimated by Soares *et al*. (2009). Energy expenditure on the industrialisation of sugarcane estimated for each treatment, as a function of the production potential of the stalks, can be seen in Table 7.

Energy output

The energy output of the system was estimated by multiplying the production potential of ethanol, obtained for each treatment, by the energy coefficient of 23.7 MJ per L of ethanol, as used by Salla *et al*. (2009). The energy generated from the sugarcane bagasse was not calculated.

The normality hypothesis was tested by the Shapiro-Wilk test (W) at 5%. The data for the variables under evaluation were then submitted to analysis of variance by F-test at 1 and 5% probability. When a significant effect was verified for the analysis of variance, the qualitative data obtained in the different treatments were compared using Tukey’s test at a level of 1 and 5%; the quantitative data were submitted to regression analysis, seeking to fit equations with biological significance, selecting the mathematical models that had higher levels of significance and a higher value for the coefficient of determination (R^2), using the SAEG 9.0 UFV and Assistat 7.6 Beta statistical analysis software.

Table 5 - Estimated energy input components for the cultivation of 1 hectare of sugarcane, considered fixed

Component	Unit	Quanty	MJ ha^{-1}
Mechanised agricultural operations			6,633.6
Labour			985.9
Irrigation system			4,159.0
Seeds	Kg	2,000	252.2
Nitrogen	Kg	150	10,050.0
Phosphorus	Kg	100	1,725.0
Potassium	Kg	120	1,624.8
Micronutrients	Kg	41.67	225.0
Trasportation (GW) *	Km	18.20	2,248.0
Trasportation (E) **	Km	18.20	3,107.9
Total fixed expenditure*			28,968.7
Total fixed expenditure**			30,236.1

Energy expenditure for transportation as a function of estimated average production potential per hectare: * 177.48 stalks for sugarcane irrigated with groundwater and ** 245.37 Mg ha^{-1} stalks for sugarcane irrigated with treated domestic sewage effluent

Table 6 - Estimated energy input components as a function of obtaining and distributing the water sources

Treatment	Unit	D1	D2	D3	D4	D5
Depth	mm	312.6	468.8	625.1	781.4	937.7
Irrigation time	h	37.51	56.26	75.01	93.77	112.52
Expend. catchment GW (5hp)[1]	MJ ha^{-1}	1,143.05	1,714.58	2,286.11	2,857.63	3,429.16
Expend. irrigation GW (5hp)[2]	MJ ha^{-1}	1,143.05	1,714.58	2,286.11	2,857.63	3,429.16
Ttl. expend. irrigation. GW (5hp)	MJ ha^{-1}	2,286.11	3,429.16	4,572.21	5,715.27	6,858.32
Expend. irrigation E (5hp)	MJ ha^{-1}	1,143.05	1,714.58	2,286.11	2,857.63	3,429.16
Expend. sewage treatment E	MJ ha^{-1}	519.27	778.91	1,038.55	1,298.18	1,557.82
Ttl. expend. irrigation. E	MJ ha^{-1}	1,662.33	2,493.49	3,324.65	4,155.82	4.986.98

[1]Motor pumping system used for groundwater catchment (GW); [2] Motor pumping system used for irrigation with groundwater (GW)

Table 7 - Energy input component of sugarcane transportation for water source [groundwater (GW) and treated domestic sewage effluent (E)] and irrigation depth

Type of water	Irrigation depth (mm)				
	312.6	468.8	625.1	781.4	937.7
	Industrialisation Expenditure (MJ ha^{-1})				
GW	3,821.43	5,275.06	6,228.97	6,913.98	6,903.15
E	6,976.27	7,220.97	8,463.84	8,691.03	8,938.53

RESULTS AND DISCUSSION

The data for energy expenditure or energy input to the system (EXPD), energy output of the system (OUTP) and energy balance (BAL), were normal for the W-test. Table 8 summarises the analysis of EXPD, OUTP and BAL. A significant effect was seen from the types of water on all the variables under analysis. For the treatments with irrigation depth, significant effects were also found for all the analysed variables (EXPD, OUTP and BAL). The same

Table 8 - Summary of the analysis of variance of the data for energy expenditure (EXPD) and energy output of the system (OUTP), and energy balance (BAL) for sugarcane under two types of irrigation water (W) and five irrigation depths (D)

Source of variation	DF	Square root		
		EXPD	OUTP	BAL
Block	3	166,812.35^{ns}	754.84^{ns}	0.39^{ns}
Treatment (W)	1	50,601,152.81**	134,248.32 **	64.03 *
Residual W	3	19,223.48	3,536.54	2.18
Plots	7			
Treatment (D)	4	54,991,289.77**	23,162.19 **	7.40 **
Int. W x D	4	1,826,887.05**	4,288.91 *	2.40 *
Residual D	24	74,262.95	1,058.77	0.59
Total	39			

W - Type of water; D - Irrigation depth; ns - not significant; * - significant at 0.05 probability; **- significant at 0.01 probability

was seen with the interaction W x D, which was significant for all the variables being analysed, demonstrating the dependence between these factors.

The greatest energy expenditure or energy input to the system of 41,618.9 MJ ha^{-1} was found for irrigation with domestic sewage effluent, which was statistically different ($P < 0.05$) from the expenditure of 39,369.5 MJ ha^{-1}, found for irrigation with groundwater. These values are close to those seen by Macedo, Leal and Silva (2004), of 41,078 and 61,547 MJ ha^{-1} for sugarcane irrigated with well water and treated domestic sewage effluent respectively.

Comparing the productive energy expenditure for each irrigation depth, it was found that sugarcane irrigated with treated domestic sewage effluent consumed more energy (Table 9). This is due to the energy expended on the treatment of domestic sewage (0.166 J L^{-1}), together with the higher values for productive potential recorded for sugarcane irrigated with treated domestic sewage effluent (on average, 38% more productivity), which consequently consumes more energy on transportation. According to Soares *et al*. (2009), the energy expenditure for the agricultural operations and transportation of the sugarcane are quite significant, possibly making the sustainability of biofuels unfeasible. The energy expended on transportation is from 19.01 to 21.28% of the energy expended on the production and transportation of the sugarcane (MACEDO; LEAL; SILVA, 2004).

The sugarcane irrigated with treated domestic sewage effluent gave the greatest mean energy output of the system (321.49 GJ ha^{-1}), statistically different from the mean value seen for irrigation with groundwater, of approximately 205.63 GJ ha^{-1}. These values were higher than those found by Soares *et al*. (2009) and Urquiaga, Alves and Boodey (2005), of approximately 139.64 and 161.10 GJ ha^{-1} respectively.

The increase in water availability provided an increase in energy yield. The highest energy outputs of the system were seen for the depths relative to 150 and 125% of the ECA for the sugarcane irrigated with groundwater and treated domestic sewage effluent respectively (Table 9).

Irrigation of the sugarcane with treated domestic sewage effluent favoured a more positive balance per unit of energy used throughout the production process. A mean value of 7.69 was found; this is statistically different from the energy balance obtained for sugarcane irrigated with groundwater (1:5.16). These values were lower than the range proposed by Macedo, Leal and Silva (2004) of 1:8.3 to 1:10.2. This difference can be explained by the above authors having included the surplus energy generated with the bagasse. In the present study, only the ethanol was considered as an energy output.

Soares *et al*. (2009) did not consider the excess energy with the bagasse. They estimated an energy balance of approximately 1:9.35, higher therefore than in the present study. This was due to not including the energy expended on sugarcane irrigation, which was included in the present work. Consequently, it can be understood how the energy balance is directly associated with crop management under field conditions and with the technologies involved in the production process, as found by Karimi *et al*. (2008). The increase in water availability produced a more productive energy balance. The greatest energy balance obtained for sugarcane irrigated with groundwater was 1:6.80 at an irrigation depth of 150% of the ECA (Table 9). For sugarcane irrigated with treated domestic sewage effluent, the irrigation depth of 125% of

Table 9 - Energy expenditure, energy output of the system, and energy balance of the ethanol from sugarcane irrigated with groundwater (GW) and domestic sewage effluent (E) at five irrigation depths based on percentages of the evaporation estimated in a Class A pan (ECA)

Type of Water	Irrigation depth (% ECA)					CV (%)
	50	75	100	125	150	
	Energy expenditure (MJ ha^{-1})					
GW	35,076.27 b	37,672.95 b	39,769.91 b	41,597.97 b	42,730.20 b	0.34
E	38,874.75 a	39,950.61 a	42,024.64 a	43,082.99 a	44,161.66 a	
CV (%)	0.67					
	Energy output (GJ ha^{-1})					
GW	134.93 b	179.54 b	198.18 b	224.98 b	290.51 a	22.56
E	233.68 a	296.96 a	347.16 a	391.37 a	338.30 a	
CV (%)	12.35					
	Energy balance					
GW	3.84 b	4.77 b	4.98 b	5.40 b	6.80 a	22.98
E	6.01 a	7.43 a	8.26 a	9.08 a	7.66 a	
CV (%)	12.02					

[*]Mean values followed by the same lowercase letter in a column do not differ statistically by Tukey's test at 0.05 probability

the ECA gave the most positive energy balance of 1:9.08. This value agrees with that estimated by Soares *et al*. (2009), of 1:9.35.

Increases of approximately 21.8 and 13.6% were estimated when comparing the calculated energy expenditure at irrigation depths of 312.6 and 937.7 mm for irrigation with groundwater and sewage effluent respectively (Figure 1A).

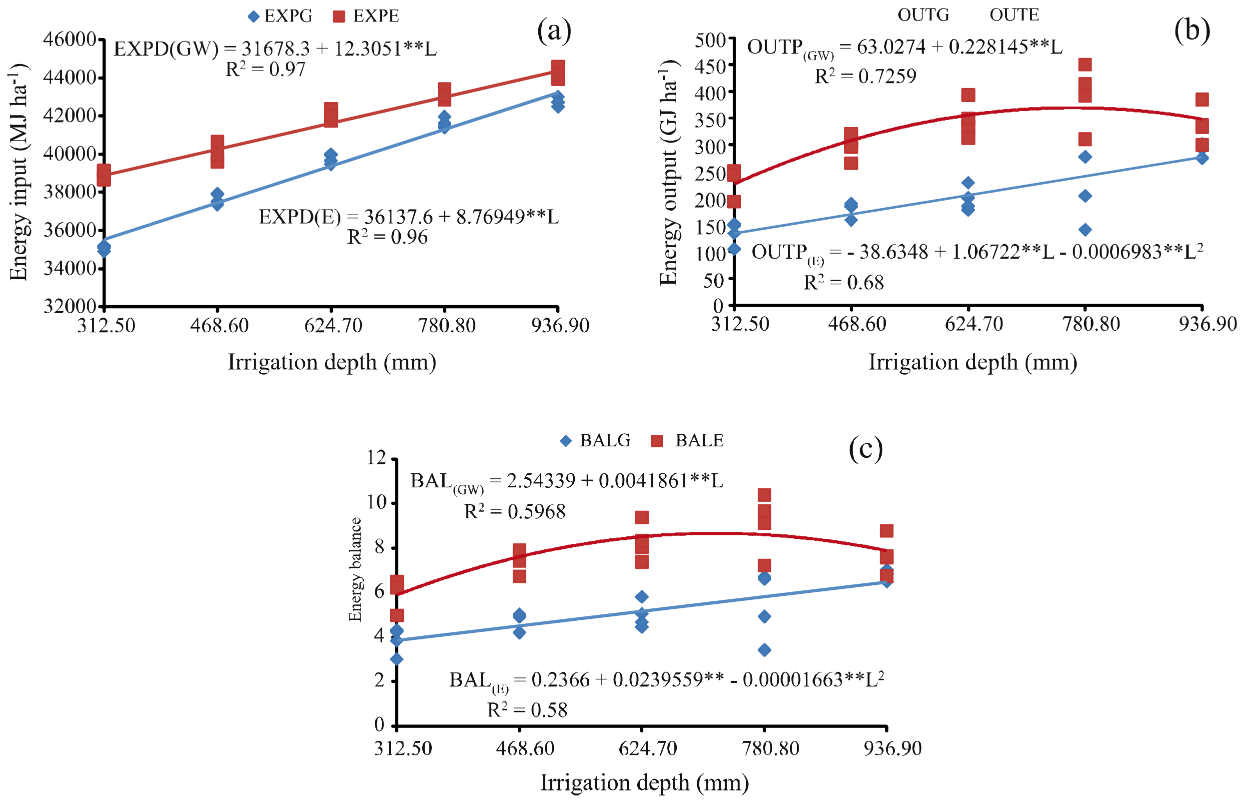
According to Karimi *et al*. (2008), the highest energy expenditure for sugarcane agricultural production is associated with irrigation, and can total 43%. This value is much higher than that seen in the present study, in which the energy expended on the irrigation system, added to that expended on application of the irrigation depths, was from 23 to 34% and from 21 to 30% for groundwater and sewage effluent respectively. Consequently, strengthening production by minimising water wastage resulting from excessive water application, can guarantee the sustainability of sugarcane ethanol production.

Maximum values for the estimated energy output of the system were 276.9 GJ ha^{-1} and 368.9 GJ ha^{-1} at irrigation depths of 937.6 mm and 781.4 mm, for sugarcane irrigated with groundwater and sewage effluent respectively (Figure 1B). Considering these estimates, the use of sewage effluent in sugarcane irrigation produced a higher energy yield, greater by approximately 33% when compared to the maximum energy output estimated for sugarcane irrigated with groundwater.

Another advantage from the use of sewage in irrigation was a reduction of about 20% in irrigation depth to achieve the maximum values for energy output. This is probably due to the intrinsic qualities of irrigating with sewage effluent, such as the macro- and micronutrients present; where with each irrigation, fertirrigation occurs from the nutrients dissolved in the reused water. These assertions agree with Sousa Neto *et al*. (2012), who state that the nutrients contained in treated effluents favour fertility, and may reduce or even eliminate the need to add commercial fertilisers. According to Monteiro *et al*. (2008), the increase in soil fertility in particular, promotes greater water-use efficiency in crops.

The most positive values for energy balance, 1:6.47 and 1:8.59, were estimated at the irrigation depths of 937.6 and 720.3 mm (150% and 115% of the ECA) for sugarcane irrigated with groundwater and sewage effluent respectively. The maximum energy balance estimated for sugarcane irrigated with groundwater was less than that estimated by several authors, from 1:8.0 to 1:19.90 (MACEDO; LEAL; SILVA, 2004; SOARES *et al*., 2009; VIEIRA, 2007). Whereas for the sugarcane irrigated with sewage effluent, the maximum estimated energy balance of 1:8.59 was close to that estimated by Urquiaga, Alves and Boodey (2005), of 1:8.06.

Figure 1 - Energy expenditure (A), energy output of the system (B) and energy balance (C) of sugarcane ethanol irrigated with groundwater (GW) and treated domestic sewage effluent (E) for irrigation depths based on percentages of the evaporation estimated in a Class A pan (ECA)



According to the estimates of maximum energy balance, sugarcane irrigated with sewage effluent would result in a more positive energy balance of approximately 32%, and with a reduction in water expenditure of around 23% (Figure 1C), indicating that treated domestic sewage is an ecologically viable alternative for the irrigation of sugarcane destined for biofuel production.

CONCLUSIONS

1. For both sources of water (treated sewage effluent and groundwater), the irrigation depth that expends the most energy is that relative to 150% of the ECA;
2. Domestic sewage effluent has the best energy yield, and its use is viable in a system of sugarcane production;
3. Irrigation with treated domestic sewage effluent gives a higher energy yield (368.9 GJ ha^{-1}) through the application of a depth equal to 781.4 mm (125% of the ECA), while irrigation with groundwater at a depth of 937.6 mm (150% of the ECA) is recommended to achieve the highest energy yield (276.9 GJ ha^{-1}).

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