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Energy efficiency assessment by life cycle simulation of cassava-based fuel ethanol for automotive use in Chinese Guangxi context

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ABSTRACT

Interest has been renewed in bio-ethanol products for their contributions in moderating oil crises. So far, most research on bio-ethanol in China is based on pilot-level experimental studies. But this work only discloses information regarding material balances and reached yields without any further energy analysis.

This paper aims to assess the energy efficiency of the cassava-based fuel ethanol (KFE) product from southwest China. For the purpose of a life cycle study of the KFE product as replacement transportation fuel, the study chose a "vehicle fueled by cassava-based E10 (a blend of 10% ethanol and 90% gasoline by volume)" as the subject and accordingly defined the scope of this study. Then, the life cycle model of the KFE product concerning energetically relevant in- and outputs was built. Due to variations in data collected, as well as some estimates and assumptions used in this study, the Monte Carlo method was introduced to develop the statistical dispersion of calculated outputs of the assessing model. Assessment results show that, within the boundary of this study, KFE has a positive net energy value, with an energy ratio of around 0.70 MJ/MJ, which means 7 MJ into the processing for each MJ of KFE output.

1. Introduction

Petroleum supply shortage caused by the rapid expansion of the Chinese transportation sector, which is almost entirely dependent on petroleum, has created much concern over the security of China's energy supplies. Fuel ethanol became attractive as a gasoline extender and was considered as a means of prolonging the Nation's gasoline supply. In 2002, the Chinese central government issued Policy [2002]174 aimed at encouraging biomass-based fuel ethanol (BFE) development to enhance energy security.

BFE is ethyl alcohol derived from agricultural crops. It is a renewable energy resource. The dominant regional agricultural crops are often used as the primary feedstock choices for BFE: for examples, the dominant BFE feedstock in Brazil is sugar cane, while it is corn in the United States and lower value grain such as barley, corn and feed wheat in Canada [1–3]. Among various feedstock choices for producing ethanol, cassava is the focus of this study. Cassava is widely grown for its enlarged starch-filled roots, which contain nearly the maximum theoretical concentration of starch on a dry weight basis among food crops. Therefore, cassava is a promising crop for ethanol production because ethanol can be generated from starch. Furthermore, for a densely populated developing country like China, cassava, which is not the main Chinese food crop, is a good supplement to the feedstock for domestic ethanol production such as wheat and corn because of food shortage concerns. Guangxi Zhuang Ethnic Autonomous Region, along with some parts of its neighboring provinces, is the biggest and most suitable cassava-cultivating area in China. According to the investigation done by the High-Tech Industry Development Division of Guangxi Development Planning Commission, as cassava is able to grow in poor soils on marginal lands with minimal amounts of fertilizer, pesticides and water, expansion of cassava cultivation in the Region can make use of 267,000 ha of hillside wasteland in southwest China and offer jobs to 1.36 million local people.

Concerning all the factors mentioned above, we can conclude that BFE products are promising fossil fuel substitutes for their renewability, and excellent fuel properties. China has plentiful natural resources to develop a cassava-based fuel ethanol (KFE) industry. The development of the KFE industry is expected to not only provide an economic stimulus for local agriculture but also to help guarantee a perpetual energy supply. However, critics question the rationale behind policies that promote ethanol for energy security benefits. If the energy sources required to grow and convert certain biomass into ethanol are greater than the

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Nomenclature

LCA	life cycle assessment
BFE	biomass-based fuel ethanol
KFE	cassava-based fuel ethanol
E10	blend of 10% ethanol and 90% gasoline by volume
EF	energy feedstock
PF	process fuel
EO	energy presented in energy product
Cff	energy coefficient
TECff	total energy coefficient
NEV	Net energy value
v/v	by volume

Subscripts

i	*i*th lifecycle activity unit
j	*j*th process fuel
k	*k*th energy feedstock
l	*l*th energy product

energy value present in the ethanol fuel, which indicates a negative net energy value (NEV) of BFE, increasing BFE production does little to displace oil imports and increase energy security. Actually, if they are greater than the input, then they will likely cause an increase in oil imports, not simply do little to displace them.

The complexity of the problems that should be taken into account within societal, economic, and environmental dynamics suggests analysis of the biomass-to-fuel conversion system with useful indicators about system behaviors. Several methods have been suggested to perform analyses of such a conversion system. The primary tools are the life cycle assessment (LCA) method, the thermoeconomic theory [4], further extended to include the cumulative exergy cost accounting (CExC) [5], the extended exergy accounting (EEA) [6] and energy accounting [7]. Unfortunately, except for the LCA method, very few examples of application of the other methods have been published, due to the relatively recent introduction of most of them. Considering the feasibility and efficiency of these methods in China, LCA is applied in this study because it is standardized and popular in the industrial circles.

The purpose of this study is to analyze the energy efficiency of the conversion from cassava to automotive power: first, to evaluate the energy ratio of KFE, which is defined as energy required to grow and convert cassava into ethanol divided by energy value present in the ethanol fuel. If the ratio is less than 1, the product is acceptable as a fuel, and the smaller the ratio is, the better; second, to assess the energy consumption of a vehicle fueled by E10 (a blend of 10% ethanol and 90% gasoline by volume) from cassava and compare it with that fueled by gasoline. Though few energy studies of ethanol from cassava have been published, there are some recent applications of quality of LCA of corn, wheat and sugar beet worth referring to, such as studies of Morris and Ahmed [8], Shapouri Hosein et al. [9] von Blottnitz and Curran [10]. Some key issues of energy assessment can be concluded from the review of these studies. The first issue is related to the time-space window of interest. With respect to growing the feedstock, differences among these studies are related to various assumptions about feedstock yields, fertilizer-manufacturing efficiency, fertilizer application rates. Yields have been increasing over time, while fertilizer-manufacturing efficiency has been increasing. The efficiency of farm production and ethanol conversion technology is progressing. Fertilizer application rates, which vary with locations, can also make a difference in energy estimates. Assumptions about ethanol conversion facilities differ among studies because of the different data collection periods. The second issue is the quantification of energy credits of co-products. Which co-products are included in the energy assessment and how their energy credits are calculated have a major influence on total energy estimates. In 2003, the authors visited some pilot plants of KFE and cassava-planting villages in Guangxi, China to collect current data to build the life cycle model of E10 from cassava and to do the energetically relevant inventory analysis. Then, energy index functions were formulated to quantify the energy efficiency of KFE and the E10-fueled vehicle. With respect to the calculation of co-products' energy credits, the authors have used three different methods. These methods are discussed in more detail in later sections. To this end, total energy coefficiency (*TECff*), NEVs of KFE as well as *TECff* of vehicles fueled by the E10 from cassava should be determined. To deal with the variations and uncertainty in data adopted by the LCA model in this paper, the Monte Carlo method is introduced to develop the statistical dispersion of calculated outputs of the assessing indications.

2. Goal and boundary definition

For the purpose of the "from cradle to grave" process of KFE and its E10 as gasoline substitute, this study examines a vehicle fueled by E10 as its subject, and accordingly defined the boundary of the study as shown in Fig. 1, which is composed of a "fuel cycle" and a "vehicle cycle".

The "fuel cycle" consists of a "cassava-planting" unit, a "KFE production" unit, an "E10 blending and distribution" unit, and an "E10-burning" unit. The "vehicle cycle" consists of a "vehicle manufacture" unit, a "vehicle use" unit, and a "vehicle disposal" unit. This study focuses its attention on automobiles. Therefore, a "vehicle" within the framework of this study refers to an "automobile".

2.1. General descriptions of " the fuel cycle"

Cassava are planted using 7–30 cm portions of mature stem as propagules. No irrigation is needed for the Guangxi cassava planting, while fertilizing and weeding are necessary to achieve high yield. All the fertilizers and herbicides are assumed to be domestically produced. Agricultural machineries such as tractors are diesel fueled. Fresh cassavas are usually processed into dry chips (moisture content: 13%, starch content: 75%) and then packed for sale. This study takes account of the basic energy inputs of cassava planting including fertilizer, herbicides, and farm machinery work.

It is assumed that the ethanol plant buys cassava dry chips from local cassava cultivators. The KFE production process is similar to that of edible ethanol, differing primarily in the addition of dehydration facilities usually adopted by industrial-grade ethanol production [11,12].

It is known that ethanol can be generated from a number of feedstocks, which are usually categorised into starch, molasses and cellulose-based feedstocks. Cassava is in the starch-containing feedstock category. The technology to convert starch-containing feedstock to ethanol is based on the hydrolysis of starch and fermentation of sugar. In more general terms, the process is as follows: the mixture of pretreated cassava dry chips, water and special amylase is kept under certain temperature conditions and is liquidized and subsequently saccharificated so that starch contained in the feedstock will be converted into monomeric sugars suitable for fermentation. After fermentation, low-concentration ethanol passes on to distillation where it is concentrated to 95.6% w/w ethanol. Molecular sieves follow to recover

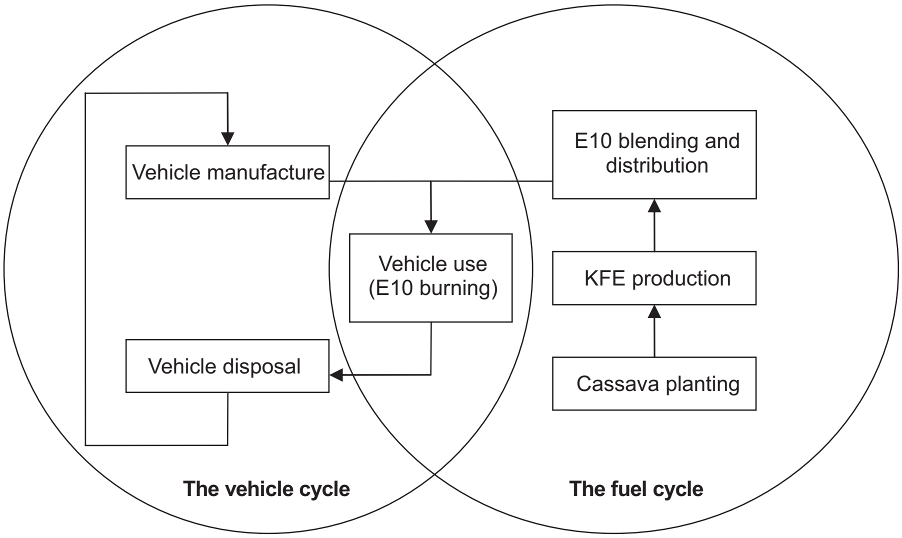


Fig. 1. Life cycle boundary of KFE and an E10-fueled vehicle.

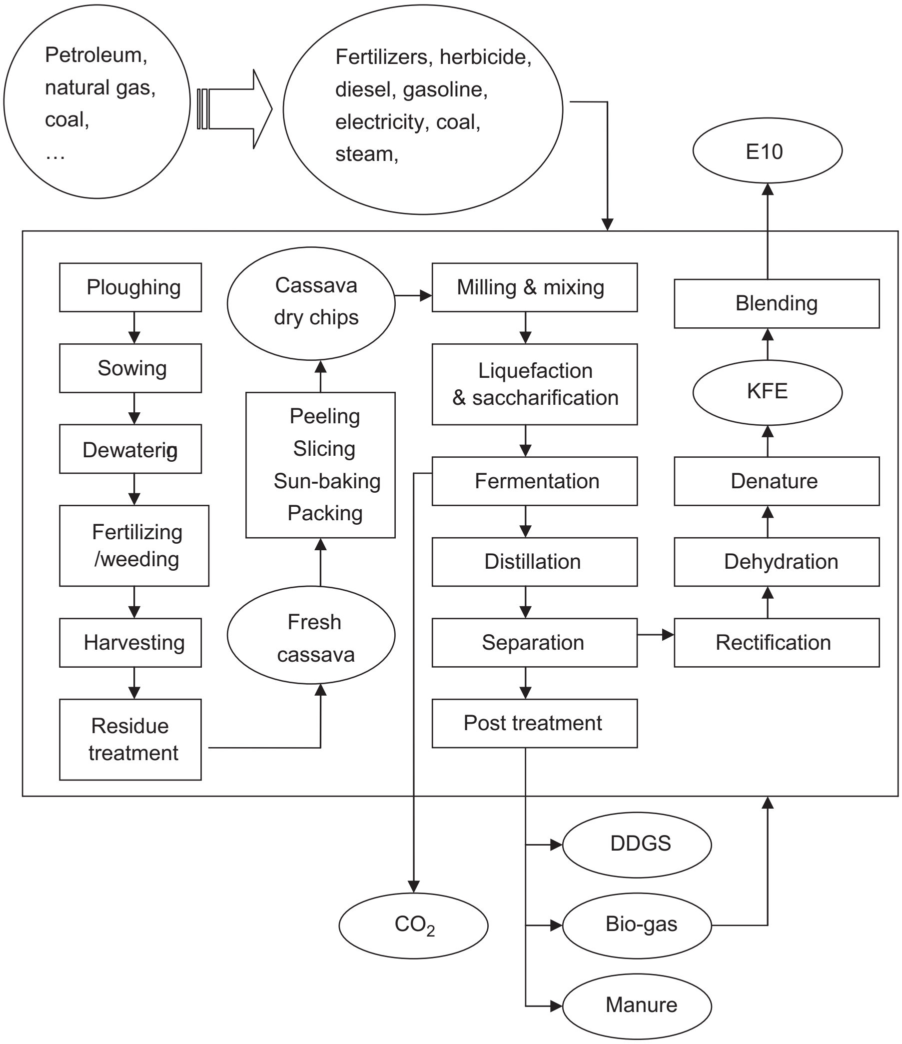


Fig. 2. The fuel cycle.

99.5% w/w ethanol suitable for blending with gasoline. Finally, the fuel ethanol is denatured by small volume of gasoline. Thus KFE is produced (Figs. 2–7).

The co-products of KFE production include CO_2, dried distillers' grains with solubles (DDGS, a kind of dried animal food), and biogas. The co-products might also involve manure. All the biogas is collected for cogeneration that produces steam and electricity for in-plant use simultaneously. If the cogeneration electricity exceeds in-plant use, it may be supplied to the grid.

The denatured KFE is blended with 90% gasoline by volume to make an E10 fuel that can combust in an internal combustion engine without changing its structure. Considering the high cost of ethanol's transportation and storage, the supply range of E10 is assumed to be Guangxi and its neighbor provinces in south China (Table 1).

2.2. *General descriptions of "the vehicle cycle"*

Fuel feed rate of an E10-fueled vehicle is 8 l/100 km

Life distance is 200,000 km.

According to tests by China Automobile Technology Research Center in February 2001, it was difficult to distinguish performances of E10 and 90# gasoline in experiment. One point of view of this paper is that the energy consumption of E10 vehicle manufacturing, maintenance and vehicle disposal is almost the same as that of gasoline vehicles, so we focus on the energy consumption due to fuel use of an E10 vehicle to see if there is any advantage of E10 over gasoline in energy conservation. The energy consumption of an E10 vehicle is considered to involve energy consumptions of "cassava planting", "KFE production", "E10 blending and distribution", and "vehicle use (E10 burning)".

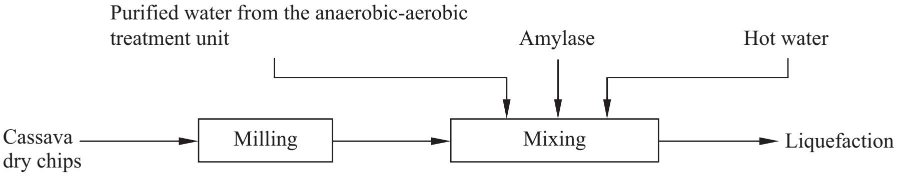


Fig. 3. Flowchart of pretreatment of cassava chips.

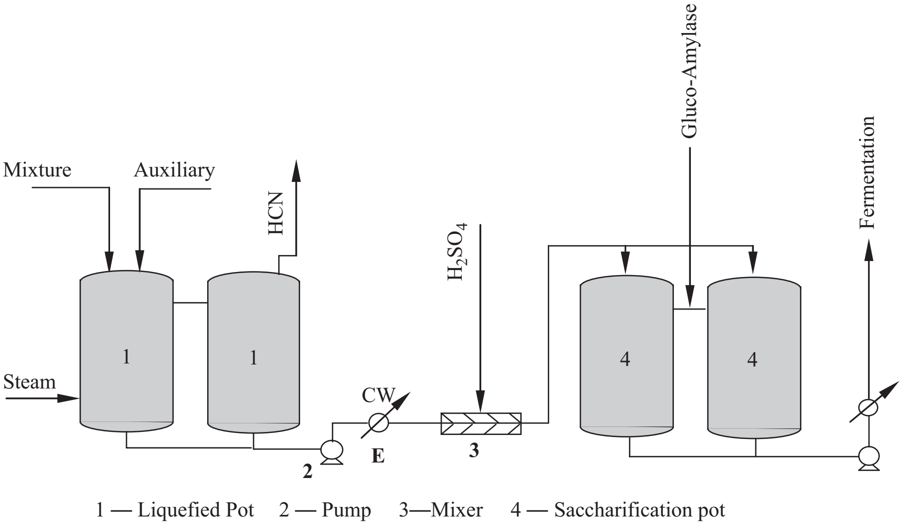


Fig. 4. Flowchart of liquefaction and saccharification.

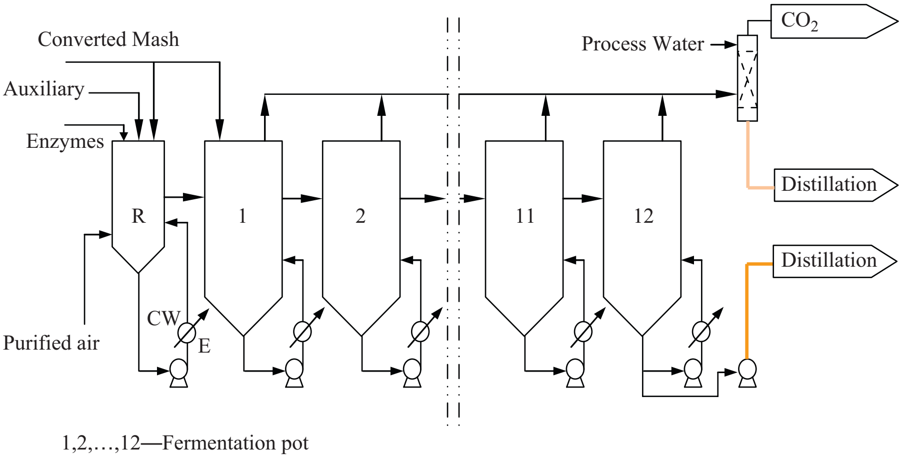
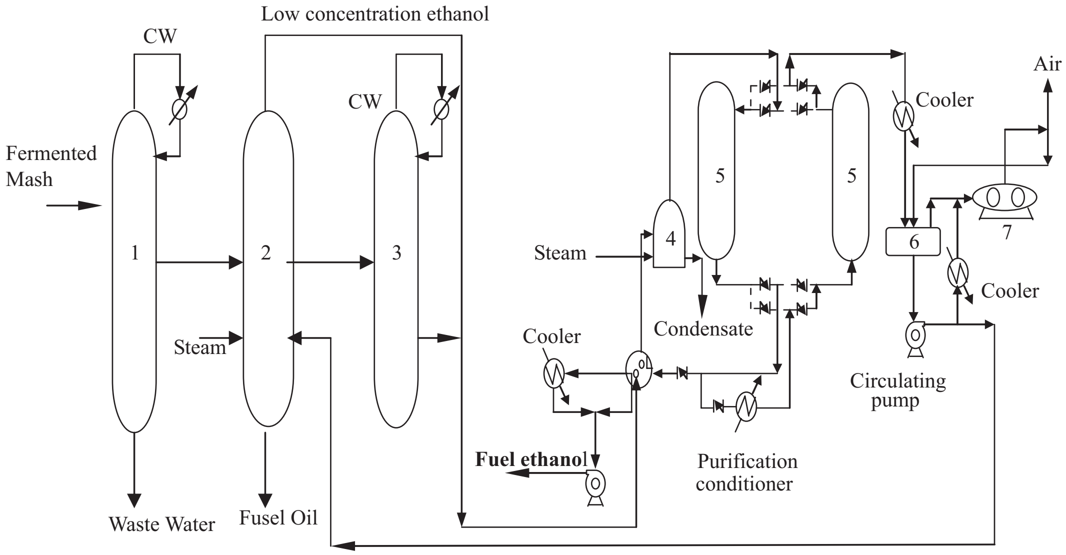


Fig. 5. Flowchart of fermentation.



1—Coarse fractionating tower, 2—Fine fractionating tower, 3—Methanol column,
4—Evaporator, 5—Molecular sieves, 6—Circulation groove, 7—Vacuum pump

Fig. 6. Flowchart of distillation.

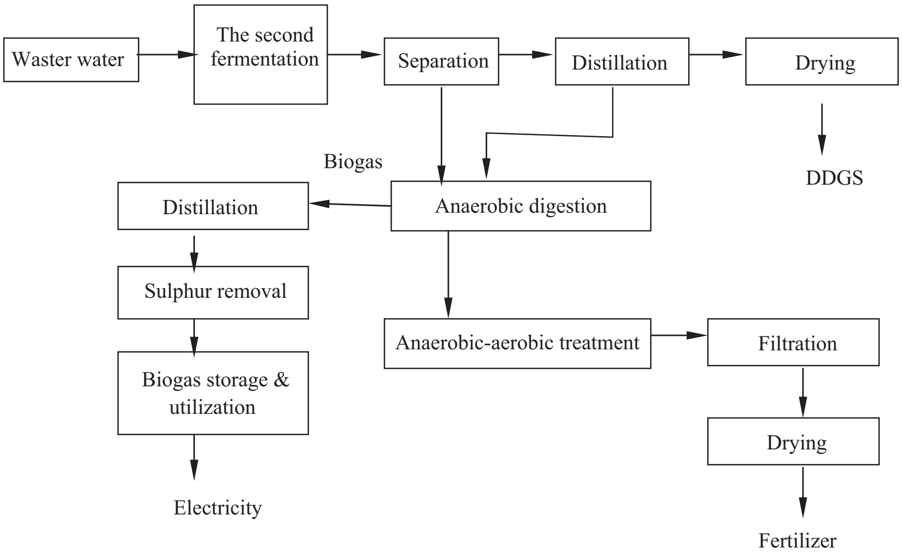


Fig. 7. Flowchart of post-treatment.

Table 1
Primary parameters of the “fuel cycle”

Feedstock	Cassava[a]
Feedstock conversion rate (ton of fuel ethanol:ton of feedstock)[b]	1:2.6
Location	Guangxi, Southwest China
KFE plant type	Stand alone
Annual ethanol (95.6%) production (ton/yr)	100,000
Annual fuel ethanol (99.5%) production (ton/yr)	95,360
On-stream days/yr	330
Reference time horizon	2003

[a] Water contents 13% w/w.
[b] Data resource: Guangxi Tianchang Investment Co. Ltd.

3. Energy index function

Generally speaking, energetically relevant materials can be categorized into energy feedstock, denoted as *EF*, and process fuel, denoted as *PF*. The former referring to the raw material inputs to generate a certain type of energy or manufacture certain products. While the latter refers to the additional resources, especially energy resources, needed to process the energy feedstock. For example, during the ethanol conversion unit, the coal to produce steam and electric power to run machines are regarded as a process fuel, while the biomass to produce ethanol is regarded as an energy feedstock. One point of view of this paper is that the solar energy involved in any activity unit is excluded from our calculation because of difficulties in its quantification. Besides, solar energy is regarded as a free resource. In fact, any energy gained in the production of ethanol is a result of the stored solar energy in the biomass feedstock. Without the solar energy introduced into the cassava fuel ethanol system, the NEV must be negative for energy depletion. Another point of view of this study is that only primary energy inputs are included in the evaluation. Secondary inputs, such as energy required to build ethanol facilities and produce transportation equipments are extremely difficult to quantify. For example, collecting data on the energy embodied in an ethanol plant would require a tremendous amount of data on a wide range of building materials. It would be necessary to allocate this energy among all the products manufactured in the plant over its lifetime. After going through all this trouble, the final result would have very few impacts on the energy efficiency of KFE.

The *TECff* of certain activity unit *i* is defined as

$$TECff_i = \frac{\sum_j [PF_{ij} \times Cff_j] + \sum_k [EF_{ik} \times Cff'_k]}{\sum_l EO_{il}} \tag{1}$$

where PF_{ij} is defined as the consumption of *j*th process fuel in the *i*th lifecycle activity unit with an energy coefficient Cff_j, EF_{ik} is the consumption of *k*th energy feedstock in the activity unit with an energy coefficient Cff'_k, and EO_{il} is the energy present in the *l*th products of the *i*th activity unit. A model of the greenhouse gases, regulated emissions and energy use in transportation (GREET) [10] provides the energy coefficients to convert certain energy inputs, such as diesel fuel and gasoline into primary energy in MJ.

According to the law of conservation of energy, the energy conservation formula is

$$\begin{aligned} \textit{Total energy input} &= \textit{Solar energy} \\ &\quad + (\textit{Energy from process fuels} \\ &\quad + \textit{Energy from energy feedstocks}) \\ &= \textit{Energy loss} + \textit{Energy in products} \\ &= \textit{Total energy output} \end{aligned} \tag{2}$$

Then,

$$\begin{aligned} TECff &= \frac{\textit{Energy from process fuels} + \textit{Energy from energy feedstocks}}{\textit{Energy in products}} \\ &= \frac{\textit{Energy loss} + \textit{Energy in products} - \textit{Solar energy}}{\textit{Energy in products}} \\ &= 1 + \frac{\textit{Energy loss} - \textit{Solar energy}}{\textit{Energy in Products}} \end{aligned} \tag{3}$$

If the solar energy directly or indirectly absorbed cannot make up for the energy loss, *TECff* is lager than one. That implies the NEV is negative. If *TECff* is less than one, then NEV is positive, and thus, provides no benefit in gasoline extension.

4. New approaches to energy assessment

Evaluation of the energy efficiency of KFE as well as that of a vehicle fueled by E10 from cassava will depend on the inventory information needed to map the energy flows into and out of system of interest.

Uncertainties of inventory data mainly arise from errors in measurement or transcription of data and applications of data measured at particular locations and time scales to characterize the state of the system at different scales represented by the evaluation models, i.e. necessary use of inconsistent or heterogeneous data sets due to time, space or financial limitations [13]. In this study, the authors have encountered the problems concerning the dispersion of data relevant to agricultural activities. According to local Agriculture Department, most of the cassava cultivation in Guangxi is undertaken by individual cultivators in widely dispersed areas. Therefore, the authors have visited different cassava-planting villages to characterize the pattern of cassava planting in this region. Due to the differences in soil condition and planting techniques, there is dispersion of

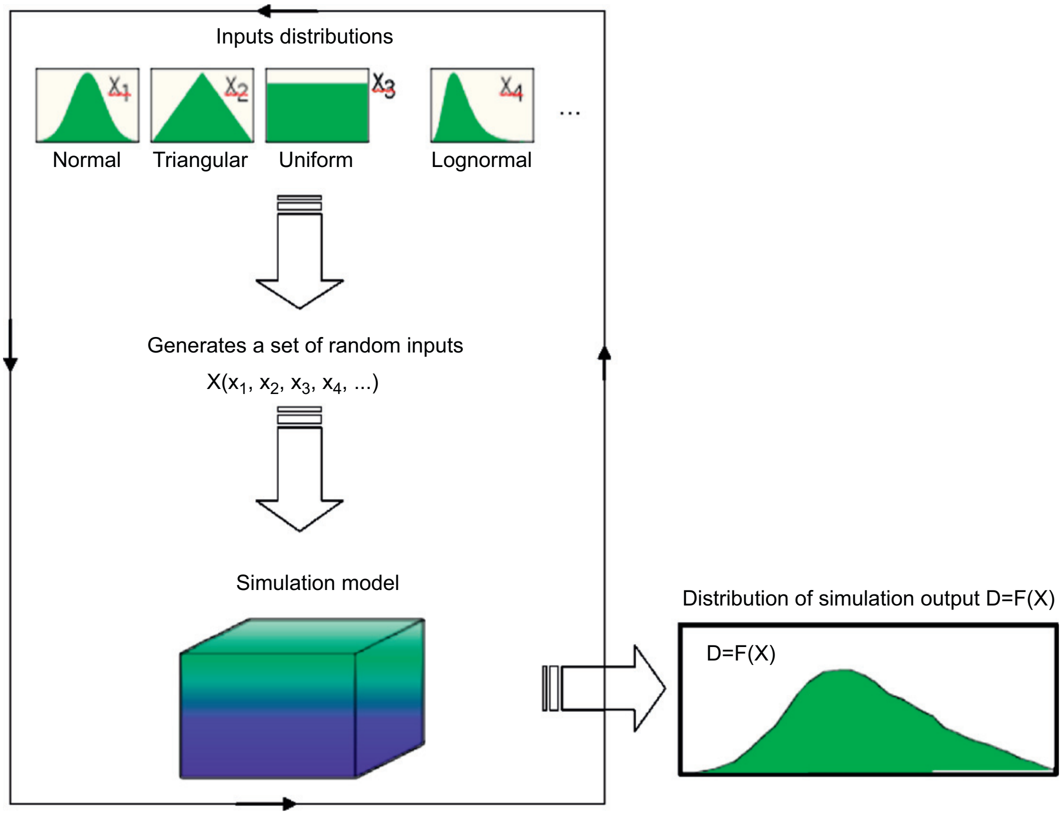


Fig. 8. Principles of Monte Carlo simulation.

the data regarding the amounts of chemicals used and the working time of farm machinery. Further, because of the scattered distribution of cassava fields in Guangxi and lack of communication between cultivators and the KFE industry, it is difficult to specify the precise origin or the range of origin of cassava dry chips received by the ethanol plant. Due to logistics factors, data dispersion occurs in energy evaluation of transportation of cassava chips. Similarly, the discrete distribution of gas stations refueling E10 results in variations in data regarding the delivery of KFE from the ethanol plant to gas stations, and consequently in energy calculation outputs of KFE transportation (Fig. 8).

To deal with the uncertain parameters and input and output variables of the evaluation model, the Monte Carlo method is applied due to its wide application and the easy development of statistical dispersion of calculated quantities. The Monte Carlo method is based on the assumption that all the uncertain model parameters and input and output variables are random variables and the probability distributions of these variables are known.

Table 2
Energy-related inventory information

Cassava planting

Planting size (mu; 1 mu = 1/15 ha)	300,000

Farming machine use

Planting stages	Options	Shares (%)	Tractor's power (kw)	Machine's working efficiency (mu/h)
Ploughing	Machine	60	14.1	Triangular(13,16,23)[a]
	Manual	40		
Sowing	Machine	40	14.1	Triangular (40,45,53)
	Manual	60		
Dewatering	Manual	100		
Fertilizing	Manual	100		
Weeding	Manual	100		
Harvesting	Machine	40	14.1	Triangular (4,7,9)
	Manual	60		
Residue treatment	Manual	100		

Chemical use

Planting stages	Chemicals	Amount (kg/mu): 1 mu = 1/15 ha
Fertilizing	N-fertilizer, urea	Triangular (9.5,12.5,14.5)
	P-fertilizer, P_2O_5	Triangular (26.4,30,33.4)
	K-fertilizer,K_2O	Triangular (13.9,15,16.1)
	Multi-fertilizer1	Triangular (36,40,44)
	Multi-fertilizer1	3000
Weeding	Metolachlor	Triangular (1.5,2,2.5)
Insecticiding	Insecticide	0

Transportation

Options	Capacity (kg)	Distance (km)
Lorry	60,000	200
Dump truck	12,000	Triangular (30,50,80)

KFE production and E10 blending
Cassava-to-ethanol conversion

Main energy inputs	Amount
Cassava chips	2.6 ton/ton of ethanol
Steam generated by burning coal	38.88 ton/ton of ethanol
Steam generated by burning biogas	6.76 ton/ton of ethanol
Coal	0.72 ton/ton of ethanol
Grid electricity	2.28 kWh ton/ton of ethanol

Co-products	Amount
Bio-gas	237.6 m^3/ton of ethanol
CO_2	0.8 ton/ton of ethanol
DDGS	0.06 ton/ton of ethanol
Manure	0.29 ton/ton of ethanol

E10 blending

Main energy inputs	Amount
KFE	89% v/v
Gasoline	11% v/v
Grid electricity	0.7 kwh/1000 L of E10

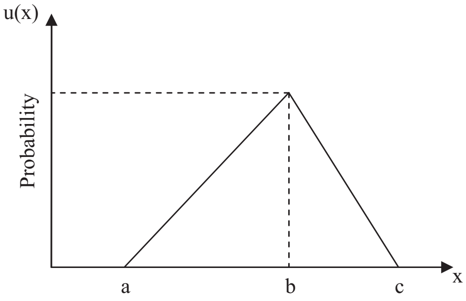
Transportation

Options	Capacity (kg)	Distance (km)
Lorry tank	–	350
Truck tank	8000	Triangle (80,100,120)

Table 2 (*continued*)

Transportation Options	Capacity (kg)		Distance (km)
E10-fueled vehicle operation			
Life cycle distance		200,000 km	
Fuel feed rate of E10		8 L/100 km	

[a] Triangular (a,b,c):



$$u(x) = \begin{cases} 0(x \leqslant a, x \geqslant c) \\ \dfrac{2(x-a)}{(b-a)(c-a)}(a < x < b) \\ \dfrac{2(c-x)}{(c-b)(c-b)}(b \leqslant x < c) \end{cases} \tag{4}$$

$$P\{a \leqslant x \leqslant c\} = \begin{cases} \frac{1}{2}(x-a)u(x)(a \leqslant x < b) \\ 1 - \frac{1}{2}(b-x)u(x)(b \leqslant x < c) \end{cases} \tag{5}$$

Values of the uncertain model variables are generated using their respective probability distributions and then are used to perform model simulations and produce desired predictions. This process is repeated many times to provide enough information to construct a probability distribution of the model output [14].

5. Simulation-based life cycle energy consumption

Microsoft Excel was adopted to do the energetically relevant life cycle inventory. As discussed in Section 4, the simulation model of energy consumption assumes that uncertain input parameters are treated as random variables. With this point in mind, the current version of the model is based on a relevant probability distribution that represents a reasonable operating definition of the uncertain parameters. The current simulation model describes the uncertain parameters by a triangular distribution. Rather than inputting a single value (representing a point estimate or a constant) of an uncertain parameter, the authors suggest a range of values which are more conform to reality. The current model used the triangular distribution, as it represents a reasonable distribution to represent input values and is easy to construct and draw values from. There are other candidate distributions that could be applied, but the authors prefer a triangular distribution because complicated assumptions of the probability distributions provide little help in improving the simulation accuracy (Tables 2 and 3).

This study referred to the GREET transportation fuel-cycle model (developed by Argonne National Laboratory for the US Department of Energy) for the energy conversion coefficient, which are not available in China. Considering the gap between China and the US in macroscopic social energy efficiency, critics may question the applicability of the GREET model in China. To solve this problem, the authors modified some parameters of the GREET model according to China's statistical yearbook (2004) [15] to get energy coefficients adapted for this study.

Table 3
Energy coefficients

	Cff	Source
Chemicals		
N-fertilizer, urea	59.40 (MJ/kg)	GREET
P-fertilizer, P_2O_5	20.36 (MJ/kg)	GREET
K-fertilizer,K_2O	9.50 (MJ/kg)	GREET
Multi-fertilizer1	2.95 (MJ/kg)	GREET
Metolachlor	37.63 (MJ/kg)	GREET
Farming machines		
Tractor	287.40 (MJ/h)	GREET
Transportation		
Lorry/tank lorry	0.24 (MJ/ton-km)	GREET
Dump truck	1.12 (MJ/ton-km)	GREET
Tank truck	0.67 (MJ/ton-km)	GREET
Other energy feedstocks and process fuels		
Coal	19513.34 (MJ/ton)	GREET
Grid electricity	11.14 (MJ/kWh)	GREET

To compute the indexes of energy efficiency of the KFE and the vehicle fueled by E10 cassava, we first draw values of the uncertain parameters by the Monte Carlo method, and then use them along with other constant parameters to process the energy index functions and record the calculation results of the functions. The above steps are repeated and we calculate the average value of each energy category in the emission results section until there are only marginal changes in the average values. In our case study, the Monte Carlo simulation was carried out using Matlab to draw the variables' values, pooling the calculated outputs and calculating their averages.

6. The results of energy consumption simulation

6.1. Total energy coefficients of cassava-based ethanol

According to the LCA simulation of unit energy consumption of KFE, the energy consumption/ton of KFE is around 20,000 MJ with a standard deviation of about 210 MJ. The slightly dispersed unit energy consumption of KFE indicates that diversity in logistics and agriculture activity has moderate impacts on energy LCA of KFE (Fig. 9).

According to the detailed analysis of the simulation results, that ethanol conversion is the most energy-consuming process and cassava planting ranks the second. It is suggested the ethanol plant replacing coal with electricity from alternative sources such as wind, solar, hydro, etc. or self-produced biogases to generate steam for factory use can efficiently reduce the energy consumption of cassava-to-ethanol conversion.

This paper also suggests some improvements of the used technologies to improve the energy efficiency of the cassava to ethanol conversion. The key technologies of fuel ethanol production are saccharification, distillation and dehydration. Most ethanol plants in China adopt the traditional high temperature (135 °C) high-pressure cooking method for saccharification. However, with the development of enzyme technology, saccharification now can also be achieved at about 85 °C with the help of α-amylase. Currently the major problem with this low-temperature technology is that its saccharification effect is not as stable and good as that of the high temperature high pressure one. However, this problem can be almost solved by the adjustment of process parameters. This low-temperature cooking method, which uses much less coal for producing steam and heat, can help improve the energy efficiency.

The energy efficiency of the distillation process depends much on the control of the process parameters such as the timing of fermented mash entering the fractionating tower, the supply of steam and cooling water, number of the fractionating tower plates, etc. Besides the conventional atmospheric distillation used by the pilot plant, which was the data source for this study, there are other distillation technologies such as differential pressure distillation, heat pump distillation and flash distillation, among which differential pressure distillation is a popular and up-to-date energy-saving process developed by some advanced countries in 1980s, but few Chinese ethanol plants used this technology until 2000. Differential pressure distillation is reported to use 35% less energy than the atmospheric distillation and it is recommended for industrial scale production (over 100,000 ton/yr) of fuel ethanol. Using fewer chemicals but more organic fertilizers is also suggested to save fossil energy resources.

The energy credits of co-products affect the final results of ethanol NEV calculation greatly. Therefore, three methods of allocation have been used to estimate the energy values of co-products and they are the energy-content-based method, the relative market-value-based method, and the replacement-value-based method. The energy content method uses the energy content of co-products to estimate their energy credits. The disadvantage of this method is that the energy contents are usually a measurement of food nutritional value and are not a good proxy for energy in a fuel context. The relative market-value-based method estimates energy credits using the relative market values of ethanol and its co-products. For example, if energy used to produce ethanol is allocated between ethanol and co-products using the relative market-value-based method, about 30% of energy used to produce ethanol should be assigned to the co-products under the circumstance that 10-yr average market values of co-products energy accounts for 1/3 of that of ethanol. The problem with this method is that prices of ethanol and ethanol co-products are determined by a large number of market factors that are unrelated to energy content. The replacement-value-based method is based on the assumption that energy credits are equal to the energy value of a substitute product which the ethanol co-product can replace. For example, in the case of corn gluten meal and corn gluten feed, which are co-products of CFE, soybean meal can be used as a substitute, and soybean oil can replace corn oil. This method has the advantage that the co-product value is measured by energy units unlike the other methods that use calories, or economic value to represent energy value. Also, since energy replacement values result in fewer energy credits than the other methods, it can be considered a conservative estimate [9].

Detailed information of NEV of cassava-based ethanol is given in Table 4.

6.2. Energy efficiency of vehicle fueled by cassava-based E10

Table 5 shows the values of fossil energy, respectively needed by vehicles fueled by cassava-based E10 and gasoline to run 100 kM. Though the heat output of ethanol accounts for only 66% of that of gasoline (calculation result based on a low heat output of ethanol), the actual consumption in quantity of E10 per 100 kM is only 1–3% more than that of gasoline because of the

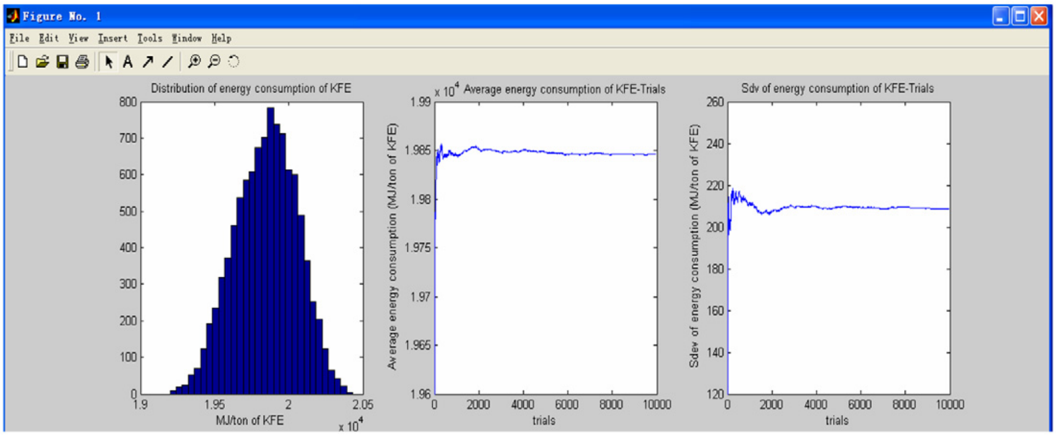


Fig. 9. Energy consumption of cassava-based ethanol (MJ/ton)—without energy allocation of co-products.

Table 4
The NEVs and lifecycle *TECff* s of cassava-based ethanol

	Energy content based	Market value based	Replacement value based	Average
Energy credits of co-products (MJ/ton of ethanol)	502	3385	1201	
Total energy output (MJ/ton of ethanol)	27265	30148	27964	
NEV (MJ/ton of ethanol)	7419	10302	8117	8613
Life cycle *TECff* (MJ/MJ)	0.73	0.66	0.71	0.70

Table 5
Energy consumption of an E10 vehicle for 100 kM

	Energy consumption/100 kM			
	Lower value	Average	Higher value	Source
Gasoline-fueled vehicle (MJ/100 kM)	–	311.35	–	GREET
E10-fueled vehicle (MJ/100 kM)	299.76	299.95	300.11	
E10/gasoline (%)	96.28	96.34	96.39	

combustion-supporting effects of ethanol. Simulation results based on 3% more consumption of E10 indicate a 3.66% average energy saving by running cassava-based E10 vehicles for 100 kM, compared with energy needed to run gasoline-fueled ones for 100 kM.

7. Conclusion

In this paper, an energy assessment of the cassava-based fuel ethanol (KFE) product from Guangxi Province is performed. Viabilities of the KFE product-E10 is analyzed based on the results of simulation-based life cycle energy assessment with Monte Carlo method in terms of total energy coefficient (*TECff*), net energy values (NEV) as well as energy consumption of vehicles fueled by the cassava-based E10. Simulation results show that the cassava-based ethanol has positive NEVs, and its average lifecycle *TECff* is 0.6986 MJ/MJ. It is also noticed that we may achieve an average 3.66% energy saving by running E10 vehicles compared with running gasoline ones. Therefore the cassava-based E10 projects are acceptable from the standpoint of energy conservation. To further promote NEVs, we proposed substitution of coal with electricity or biogases to generate steam needed for producing ethanol as well as reduction in use of fertilizers for feedstock planting in this paper.

To ensure the feasibility of the biomass-based fuel ethanol (BFE) industry in China, it is also necessary to do life cycle assessment (LCA) work of BFE products in the aspects of environmental emissions and economic and risks.

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