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NET ENERGY ANALYSES OF ETHANOL PRODUCTION FROM SUGARCANE IN NORTHEAST BRAZIL

AHMAD SAEED KHAN

Departamento de Economia Agrícola, Universidade Federal do Ceará, Caixa Postal 354, Fortaleza, Ceará, Brazil 60.000

and

ROGER W. FOX

Department of Agricultural Economics, College of Agriculture, The University of Arizona, Tucson, Arizona 85721, USA

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ABSTRACT

Net energy analyses of alcohol production from sugarcane production technologies based on intensive use of fertiliser (System I) and on improved cultural practices without chemical fertiliser (System II) were considered. The energy analysis considered the total system inputs. The results indicate that both systems are almost equally efficient in terms of energy ratio.

Key words: energy ratio, sugarcane, ethanol, stillage treatment.

INTRODUCTION

Following the situation created by the 1973 petroleum crisis, the Government of Brazil established the 'Programa Tecnologico do Etanol' (PTE) in 1974. Complementing the work of PTE, as well as to save the sugar industry which was facing low prices in the international market in the early 1970s, the Government also created, on 14 November, 1975, 'Programa Nacional do Álcool' (PROÁLCOOL) which it was hoped would also bring many socio-economic benefits.

In order to reduce the extent of oil imports, PROÁLCOOL initially aimed at producing 3×10^9 litres of alcohol during 1980.[1] To achieve this goal, the Government of Brazil financed through PROÁLCOOL the installation of annexed and

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autonomous distilleries of large capacity, mainly in the state of São Paulo. The concentration of distilleries in one state led to the failure of PROÁLCOOL in accomplishing most of the socio-economic goals originally desired by the Government.[2]

During 1979, the Government of Brazil revised its energy policy and set an alcohol production target of $10{\cdot}7 \times 10^9$ litres in the year 1985.[3] To achieve this goal, PROÁLCOOL will finance the installation of different capacity distilleries in various sugarcane and manioc growing areas of the country and particularly in northeast Brazil.

MATERIALS AND METHODS

Sugarcane production yields in northeast Brazil are lower than in its southeastern region. The average yield of sugarcane in the state of Ceará is one of the lowest in the nation (37 t ha^{-1} $year^{-1}$ compared to 66 t ha^{-1} $year^{-1}$ in the state of São Paulo), and this situation is attributable to the fact that sugarcane growers in the northeast, in general, do not use modern agricultural technologies. The para-governmental state and federal agencies developed and have been recommending since 1977 new semi-mechanised technologies based on intensive use of fertilisers (System I) and on improved cultural practices without chemical fertiliser (System II). On the average, System I is expected to produce 80 t ha^{-1} $year^{-1}$ of sugarcane and System II 60 t ha^{-1} $year^{-1}$.

The data on physical coefficients of various inputs and associated expected yields for both production systems were obtained from the bulletin entitled 'Sistemas de Produção para Cana-de-Açúcar', prepared jointly by federal and state agriculture agencies.[4]

Total labour, farm machinery and equipment, fertilisers and insecticides were translated into energy equivalents using the conversion factors reported by Heichel,[5,6] Pimentel *et al.*,[7] da Silva *et al.*,[8] and Hopkinson and Day,[9] and shown in Table 1. The energy embodied in the distillery machinery was calculated by using the information provided by Birkett and Polack,[10] and Hopkinson and Day.[9]

The total weights of farm machinery and equipment, excluding hand tools, required for the production of one hectare of first crop sugarcane and its transportation to a distillery under Systems I and II are estimated at 21·58 kg and 18·79 kg, respectively. These machinery weights were translated into equivalent energy by using the estimated energy input for manufacturing and maintenance of farm machinery as reported by Berry and Fels,[11] Pimentel *et al.*,[7] and Hopkinson and Day;[9] they calculated the energy equivalent of 20 691 kcal kg^{-1} for machinery and equipment which functions from 4 to 15 years.[9] Maintenance was assumed to be 6% of the total machinery energy value.[7]

For industrial ethyl alcohol production, it was assumed that each ton of sugarcane will produce 66 litres of anhydrous alcohol and 250 kg of bagasse. Each litre of alcohol

TABLE 1
Energy conversion coefficients of various inputs and products

Inputs, products	*Unit*	*Energy equivalent*	
		Mcal	*MJ*
Labour	man-hour	0·54	2·3
Nitrogen (N)	kg	18·51	77·5
Phosphorus (P)	kg	3·35	14·0
Potassium (K)	kg	2·31	9·7
Insecticide	kg	24·24	101·5
Seed	kg	0·10	0·4
Diesel oil	litres	8·45	35·4
Farm machinery and equipment	kg	20·73	86·8
Bagasse	kg	1·30	5·4
Anhydrous alcohol	litres	5·26	22·0

Source: For labour, nitrogen, phosphorus, potassium, insecticide, see ref. 7; for seed, diesel oil, bagasse, anhydrous alcohol, see ref. 8; for farm machinery and equipment, see refs 5, 6, 7.

requires 5·5 kg of steam and each kg of bagasse can generate 1·1 kg of steam.[8] The energy requirement for ethanol production from sugarcane includes the energy necessary for feedstock processing, ethanol distillation, and evaporation and drying of stillage, all of which is accomplished with steam generated by burning bagasse. The distillery machinery necessary to produce alcohol from one hectare of sugarcane was translated into its energy equivalents: 2·5 GJ and 2·1 GJ under System I and System II, respectively.[10]

For part of the analysis, it was assumed that distillery effluent (stillage) would be evaporated and dried in order to use it as one of the components of animal feed. Jenkins *et al.*[12] reported that the stillage associated with each kJ of alcohol requires 0·085 kJ to transform it into animal feed of energy equivalent to 0·011 kJ. On the surface, it appears that the conversion of stillage to animal feed is irrational. However, the private and social costs of disposing of large volumes of stillage may force the use of inefficient (in terms of energy) conversion techniques. In this study, results for both conversion and nonconversion of stillage are presented.

In summary, the following hypothetical systems were studied:

System I. New cultural practices and the use of chemical fertiliser for producing sugarcane.

System II. New cultural practices without the use of chemical fertiliser for producing sugarcane.

Case 1. Converting all bagasse to steam and not evaporating and drying the stillage.

Case 2. Converting enough bagasse to steam in order to provide process heat for alcohol production.

Case 3. Converting all bagasse to steam and also transforming the stillage into dried distillers grain.

Case 4. Converting enough bagasse to steam in order to provide heat for alcohol production and for evaporation and drying of stillage.
Case 5. Considering only energy expended in agricultural phase plus industrial structure and energy produced in the form of ethanol.

RESULTS AND DISCUSSION

The energy analysis considered the total system inputs. These included energy to grow feedstock; energy to produce fertiliser and insecticide; energy to manufacture machinery to grow and transport feedstock to a distillery; energy needed to manufacture industrial machinery to process sugarcane into ethanol; and energy consumed to transform stillage, a by-product, into animal feed. This approach differs from the energy analyses performed by da Silva *et al.*,[8] Hopkinson and Day,[9] and Ruas[13] which did not include the energy embodied in the industrial machinery used in ethyl alcohol production, nor consider the treatment of stillage.

Sugarcane production and transportation

The energy requirements to grow, harvest and transport sugarcane to a distillery under both Systems in the irrigated areas and for three crops, i.e. first crop, first ratoon and second ratoon, are shown in Table 2. The energy expended on machinery also includes the energy equivalent of hand tools, such as axes and hoes used to perform some of the manual agricultural operations. The fuel estimate includes the quantity of diesel oil consumed in the agricultural phase of sugarcane production and its transportation to a distillery.

Table 3 provides a comparison between the two different production and transportation systems. One hectare of sugarcane production and transportation requires about 74% more energy under System I than under System II. The single largest energy input in sugarcane production is fertiliser; nitrogen alone accounts for more than 33% and fertiliser as a whole for about 37% of the total energy consumption. The high energy input from fertiliser use might be brought down by replacing fertiliser with animal manure; however, the use of manure was not investigated in this study. Fuel takes second place, followed by labour. In System II, fuel and labour occupy the first and second places.

The energy input for insecticides in sugarcane production under both systems is the same and the smallest of all inputs, about 0·068 GJ. The machinery share of total energy consumption is substantially lower than that reported by Pimentel *et al.*,[7] da Silva *et al.*[8] and Hopkinson and Day.[9] This results from performing some of the agricultural operations by manual labour and hand tools rather than relying heavily on mechanisation. However, total energy consumed by System I in the agricultural phase is the same as that calculated by da Silva in São Paulo.[8]

TABLE 2
Energy expended in the production and transportation of one hectare of sugarcane in the irrigated areas of northeast Brazil – Systems I and II

Inputs	First crop				First ratoon				Second ratoon				Average			
	System I		System II		System I		System II		System I		System II		System I		System II	
	(GJ)	(%)	(GJ)	(%)	(GJ)	(%)	(GJ)	(%)	(GJ)	(%)	(GJ)	(%)	(GJ)	(%)	(GJ)	(%)
Labour[a]	3·938	18·0	3·606	26·0	3·006	23·0	2·710	39·0	3·006	23·0	2·710	39·0	3·317	20·0	3·009	32·0
Machinery[b]	1·955	9·0	1·713	12·0	1·434	11·0	1·192	17·0	1·434	11·0	1·192	17·0	1·607	10·0	1·366	15·0
Seed	3·429	16·0	3·429	25·0	–	–	–	–	–	–	–	–	1·143	7·0	1·143	12·0
Insecticide	0·205	0·9	0·205	1·5	–	–	–	–	–	–	–	–	0·068	0·4	0·068	0·7
Fuel[c]	5·121	23·0	4·819	35·0	3·429	25·8	3·127	44·0	3·429	25·8	3·127	44·0	3·993	24·0	3·691	40·0
Nitrogen	6·429	29·0	–	–	4·822	36·0	–	–	4·822	36·0	–	–	5·358	33·0	–	–
Phosphorus	0·365	1·7	–	–	0·252	1·9	–	–	0·252	1·9	–	–	0·290	1·8	–	–
Potassium	0·490	2·2	–	–	0·343	2·6	–	–	0·343	2·6	–	–	0·392	2·4	–	–
Total	21·932	100·0	13·772	100·0	13·286	100·0	7·029	100·0	13·286	100·0	7·029	100·0	16·168	100·0	9·277	100·0

[a] Includes labour for transportation to a distillery and for irrigation.
[b] Energy expended on machinery includes 10 164 J energy equivalent of 8 h use of a hand sprayer to spray insecticide on the first crop, and 69 594 J energy equivalent for axe and manual hoe are included in the calculation for all three crops. Also includes machinery for transportation to a distillery.
[c] Includes fuel for transportation of feedstock to a distillery.

TABLE 3
Summary of energy expended in the production and transportation of one hectare of sugarcane in the irrigated regions of northeast Brazil – Systems I and II[a]

Inputs	System I (Expected yield 80 t ha^{-1} year^{-1})		System II (Expected yield 60 t ha^{-1} year^{-1})	
	(GJ)	(%)	(GJ)	(%)
Labour	3·317	20·0	3·009	32·0
Machinery	1·607	10·0	1·366	15·0
Seed	1·143	7·0	1·143	12·3
Insecticides	0·068	0·4	0·068	0·7
Combustibles	3·993	24·4	3·691	40·0
Nitrogen	5·358	33·0	–	–
Phosphorus	0·290	1·8	–	–
Potassium	0·392	2·4	–	–
Total	16·168	100·0	9·277	100·0

[a] See Table 2 for details.

Alcohol production

The total energy expended in the operation of the distillery depends on the distillery capacity and the technology used in the conversion of feedstock to ethyl alcohol. Distillery machinery equivalents of 2·5 GJ and 2·1 GJ are required to process one hectare of sugarcane under Systems I and II, respectively (Table 4). In addition, large amounts of energy are used to provide process heat for the industrial phase, with System I using 16·5 GJ ha^{-1} year^{-1} more than System II (Table 4). For Cases 3 and 4, which include the treatment of stillage, about 10 and 7 GJ of additional energy are expended by Systems I and II, respectively.

Overall energy balance

Table 4 also provides information on the energy balance for both systems, depicting total energy expended (agricultural and industrial phases), the energy produced, and the energy ratio. The energy consumed by the industrial phase, except in Case 5, is 4·23–4·84 and 5·55–6·35 times higher than that in the agricultural phase under Systems I and II, respectively, depending on the treatment of stillage and the conversion of bagasse to steam.

Case 5 of System II has the highest energy ratio of 7·7. These energy calculations did not take into account the energy that can be produced by burning bagasse and process heat required in the industrial phase.

Among other situations considered, Case 1 of System II has the highest output-input ratio, 2·78, indicating a high return on energy investment. The energy output calculations include the energy that can be obtained by burning all bagasse and not treating the stillage. There is an excess of energy, and it is possible that this excess could be economically exported from an alcohol plant to another location (e.g.

TABLE 4
Energy output–input of alcohol production from sugarcane in the irrigated areas of northeast Brazil

System	Case[a]	Agricultural yield ($t\ ha^{-1}\ year^{-1}$)	Alcohol production		Energy produced ($GJ\ ha^{-1}\ year^{-1}$)				Energy expended ($GJ\ ha^{-1}\ year^{-1}$)						Energy ratio (produced/consumed)
			(litres t^{-1})	(litres ha^{-1} ($\times 10^3$))	Alcohol	Bagasse	Animal feed	Total	Agriculture	Industry: Industrial structure	Industry: Process heat for alcohol	Industry: Evaporation and drying of stillage	Industry: Subtotal	Total	
I	1	80	66	5·28	116·6	108·9	–	225·5	16·2	2·5	65·9	–	68·4	84·6	2·67
	2	80	66	5·28	116·6	65·8	–	182·4	16·2	2·5	65·9	–	68·4	84·6	2·16
	3	80	66	5·28	116·6	108·9	1·2	226·7	16·2	2·5	65·9	9·9	78·3	94·5	2·40
	4	80	66	5·28	116·6	75·8	1·2	193·6	16·2	2·5	65·9	9·9	78·3	94·5	2·05
	5	80	66	5·28	116·6	–	–	116·6	16·2	2·5	–	–	2·5	18·7	6·24
II	1	60	66	3·96	87·5	81·6	–	169·1	9·3	2·1	49·4	–	51·5	60·8	2·78
	2	60	66	3·96	87·5	49·4	–	136·9	9·3	2·1	49·4	–	51·5	60·8	2·25
	3	60	66	3·96	87·5	81·6	0·9	170·0	9·3	2·1	49·4	7·4	58·9	68·2	2·49
	4	60	66	3·96	87·5	56·8	0·9	145·2	9·3	2·1	49·4	7·4	58·9	68·2	2·13
	5	60	66	3·96	87·5	–	–	87·5	9·3	2·1	–	–	2·1	11·4	7·68

[a] Case 1. Converting all bagasse to steam and not evaporating and drying the stillage.
Case 2. Converting enough bagasse to steam in order to provide process heat for alcohol production.
Case 3. Converting all bagasse to steam and also transforming the stillage into animal feed.
Case 4. Converting enough bagasse to steam in order to provide process heat for alcohol production and for evaporation and drying of stillage.
Case 5. Considering only energy expended in agricultural phase plus industrial structure and energy produced in the form of ethanol.

another processing plant) or used for electricity generation. It might also be possible to integrate another process with the distillery at the same location (e.g. pumping irrigation water).

CONCLUSIONS

Energy analysis of the type presented in this paper is subject to several limitations. First, the results should not be immediately extended to other producing regions of the country without careful consideration of the differences in sugarcane production technologies. Once the differences have been identified and quantified, it is fairly easy to adjust the analyses reported in this paper to reflect different cultural practices and resource productivities. Second, the study is limited by the inability to compare the two new production technologies with the existing traditional methods of producing sugarcane in northeast Brazil. Such a comparison was not possible because of the lack of input-output data for the traditional system. Third, because of lack of data, we were unable to estimate the energy needed to dispose of the stillage under Cases 1 and 2. Consequently, although Cases 3 and 4 use more energy, the comparisons are incomplete.

The results indicate that System I (using chemical fertiliser) and System II (no chemical fertiliser) are almost equally efficient in terms of the energy ratio. Within the context of risk aversion and broader economic considerations, System II may be preferred. The omission of fertiliser reduces economic risk, particularly in drought-prone areas such as are found in parts of northeast Brazil. Also, omitting fertiliser might be attractive from the point of view of reducing fertiliser imports and saving scarce resources.

Overall, the analysis confirmed the findings of da Silva *et al.*[8] that sugarcane can be used as an energy-efficient feedstock for ethanol production in Brazil.

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