



Life cycle assessment of optimized cassava ethanol production process based on operating data from Guangxi factory in China

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Received: 26 April 2022 / Revised: 2 October 2022 / Accepted: 15 October 2022
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Abstract

In cassava ethanol studies, few studies have combined production data from plants with simulation models, and further investigated the environmental emissions caused by different production processes. In this paper, based on the survey data of cassava ethanol plants in Guangxi, we established an ethanol production process model and conducted a life cycle assessment of the raw meal fermentation (RMF) process and traditional clinker fermentation (CF) process. The impact of fermentation broth alcohol concentration on the environmental emissions of the whole process was also investigated based on the conventional CF process. The results showed that the RMF production process had more advantages than the CF production process in terms of energy savings, with 633 MJ per ton of ethanol and 37.39 kg eq/t ethanol of CO₂ reduction. Increasing the alcohol concentration of the fermentation broth facilitated the removal of environmental emissions from the process. All cassava ethanol production models exhibited net energy ratios of no less than 2.74. Of these, the RMF 15% showed the most competitive net energy ratio of 2.97, the highest renewability of 4.52, and the lowest environmental emissions. A detailed analysis of the environmental impacts by the ethanol production phase showed that the distillation section was the critical point for energy saving and emission reduction. Sensitivity analysis showed that fertilizer and natural gas consumption could not be ignored.

Keywords Cassava · Bioethanol · Process simulation · LCA · Carbon footprint · Sensitivity analysis

Abbreviations

LCA	Life cycle assessment
RMF	Raw meal fermentation
CF	Clinker fermentation
CCS	Carbon dioxide capture and storage
GWP	Global warming potential
AP	Acidification potential
EP	Eutrophication potential
ODP	Ozone layer depletion potential
POCP	Photochemical ozone generation potential

HTP	Human toxicity potential
Ne	Alcohol volume of fermentation broth
E_{in}	Total net input energy
E_{inf}	Total non-renewable energy input
E_{out}	Total net output energy
NEV	Net energy value
NER	Net energy ratio
NRnEV	Net renewable energy value

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1 Introduction

In recent years, with the rapid development of the economy, sustainability of energy consumption, environmental protection, and agricultural promotion has become increasingly prominent. Using biomass fuels to replace petroleum-based fuels has been regarded as an essential strategy to reduce environmental pollution and save fossil resources. As a popular fuel, bioethanol has been widely used in many countries [1–4]. The Chinese government has pledged to reduce carbon emission intensity to 60–65% by 2030 [5, 6]. To this end, the Chinese government has issued a series of policies

among which the use of ethanol-blended gasoline is encouraged. As an excellent raw material for biomass fuel ethanol production, cassava has the following advantages: (1) As a non-edible raw material for bioethanol production, cassava can avoid conflicts between food security and bioethanol production. (2) Cassava is a cheap and easy-to-obtain raw material. (3) The cassava planting cycle is short, and the demand for pesticides, herbicides, and other pesticides during the growth process is minimal [7] [8].

Life cycle assessment has contributed significantly as a broad approach in the assessment of bioethanol. DA I Du [9] attempted to assess the greenhouse gas emissions of E10 fuel using a hybrid life cycle model, which covered bio-ethanol from biofuel ethanol based on corn, wheat, and cassava. The results proved that E10 fuels had an emission reduction effect in terms of carbon monoxide and carbon dioxide compared to conventional gasoline. Ding [10] combined the biogeochemical process model-GEPIC model with LCA to estimate the energy saving and carbon emission reduction potential of cassava-based fuel ethanol in China. The results showed that the net energy surplus of cassava-based fuel ethanol in China was 92,920.58 million MJ, and the carbon emission reduction was 45,938,900 kg C. Wang et al. [11] used a hybrid input–output life-cycle assessment model to estimate the use of water and farmland and CO₂ emissions for first- and second-generation bioethanol production technologies in China. The first-generation technology has higher resource consumption and environmental impacts than the second-generation technology. Parascanu et al. [12] studied the environmental and economic feasibility of bioethanol production from sugarcane molasses and agave juice in Mexico and observed that cultivation and fermentation are the most environmentally harmful stages, respectively. Sandra Belboom's [13] environmental assessment of wheat-based ethanol in Belgium found that Belgian wheat bioethanol is 5% higher than the greenhouse gas reductions mentioned in the European Directive and highlighted the importance of the growing step. A life cycle assessment concerning different raw materials (cassava, sugarcane molasses, rice straw) to produce bio-ethanol indicates that cassava ethanol is more environmentally friendly [14]. Yu, Tao's [15] 3E LCA analysis showed that ethanol gasoline production from cassava is more energy-efficient than from wheat and corn.

As a typical process of converting biomass resources to fuel, the cassava ethanol process aimed mainly to achieve the maximum carbon neutralization as well as industrial profit. However, Ou et al. [16] pointed out through LCA analysis that the energy input of the cassava ethanol production route was higher than that of the traditional gasoline route, even though cassava ethanol can reduce fossil fuel consumption and greenhouse gas emissions. To realize the maximum use of raw material, Lyu et al.

[17] investigated the process in which the entire cassava plant, including cassava straw, was used to produce ethanol. The results showed that the cassava root ethanol process had the lowest energy consumption, but whole plant cassava ethanol showed the lowest environmental emissions. As for the optimization of production technology, there is also a large amount of research. Reducing energy consumption is regarded as an essential way to improve the production process [18]. Meanwhile, the ethanol concentration produced in the fermentation section has a significant impact on the entire ethanol production. Furthermore, Poonsrisawat et al. [19] developed an ethanol production process that uses dry cassava flakes without high-temperature gelatinization and liquefaction steps but adds cell wall-degrading enzyme preparations directly into the fermentation process, which can be used for low-energy cassava ethanol processing. Li [20] proposed energy-saving measures from the aspects of cassava raw materials, enzyme preparations, and technology. Satisfactory energy-saving results can be achieved by breeding energy-oriented cassava varieties, constructing highly alcohol-resistant enzymes with targeted molecular modifications, and adopting advanced energy-saving technologies such as concentrated mash fermentation and flash fermentation. Luo Hu [21] explored the optimization of the cassava raw meal fermentation process and found that the best water-to-feed ratio is 1:2, and the alcohol concentration can reach 15.12%v/v.

However, the production data of the working factory is seldom analyzed and compared with the simulation model in the reported research. As for each process section, it is somehow inaccurate to obtain statistics, which are collected for the economic management of the whole factory. Therefore, based on our onset survey data of an ethanol plant with an annual output of 200,000 tons, a process framework model for cassava ethanol production was established and verified. According to the technical improvements of reported research mentioned above, the different scenario was investigated, including varied fermentation concentration, ferment method, and distillation process. The net energy analysis and environmental impact assessment of scenarios were then compared. The work aimed at providing a more comprehensive understanding of process optimization, as well as the validated version of the evaluation of the cassava ethanol production system.

2 Methodology

Aspen Plus (v8.8) is used for ethanol conversion process simulation, and SimPro (v7.1) is used for LCA. The technical process of this research is divided into four steps.

1. Determine the cassava ethanol production process based on the ethanol plant production data and determine the boundaries of the entire process system.
2. Data is obtained through simulation of the ethanol conversion process, and plant data is used to verify the simulation data.
3. LCA is used for energy analysis and environmental impact assessment of input materials.
4. Analysis of critical factors and sensitivity analysis.

2.1 Goal and scope definition

The goal is to evaluate the environmental impact of different ethanol production processes through the life cycle to find a more energy-saving and environmentally friendly production route. Figure 1 displays the system boundary of ethanol production from the cassava. The functional unit is 1 t (99.7%, 26,840 MJ) of bioethanol [22]. The system includes four sections, namely, cassava planting and harvesting section, transportation section, preparation section, and ethanol conversion section. Biomass ethanol as a downstream application of gasoline is not considered. The data on cassava planting, harvesting, and transportation comes from literature already reported. The material conversion and energy balance of the cassava ethanol conversion process are from

the simulation model, which is constructed according to the actual production process of ethanol production in Guangxi Province of China.

The simulations in this study used the following assumptions and calculations from reported literature:

- (1) Carbon neutral rules apply to this study [23].
- (2) Use Eq. (1) to calculate the amount of biogas produced by anaerobic fermentation [24]:

$$\text{Biogas} = \text{Wastewater volume} \times \text{COD} \times 0.328 \times 0.925 \tag{1}$$

Biogas, m³; wastewater volume, m³; COD, kg/m³. 0.328, biogas production rate; 0.925, COD removal rate [25].

- (3) The production environment is the same in different cases.
- (4) The energy input by labor during the planting process is not included in the boundary of the system [26].

2.1.1 Planting and harvesting

In the process of planting, potash fertilizer, nitrogen fertilizer, phosphate fertilizer, and herbicide are used in the growth process of cassava. These fertilizers, pesticides, and

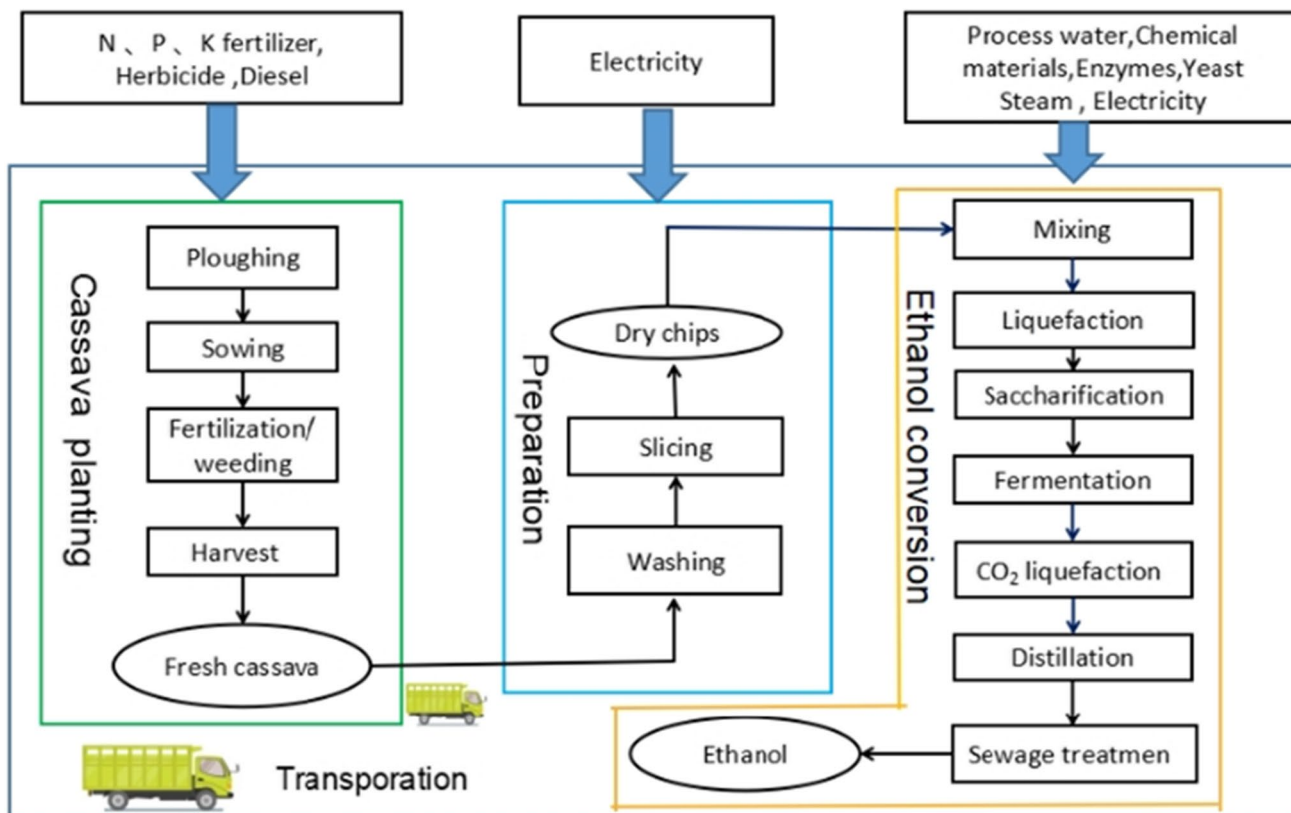


Fig. 1 Life cycle system boundaries for bioethanol

chemicals will produce adverse effects on the environment. The environmental emission factors for fertilizers and herbicides are shown in Table S1. The weight of the cassava plant is 60% of the rhizome and 40% of the straw [27]. According to the proportional allocation method, the resource consumption and emissions of biomass feedstock input pre-processing are allocated to cassava root mass and straw. In the harvesting process, machinery is used to harvest cassava, consuming a certain amount of diesel. Although cassava can convert the CO_2 from the atmosphere into starch through photosynthesis during the growth of cassava, the process of planting and harvesting will produce CO_2 , CH_4 , SO_2 , and other harmful gas emissions. The material inputs for the planting phase of biomass ethanol are presented in Table S2.

2.1.2 Preparation and transportation

After the cassava is harvested, it will be transported to the alcohol factory to be sliced and dried by air into dried cassava chips. The distance from the cassava field to the ethanol plant is 125 km on average. A truck with a load of 16 tons is adopted for transportation. In the transportation process, only single-item transportation is considered, because the truck will be loaded with other items when it returns. Next is the preparation stage. Generally, about 7 t of fresh cassava is sliced and dried into 2.95 t dry slices. This process consumes a total of 13.125 kWh of electricity [7]. Table S3 shows the energy consumed during the preparation section and the transportation process.

2.1.3 Bioethanol conversion

The process flow chart of the ethanol conversion process is displayed in Fig. 2. After being crushed, the dried cassava chips are mixed with water in a particular proportionally, and then enter the liquefaction section. The liquefied mash enters the saccharification section to produce saccharified mash, and the saccharified mash enters the fermentation section to produce alcohol. However, the fermentation section will produce a large amount of CO_2 . In order to reduce the contribution to GWP, the CO_2 will be captured and made into dry ice. The CO_2 obtained through CCS technology is equivalent to net-negative carbon. To save energy, the separation of ethanol from fermentation liquid employs three-stage distillation which operates at different pressure and composes a thermal coupling separation system. Furthermore, the pressure swing adsorption unit is used downstream of the distillation product to achieve a final effect of 99.7% ethanol concentration. The waste mash produced by rectification is used for anaerobic fermentation, during which biogas is produced and used to provide energy to the ethanol conversion system. The wastewater is further treated and recycled as process water and other cooling water.

Electricity comes from the power stations. Steam is provided by the combustion of biogas from anaerobic treatment and natural gas. Table S4 shows the average low heating values of the different energy sources and their utilization efficiency.

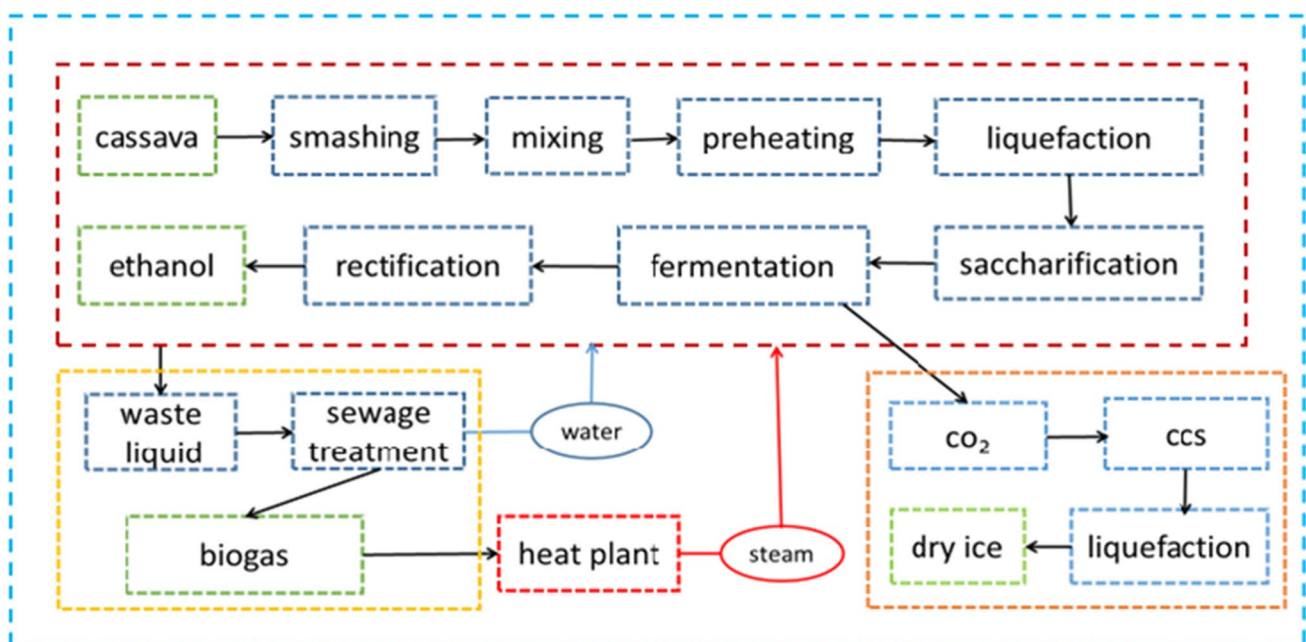


Fig. 2 Ethanol conversion flow chart

2.2 Process simulation of different scenarios

This study establishes a cassava ethanol production system based on ethanol plant production data. It uses net energy analysis to find out the critical points of the most enormous energy consumption in the production process. Based on the above data and materials, the factory production model is established as a basic analysis model. The different process routes of bioethanol are shown in Fig. 3. As a raw material, cassava is first crushed, liquefied, fermented, distilled, and then dehydrated to produce absolute ethanol. In this study, in order to compare the effect of different alcohol concentrations on ethanol production, the alcohol concentrations fermented were 12.5%v/v, 15%v/v, 17.5%v/v, and 20%v/v. And the raw material fermentation process is compared with the traditional clinker fermentation production process. The raw material fermentation process, also known as the one-step fermentation process, does not require steaming and liquefaction, and fermentation is carried out directly, which can save a lot of steam and cooling water.

The bioethanol conversion process is simulated in Aspen Plus V 8.8, and the rectification process uses the RadFrac rectification tower model in the software. The reactions required for saccharification and fermentation are selected in the Stoic reactor model. The reaction process is that after the cassava is crushed, it is liquefied to destroy the cell wall of the starch. Under the action of amylase, hydrolysis produces dextrin. Yeast can carry out homo-ethanol fermentation through the EMP (Embden-Meyerhof-Parnas) pathway; that is, the pyruvate produced by the EMP pathway metabolism is released after decarboxylation. At the same time, acetaldehyde is produced. Acetaldehyde receives H⁺ released during glycolysis and is reduced to ethanol. Simulation adopts NRTL thermodynamic property method. Specific operating conditions and material input are shown in Table S5. The case description is as follows:

Base case The boundaries of the system defined above are considered the basis of all cases. The basic case is established through simulation on the basis of known factory data. The traditional clinker fermentation (CF) production

process is used, and the alcohol concentration of the fermentation broth is 15%v/v. The CF fermentation process means that the raw material needs to be liquefied by high-temperature steaming before fermentation. This is a complete process, including sewage treatment and the recovery of biogas produced to heat the system.

Case a To explore the impact of different alcohol concentrations on the energy consumption of ethanol production and the environment, this case also uses the clinker fermentation production process. However, change the alcohol concentration of the fermentation broth. The alcohol concentration, in this case, is 12.5%v/v.

Case b Using the clinker fermentation process, the alcohol concentration increased by 2.5% compared with the base case to 17.5%v/v. It is to observe the impact of increasing the alcohol concentration on ethanol production and to find the key points for improving the clinker fermentation process.

Case c This case is similar to the basic case, but also uses the clinker fermentation production process. The alcohol concentration of the fermentation broth is 20%v/v, which is increased by 5% since the basic case, and the rest are the same.

Case d Different from the previous cases, this case uses the raw material fermentation production process. In order to explore the impact of different fermentation processes on ethanol production, the alcohol concentration of the fermentation broth, in this case, is 15%v/v.

2.3 Life cycle assessment

In this study, all scenarios use two analysis and comparison methods. One is environmental impact assessment, and the other is net energy analysis. The Council of Mortgage Lenders (CML) 2001 method was applied to evaluate the environmental impacts using the SimaPro (V7.1). The project Ecoinvent was selected as a background data source to maintain consistency. The environmental benefits are evaluated from the

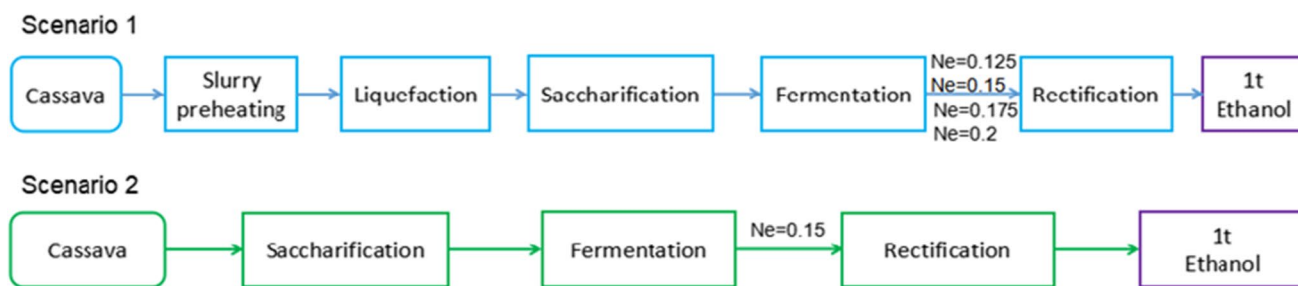


Fig. 3 Different process routes for bioethanol conversion

following aspects: global warming potential (GWP), ozone layer depletion potential (ODP), human toxicity potential (HTP), photochemical ozone generation potential (POCP), acidification potential (AP), eutrophication potential (EP). These are the most widely used categories in bioenergy environmental assessment.

In the net energy analysis, the energy of each substance is expressed according to the energy intensity and the amount of material input. Therefore, the net energy value (NEV), the net energy ratio (NER), the net renewable energy value (NRnEV), and the renewability (Rn) of the entire system are all calculated. The E_{in} was energy input throughout the process, and the E_{out} was the average low calorific value of 1t ethanol.

$$NEV = E_{out} - E_{in} \quad (2)$$

$$NRnEV = E_{out} - E_{inf} \quad (3)$$

$$NER = E_{out}/E_{in} \quad (4)$$

$$Rn = E_{out}/E_{inf} \quad (5)$$

3 Results and discussion

3.1 Model verification

In order to verify the accuracy of the data simulated by the basic model, the factory production data is used to compare with the simulated data to assure the accuracy of the simulated data. Figure 4 shows the agreement between the factory power consumption and the simulation data, which verifies the accuracy of the theoretical model prediction. The simulated value is very close to the data from the factory data. Figure 5 shows the relative error between the simulated value and the factory value. The error is between -6.99% and 11.49% . Especially the error between the simulated data and the average of the 3-year factory data is only 1.53% .

The plant's cassava ethanol production data is obtained from research. The data of this factory in 2012, 2013, and 2014 are divided into four quarters according to the seasons. Figure 4 shows the maximum value of this crushed electric energy consumption is 75.66 kWh , and the minimum value is 55.49 kWh . However, the simulated value is 63.5 kWh , which is within the actual production data range and is very close to the average value of 63.1 . The average power consumption

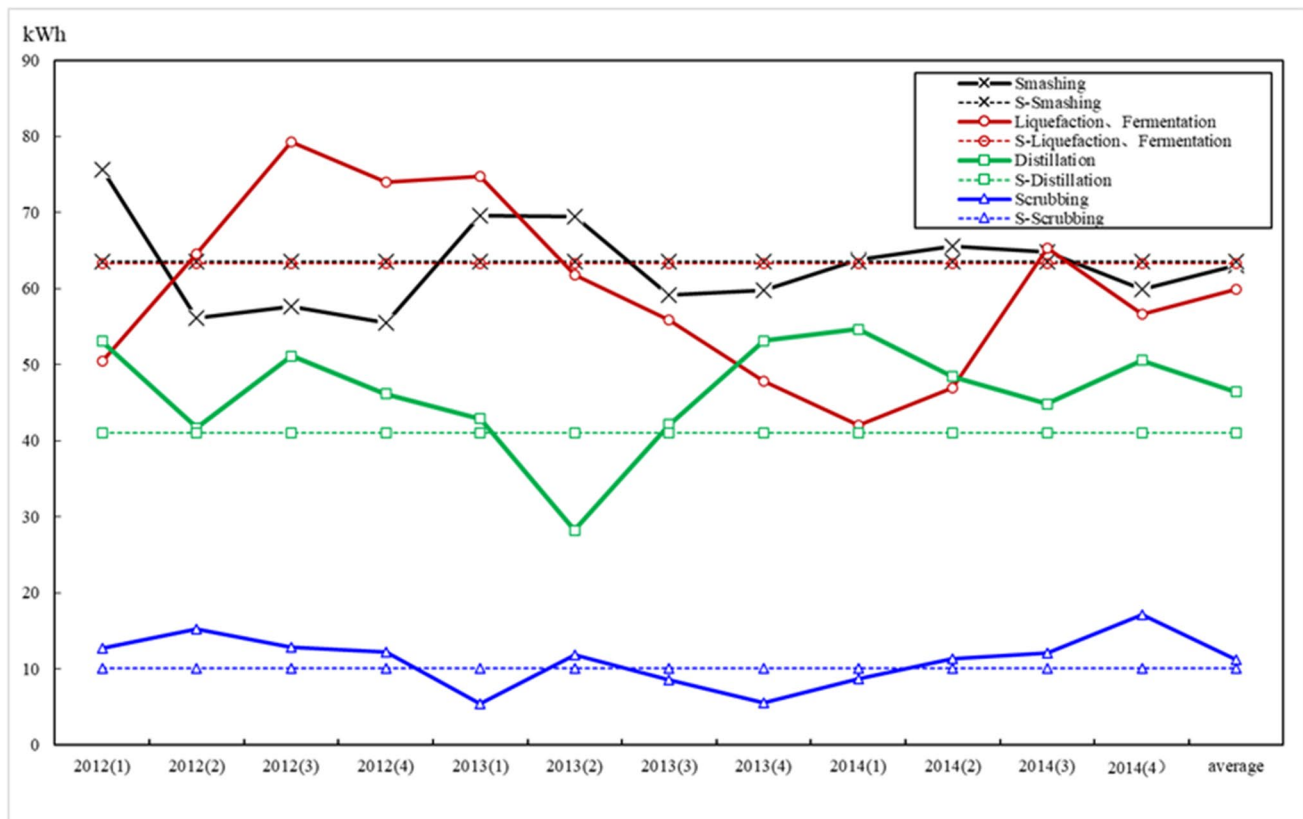
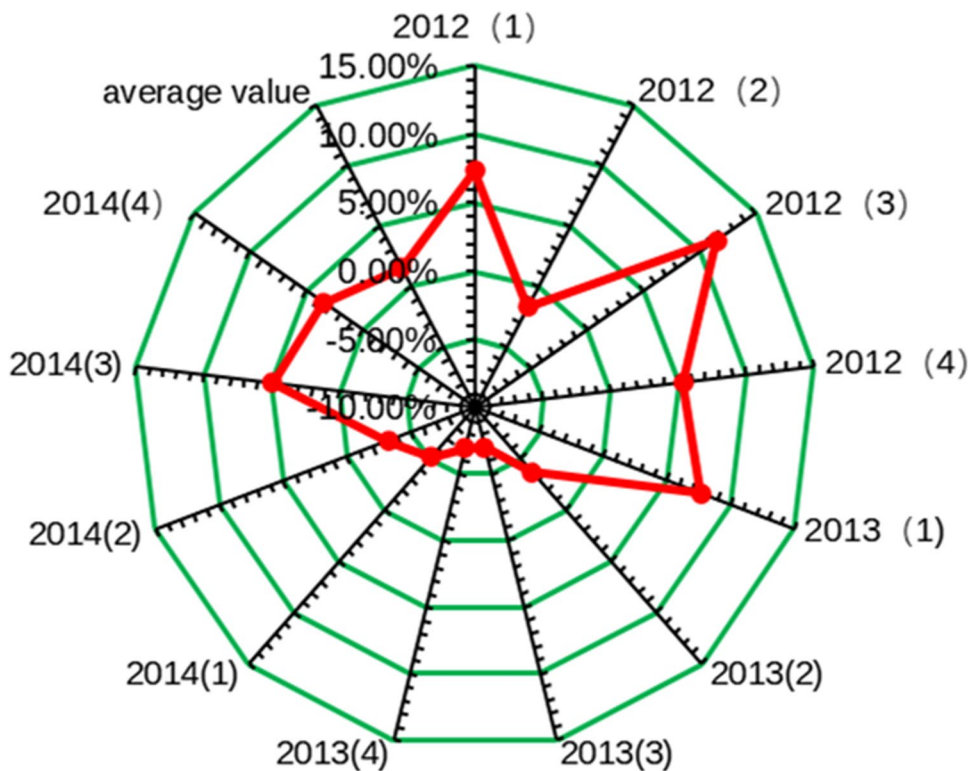


Fig. 4 Factory power consumption and simulated data of each stage

Fig. 5 Relative error between analog value and factory data



for liquefaction and fermentation is 60 kwh, and the simulated value is 63.3 kWh. This value is close to the factory data, which means that the simulated data is very accurate. For the distillation section, the actual electricity consumption value of each quarter of production fluctuates greatly between 28.22 and 54.61. Hence, it is necessary to take the average value. The power consumption of the simulated distillation stage is 41 kWh, which is 5.4 kWh lower than the average value of 46.4 kWh. The average value of the actual production data of this scrubbing section is 11.13 kWh, and the data in this article is 10 kWh. After the data analysis of the above various stages, the simulated data is relatively close to the factory data, and the errors are within a reasonable range. This further shows that the simulated data is highly reliable.

3.2 Process simulation results and energy consumption

The total energy consumption of the ethanol conversion process is shown in Table 1. The total energy consumption required for

each case is different. The detailed material and energy consumption processes of the five cases are shown in Fig. 6.

As shown in Fig. 6a, the 2.95-t dried cassava flakes are crushed by a crusher. This process will cause about 1% of the cassava dust loss, which requires 47 kWh of electricity. Add 4.84 t of water to the cassava flour and mix it evenly to make a slurry. Entering the preheating stage, the temperature rises to 65 °C. This process consumes 1.43 kWh of electricity. The 9.41-t slurry enters the high-temperature spray liquid chemical section. At this stage, 278 kg of steam is needed to bring the temperature to 105 °C. The next stage is saccharification and fermentation. The alcohol concentration of the basic model fermentation broth is 15%. The circulating water is used to cool down and absorbs 379 MJ of heat. The 805-kg CO₂ produced in the fermentation process is captured and sealed into dry ice. This process consumed 104 kWh of electricity. The rectification section adopts three-column rectification, including a crude distillation tower, rectification tower, and recovery tower. Of water-containing ethanol, 8.64 t is rectified and

Table 1 Total energy consumption of ethanol conversion process in different cases

Category	Base case	Case a	Case b	Case c	Case d
Alcohol concentration	15%v/v	12.50%v/v	17.50%v/v	20%v/v	15%v/v
Production process	CF	CF	CF	CF	RMF
Electricity(kwh)	370.38	371.19	367.97	366.64	370.21
Biogas (MJ)	3095.19	3095.19	3095.19	3095.19	3095.19
Natural gas (MJ)	834.99	938.67	774.97	722.50	204.70

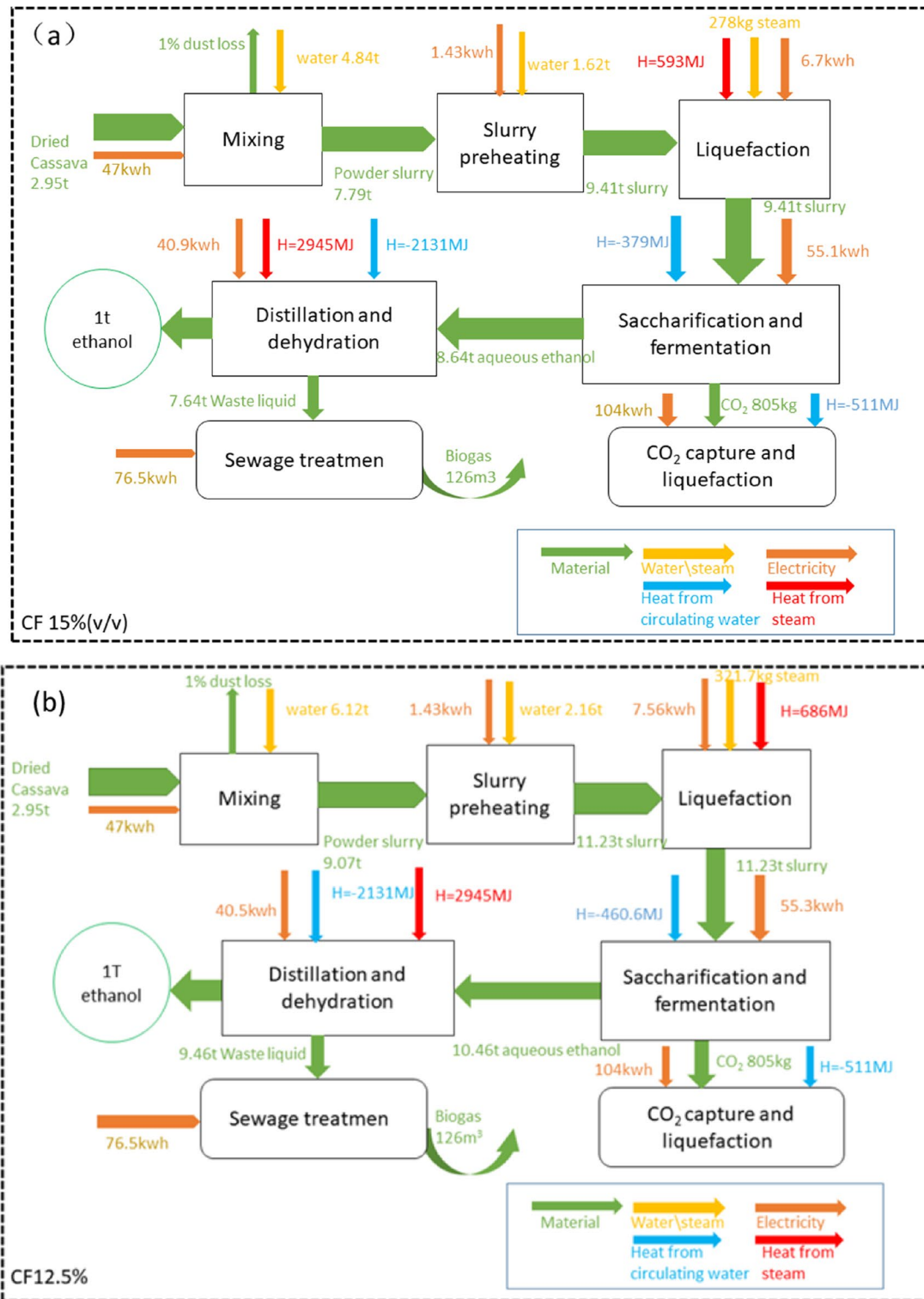


Fig. 6 Different production process materials and energy consumption processes: (a) CF 15%v/v, (b) CF 12.5%v/v, (c) CF 17.5%v/v, (d) CF 20%v/v, and (e) RMF 15%v/v

dehydrated to obtain 1 t of cassava ethanol. This stage consumes a lot of steam and circulating water, and electricity consumption is 40.5 kWh. The waste mash enters the

sewage treatment section. After anaerobic fermentation, 126 m³ of biogas is produced, which consumes 76.5 kWh of electricity.

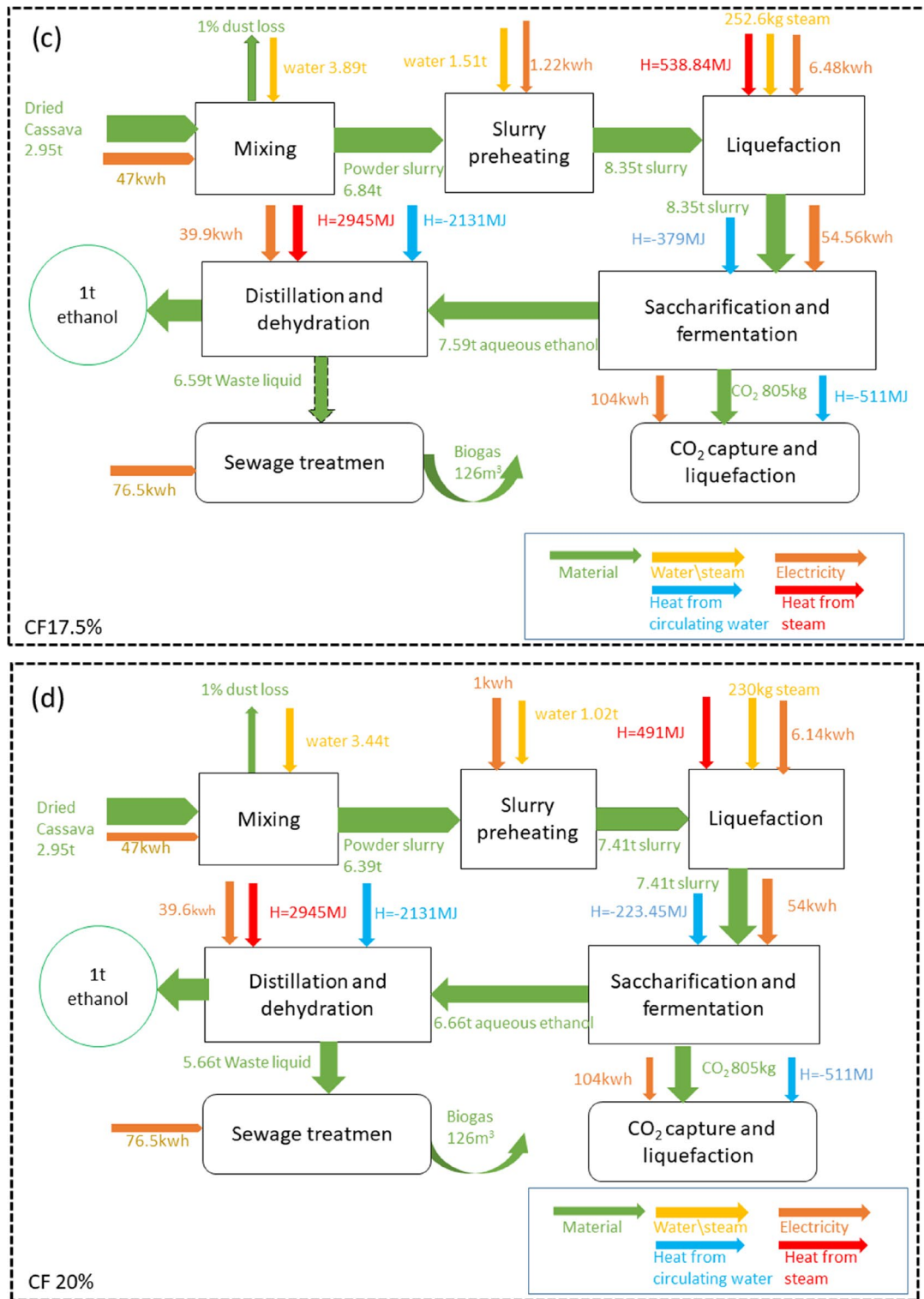


Fig. 6 (continued)

The alcohol concentration of the fermentation broth of case a is 12.5%v/v. As in Fig. 6b, the same 2.95-t cassava chips are crushed and mixed with water to make a slurry. The

slurry is transported to the preheating section by the feed pump, consuming 1.43 kWh of electrical energy. The liquefaction section puts 278 kg of steam equivalent to 593 MJ

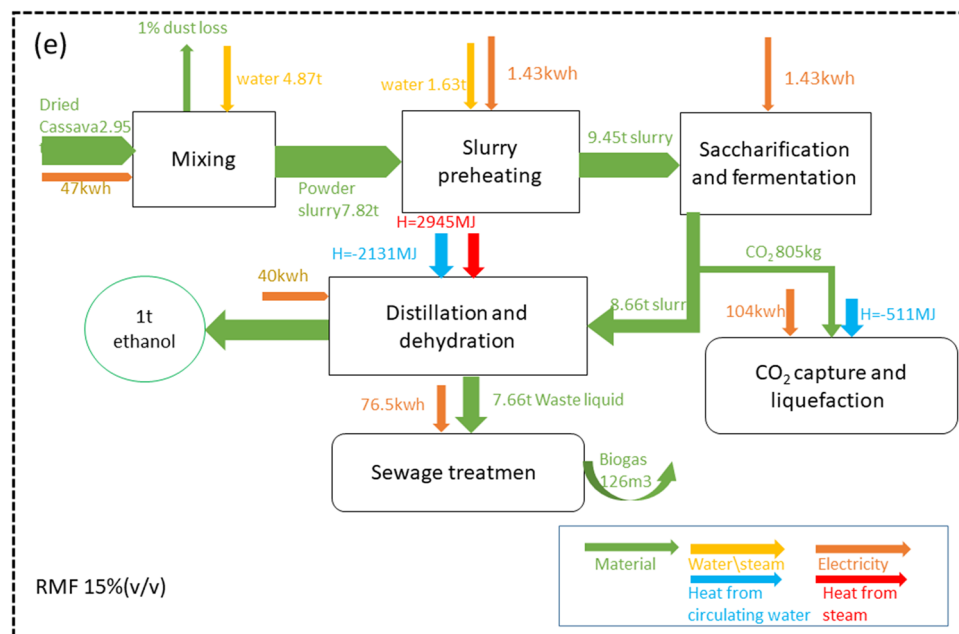


Fig. 6 (continued)

of energy, and the electricity consumption is 6.7 kWh. The saccharification and fermentation sections need circulating water to cool down. The circulating water absorbs 460.6 MJ of energy, and the process power consumption is 55.3 kWh. In case b, the alcohol concentration of the fermentation broth is 17.5%v/v, which is an increase of 2.5% compared to the base model alcohol concentration. As shown in Fig. 6c, the power consumption of the crushing, slurry preheating, liquefaction, saccharification, and fermentation sections is 47 kWh, 1.22 kWh, 6.48 kWh, and 54.56 kWh, respectively. However, heating up during the liquefaction stage consumes 252.6 kg of steam. As shown in Fig. 6d, the alcohol concentration of the fermentation broth is 20%v/v. The power consumption of the slurry preheating, liquefaction, saccharification, and fermentation sections is 1 kWh, 6.14 kWh, and 54 kWh, respectively. The power consumption of these three sections is less than that of case a. Not only the liquefaction section needs steam heating, but also the distillation section. The energy consumption of these two stages was 491 MJ and 2945 MJ respectively.

Case d demonstrated the whole process of cassava raw meal fermentation to produce bioethanol. Different from the clinker fermentation process, the raw meal fermentation goes directly to the saccharification and fermentation sections after crushing and mixing. To compare with the established basic model of clinker fermentation, the alcohol concentration of raw meal fermentation was set to 15%v/v. Other conditions were the same. As shown in Fig. 6e, the crusher uses 47 kWh of electrical energy to crush cassava.

The cassava flour is mixed with water and stirred evenly to make flour slurry directly into the fermentation process. Since yeast is more tolerant to hydrogen ions than bacteria. In this process, inhibitors (H_2SO_4) were added to inhibit the growth of bacteria. The rectification section uses steam to provide 2945 MJ of heat to the system, and then cools by absorbing 2131 MJ of heat through circulating water. Ethanol vapor is obtained from the top of the rectification tower. Gas ethanol passes through molecular sieve pressure swing adsorption, and 1 t (99.7%) of absolute ethanol is obtained. This process requires 76.5 kWh of electrical energy.

3.3 Net energy analysis

Using different processes to produce ethanol has different energy consumption. Table 2 details the full life cycle energy of biomass ethanol produced by different processes. In the production stage, energy consumption is mainly in three aspects: electricity, biogas, and natural gas. To compare the different alcohol concentrations produced by fermentation and the influence of the raw meal fermentation process on alcohol production, the input materials in the planting stage and the transportation stage are the same by default. Table S6 shows the energy consumption data for the production of the input substances.

In the CF, the E_{in} of different cases according to the alcohol concentration from low to high is 9554.90 MJ, 9612.20 MJ, 9680.91 MJ, and 9787.56 MJ, respectively. Obviously, the largest E_{in} is CF 12.5%, and the smallest is

Table 2 Energy analysis of different processes per functional unit

Energy input/output (MJ)	Base case	Case a	Case b	Case c	Case d
Planting stage	3504.26	3504.26	3504.26	3504.26	3504.26
Fertilizers (NPK)	2799.54	2799.54	2799.54	2799.54	2799.54
Herbicide	133.28	133.28	133.28	133.28	133.28
Diesel for soil preparation	571.44	571.44	571.44	571.44	571.44
Transportation stage	714.30	714.30	714.30	714.30	714.30
Transport diesel	714.30	714.30	714.30	714.30	714.30
Preparation stage	19.80	19.80	19.80	19.80	19.80
Slicing power consumption	19.80	19.80	19.80	19.80	19.80
Ethanol conversion stage	5442.55	5549.20	5373.84	5316.54	4812.02
Electricity	1377.61	1380.54	1368.93	1364.16	1377.01
circulating water	3.26	3.29	3.24	3.19	3.62
Steam comes from natural gas	834.99	938.67	774.97	722.50	204.70
Steam comes from biogas	3095.19	3095.19	3095.19	3095.19	3095.19
Chemicals	112.25	112.25	112.25	112.25	112.25
Enzyme/Yeast	19.25	19.25	19.25	19.25	19.25
Bioethanol	26,840.00	26,840.00	26,840.00	26,840.00	26,840.00
E_{in}	9680.91	9787.56	9612.20	9554.90	9050.38
E_{inf}	6543.41	6669.82	6494.52	6437.27	5932.32
E_{out}	26,840.00	26,840.00	26,840.00	26,840.00	26,840.00
NRnEV	20,296.59	20,170.18	20,345.48	20,402.73	20,907.68
NEV	17,159.09	17,052.44	17,227.80	17,285.10	17,789.62
NER	2.77	2.74	2.79	2.81	2.97
Rn	4.10	4.02	4.13	4.17	4.52

CF20%. However, the E_{in} of RMF is 9050.38 MJ, which is 630 MJ less than CF15%. Compared with the system with the smallest E_{in} for CF20%, the total input energy consumption of the RMF15% system is still small. The planting stage accounts for 35.79%, 36.19%, 36.45%, and 36.67% of the CF production process according to the alcohol concentration of the fermentation broth from low to high. The highest proportion in the planting stage is the CF20% system. For RMF15%, the planting stage accounts for 38.71% of E_{in} . It is worth noting that the net energy input in the ethanol conversion stage of these five cases accounted for about 50% of E_{in} . This means that the planting stage and the ethanol conversion stage account for more than 80% of the total energy input. These two stages are crucial stages.

The NEV of the base case is 17,159.09 MJ, and the NEVs of CF12.5%, CF17.5%, and CF20% are 17,052.44 MJ, 17,227.08 MJ, and 17,285.10 MJ, respectively. And the NEV of the RMF system is 17,789.62 MJ. Their corresponding NERs are 2.77, 2.74, 2.79, 2.81, and 2.97. All of which is greater than one, indicating that these ethanol production systems have energy surpluses. Compared with the base case, the NER of CF 12.5% is reduced by 0.03, and the rest of the system is larger than it. The largest NRnEV is that the RMF system is equal to 20,907.68 MJ, the smallest is CF 12.5%, and the difference is 611 MJ. And their NER differs by 0.2. The Rn of all systems is greater than 4, indicating

that these systems have strong renewability. Of course, the most renewable one is still RMF15%.

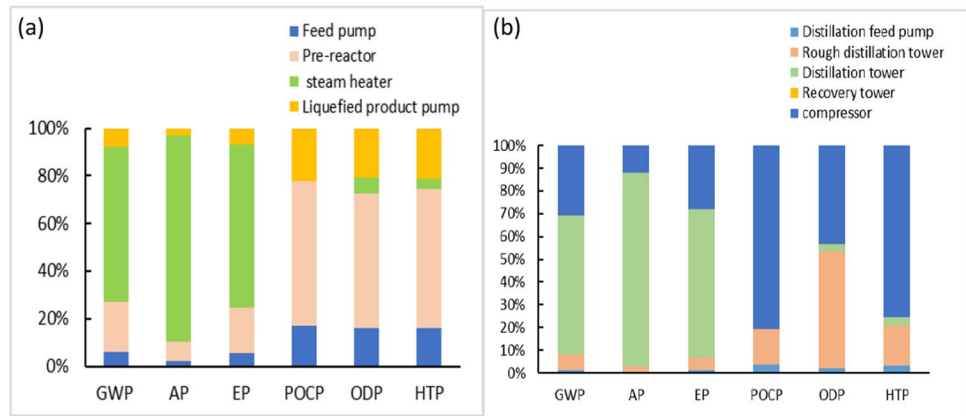
3.4 Environmental impact assessment

3.4.1 Base case production process

Detailed exploration is necessary for the environmental impact caused by the ethanol production stage. The detailed process flow diagram is shown in Figure S1. The four stages of crushing and screening, sewage treatment, saccharification, and fermentation consume only electrical energy. So, their impact on the environment is proportional to their respective electrical energy consumption. The high-temperature jetting and rectification dehydration stages are the two stages with the most enormous energy input, and they also have a more significant impact on the environment.

For the high-temperature jet liquefaction section, the main energy consumption is composed of a liquefaction feed pump, liquefaction pre-reactor, steam heater, and product pump. As shown in Fig. 7a, the liquefaction feed pump and product pump used in the liquefaction section have minimal impact on GWP, AP, and EP. They have similar effects on POCP, ODP, and HTP, accounting for 15%–20% of the liquefaction section. Steam heaters have a massive impact on GWP, AP, and EP. In particular, the

Fig. 7 Environmental impact of **a** liquefaction section and **b** distillation section



contribution to AP is more than 80%, which means that the steam heater has greatly contributed to the potential value of environmental impact. GWP and EP account for 65% and 68% of the liquefaction section, respectively. This is because the steam heater heats up the liquefaction process and consumes steam, and the steam needs biogas and natural gas for heating, which indirectly consumes natural gas and biogas. The pre-reactor has apparent effects on POCP, ODP, and HTP, accounting for 60.98%, 56.91%, and 58.21% of this stage, respectively.

For the distillation and dehydration section, it is the section with the largest energy consumption in the ethanol production process. As shown in figure S2, the rectification section adopts three-column heat-coupled rectification, including a crude distillation tower, rectification tower, and recovery tower. The fermentation broth is divided into two parts and sent to the crude distillation tower (T5101) and the product rectification tower (T5301). The T5101 tower reactor produces the distiller's waste liquor, and the top stream enters the recovery tower T5201 for further separation. The water is separated from the T5201 tower, and 90% alcohol-rich vapor and 89% alcohol-rich liquid phase are obtained at the top of the tower. These two streams enter the product rectification tower, and 93% of the gas phase product is obtained at the top of the tower to remove the molecular sieve dehydration section. In the whole process, only the reactor of the recovery tower (T5201) is heated by fresh steam. The top steam of the recovery tower (T5201) is used as the heating medium for the reboiler of the rectification tower (T5301). Finally, pressure swing adsorption is used to obtain an ethanol product with an alcohol content of 99.7%. The environmental impact assessment of these sections is shown in Fig. 7b. The distillation feed pump has a relatively small impact on these six environmental parameters, because only a tiny amount of electrical energy is consumed. The contribution of the distillation tower to GWP, AP, and EP is evident, all exceeding 60% of the rectification section. The rough distillation tower has a greater contribution to ODP,

which exceeds 50% of the rectification section. For HTP and POCP, the compressor contributes the most.

3.4.2 Environmental impact of the different production processes

Table S7 shows the impact of different cassava ethanol production processes on these six environmental impact categories. The results show that in the clinker fermentation process, CF20% is the most environmentally friendly, and CF12.5% is the least environmentally friendly. Compared with the base case, except for CF 12.5%, other cases have reduced environmental impact. The contribution of all cases to GWP is negative, because the CO₂ produced in the fermentation section is liquefied into dry ice. The amount of CO₂ made into dry ice is greater than the amount released by the entire cassava ethanol system. As shown in Fig. 8, the impact of the base case on GWP is equivalent to -74.11 kg of CO₂, and CF 12.5% is an increase of 6.74 kg of CO₂ over the base case. Compared with the base case, CF17.5% and CF20% were reduced by 5.16 kg CO₂ eq and 9.19 kg CO₂ eq, respectively. The RMF15% contribution to GWP is -111.5 kg CO₂ eq, the smallest among the five systems. Compared with other studies, the GWP of all cases is negative, which can alleviate the greenhouse effect [26]. The difference between the production system with the largest contribution to GWP and the smallest is 44.13 kg CO₂ eq, which is an imposing number. For AP's contribution, RMF has the advantage. Figure 8 shows that CF 12.5% has the most prominent impact on AP among all systems.

The contribution of these five systems to EP is relatively close, between 0.76 and 0.79 kg PO₄ eq. This means that the contributions of these five different biomass ethanol production systems to EP are not much different. The impact of the base case on POCP is 0.088457 kg C₂H₄ eq. Different from the superiority of contribution to GWP, AP, and EP, RMF15% is the maximum value of ODP. For the two environmental categories, HTP, POCP, and ODP, the smallest

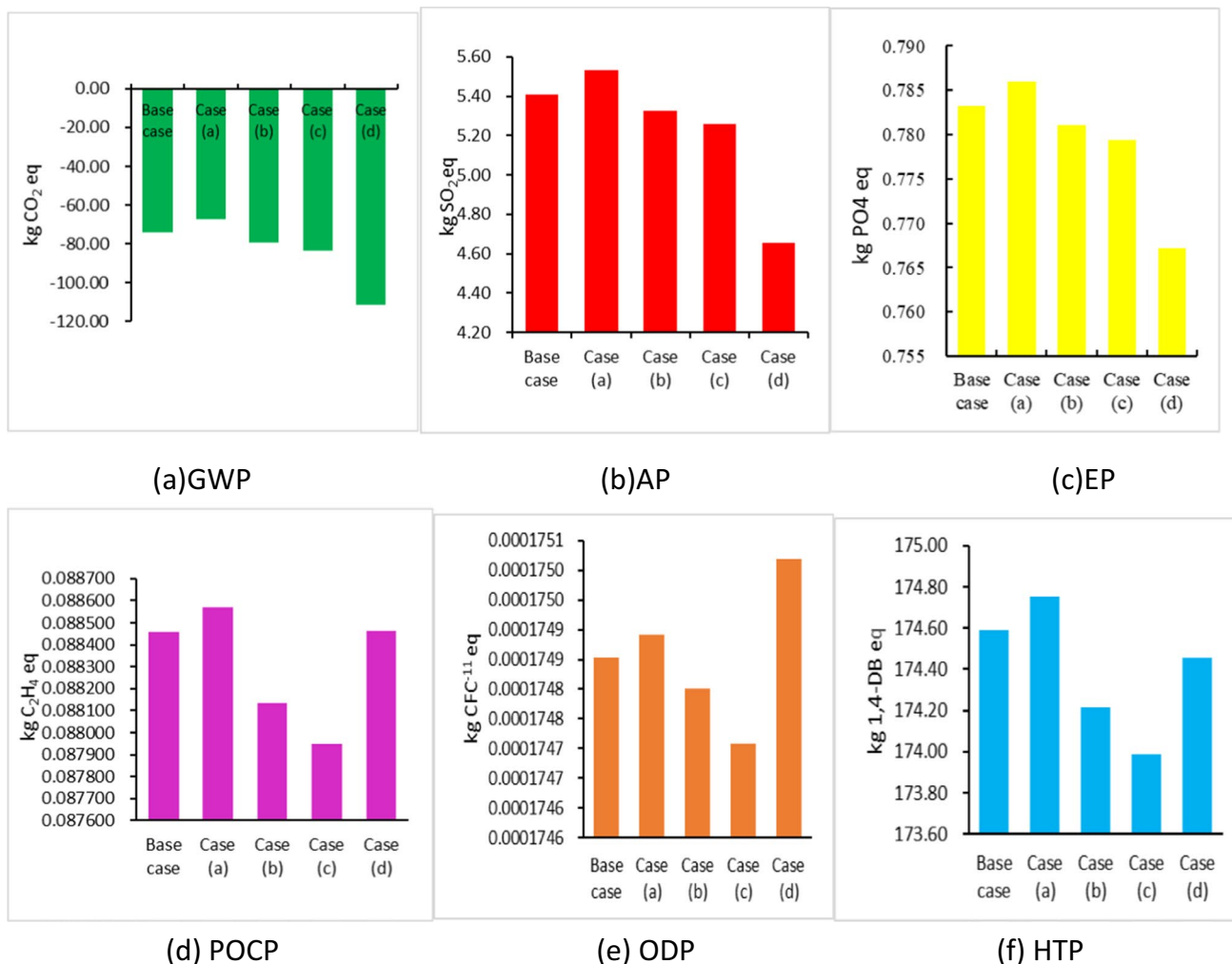


Fig. 8 Environmental impact of different ethanol production systems

contribution is CF20%. The contribution of the base case to HTP is 174.59 kg 1,4-DB eq. Compared with CF15%, the contribution of RMF15% to HTP is reduced by 0.13 kg 1,4-DB eq.

3.4.3 Impact of fermentation alcohol concentration combination analysis of energy and GWP

There is an inseparable relationship between the alcohol concentration of the fermentation broth and the alcohol output. This study explored the application potential of the ethanol production process. The E_{in} , NER, Rn, and GWP are used to measure the application potential of the integrated process, as shown in Fig. 9.

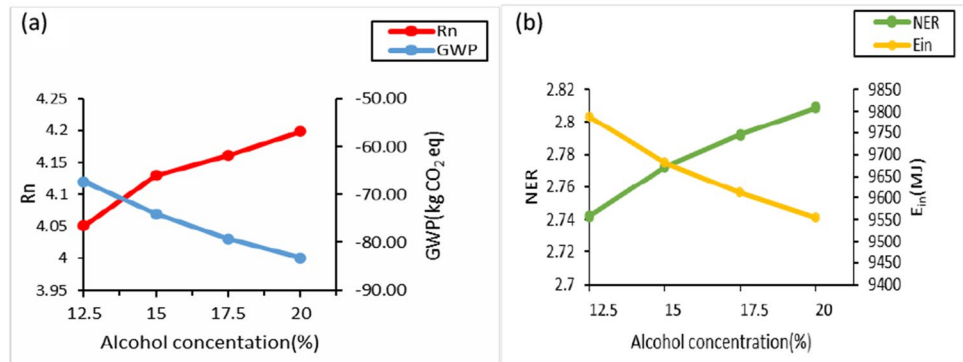
As the alcohol concentration of the fermentation broth increases, the NER gradually increases, and the E_{in} decreases. The line of alcohol concentration from 12.5 to 15%v/v is the most tortuous, which means that the increase in NER is drastic. The relationship between the E_{in} and NER

is that when E_{in} increases, the NER decreases. Therefore, from the perspective of energy saving, reducing energy input can increase the net energy surplus and increase the application potential of the system. As the alcohol concentration of the fermentation broth increases, the GWP shows a decreasing trend, and the system’s Rn gradually improves. When the alcohol concentration of the fermentation broth reaches 20%, Rn is the largest and GWP is the smallest. This means that the better the system’s Rn, and the smaller its contribution to GWP, the system is more in line with environmental protection trends.

3.5 Carbon footprint

Biochar is formed as cassava absorbs carbon dioxide from the atmosphere. According to the carbon neutral principle, the amount of carbon sequestered by cassava is equal to the total amount of carbon emitted in various forms after cassava processing and conversion.

Fig. 9 Impact of fermentation alcohol concentration on **a** Rn and GWP, **b** NER and E_{in}



The carbon footprints of one ton of biomass ethanol produced by the CF and RMF production processes are shown in Fig. 10. In order to compare the differences between the two processes, the fermentation alcohol concentration remains the same at 15% v/v. In the CF-Production process, the total carbon footprint produced by this system is 730.89 kg CO₂. Since the carbon footprint represents the global warming effect of multiple greenhouse gas emissions, the production activities with the highest carbon footprint can still have nothing to do with carbon. The planting process contributed 406 kg CO₂ eq to GWP, accounting for 55.5% of the total carbon footprint. Fertilizer application activities are the largest carbon footprint source in the planting process and the largest in the entire ethanol system. The contribution of fertilizer to the carbon footprint is 331 kg CO₂. Especially the application of nitrogen fertilizer, where N diffuses into the atmosphere in the form of N₂O, N₂O contributes 119 kg CO₂ with a warming effect coefficient of 298 times CO₂. Cultivated land diesel contributes 66.2 kg CO₂ eq. Therefore, reducing fertilizer input and fossil energy consumption can effectively reduce carbon emissions. The carbon footprint of diesel fuel consumed by the internal combustion engine of a truck during the transportation phase is 1.435 kg CO₂. The preparation stage, crushing, and liquefaction require a small amount of electricity, so it contributes a small amount of CO₂. The liquefaction section consumes steam, which is provided by the combustion of natural gas and biogas, so 8.56 kg of CO₂ is generated. The chemicals added in the fermentation section contributed 24.1 kg CO₂ eq. And the section needed to cool the circulating water, so the circulating water pump contributed 0.66 kg CO₂ eq. The electric energy consumed by the CO₂ liquefaction section contributed 4.46 kg CO₂. The distillation section consumes a large amount of steam and indirectly consumed a large amount of natural gas and biogas. Therefore, this stage contributed 69.27 kg CO₂, which is the largest contribution to the carbon footprint of the production stage.

In the RMF production system, the total carbon footprint of the entire system is 693.5 kg CO₂. The planting and harvesting stage produced 406 kg of CO₂, contributing

58.5% of the overall carbon footprint, which was 3.3% more than the CF production process. The RMF process has no high-temperature liquefaction section, so energy consumption is saved, and carbon footprint is reduced. Like the CF-production process, the distillation section contributes a lot of carbon footprint. However, the entire system produces less CO₂ than the CF-production process. Therefore, optimizing production processes and reducing non-renewable energy consumption are important measures to reduce carbon emissions.

3.6 Comparison and analysis with other studies

^aThe system has a functional unit of 1000 l ethanol; therefore, the data is divided by 0.78.

^bNo consideration of captured CO₂.

Cassava is mainly grown in Asia, Southeast Asia, and South America, so cassava ethanol production is carried out in these countries, and some scholars have evaluated cassava ethanol systems through life cycle assessment and net energy analysis. Table 3 lists the LCA results of cassava ethanol in different countries. The net energy inputs of these systems range from 9050 to 32,617 MJ, and the differences are mainly in terms of different fertilizer inputs due to different cropping patterns and energy consumption of ethanol production systems. In this study, three-tower differential pressure distillation was used to reduce steam consumption and smaller fertilizer inputs due to different soil conditions and cropping patterns, so it was more energy-saving. From the point of view of contribution to GWP, compared with other studies, this study increases the biogas produced by sewage treatment to provide energy for the entire system. The carbon dioxide capture process is capable of reducing carbon dioxide emissions from the system. Excluding CO₂ capture, the GWP of the system is close to that of countries such as Nigeria and Vietnam. The Rn is similar to Thailand (Rn = 4.52–4.96); increasing the proportion of renewable energy sources can increase the renewability of the system, such as biogas.



Fig. 10 a CF-production process and b RMF-production process carbon footprint

However, this study did not consider the use of cassava straw. The use of the entire cassava plant can increase Rn and the utilization of resources, so follow-up studies in

this area can be expanded. From the perspective of process optimization, this study uses two different fermentation

Table 3 LCA comparative analysis results of cassava ethanol (baseline: 1 t)

Country	Feedstock	E_{in} (MJ)	NER	Rn	GWP (kgCO ₂)	References
China	Cassava	18,624	1.45	2.13	2229	[17] ^a
China	Whole plant cassava	18,622	1.45	2.35	1991	[17] ^a
China	Cassava	9680.91	2.77	4.1	-74.11 (730.89) ^b	This paper
China	Cassava	9050.38	2.97	4.52	-111.5 (693.5) ^b	This paper
Thailand	Cassava	19,603.295	1.32	4.96	544.87	[14]
Thailand	Cassava	15,285.171			1600	[28]
Columbia	Cassava				311.6	[29]
Africa	Cassava peels				1559.3	[30]
Vietnam	Cassava				739.2	[31]
Brazil	Cassava	13,300	1.76			[32]
Nigerian					660.58	[33]

processes, and the results show that RMF has higher NER = 2.97 and Rn = 4.52.

3.7 Sensitivity analysis

Through the life cycle assessment of the entire cassava ethanol system, the impact on the environment is caused by many factors, including fertilizer for cassava planting, transportation distance, electricity, biogas, and natural gas. It is necessary to select variables from these factors and perform sensitivity analysis on them. Therefore, we perform a sensitivity analysis on the base case. Based on the LCA described above, fertilizer, transport distance, biogas, natural gas, and electricity consumption were selected as variables. The sensitivity analysis results of GWPs and APs are shown in Fig. 11. The range of variation for the sensitivity analysis is 20% above and below the baseline. Figure 11 a shows that natural gas has a great influence on greenhouse gases during the ethanol production stage, and the GWP value fluctuates between -8.5 and 8.5%. The value of electricity for GWP fluctuates between -7.1 and 7.1%. Phosphate fertilizer has the greatest impact on GWP among the fertilizer input in the planting stage, and its value varies from -5.4 to 5.4% through sensitivity analysis. It can be seen that the change of natural gas and electricity consumption has a greater impact on GWP than fertilizer. The effect of changes in P fertilizer on GWP was significantly higher than that of K and N fertilizers.

The sensitivity analysis of the transportation distance is performed on the 20% above and below the baseline. The change in the transportation distance will make the AP baseline value from -8.5% to 8.5%. The fluctuation range in electric energy is -5.5 to 5.5%. The most considerable fluctuation around the baseline is natural gas, ranging from -23 to 23%. And the slightest fluctuation around the baseline is P fertilizer, ranging from -0.5% to 0.5%; its change range is small and negligible. Obviously, the increase or decrease of natural gas has the greatest impact on the AP of the system.

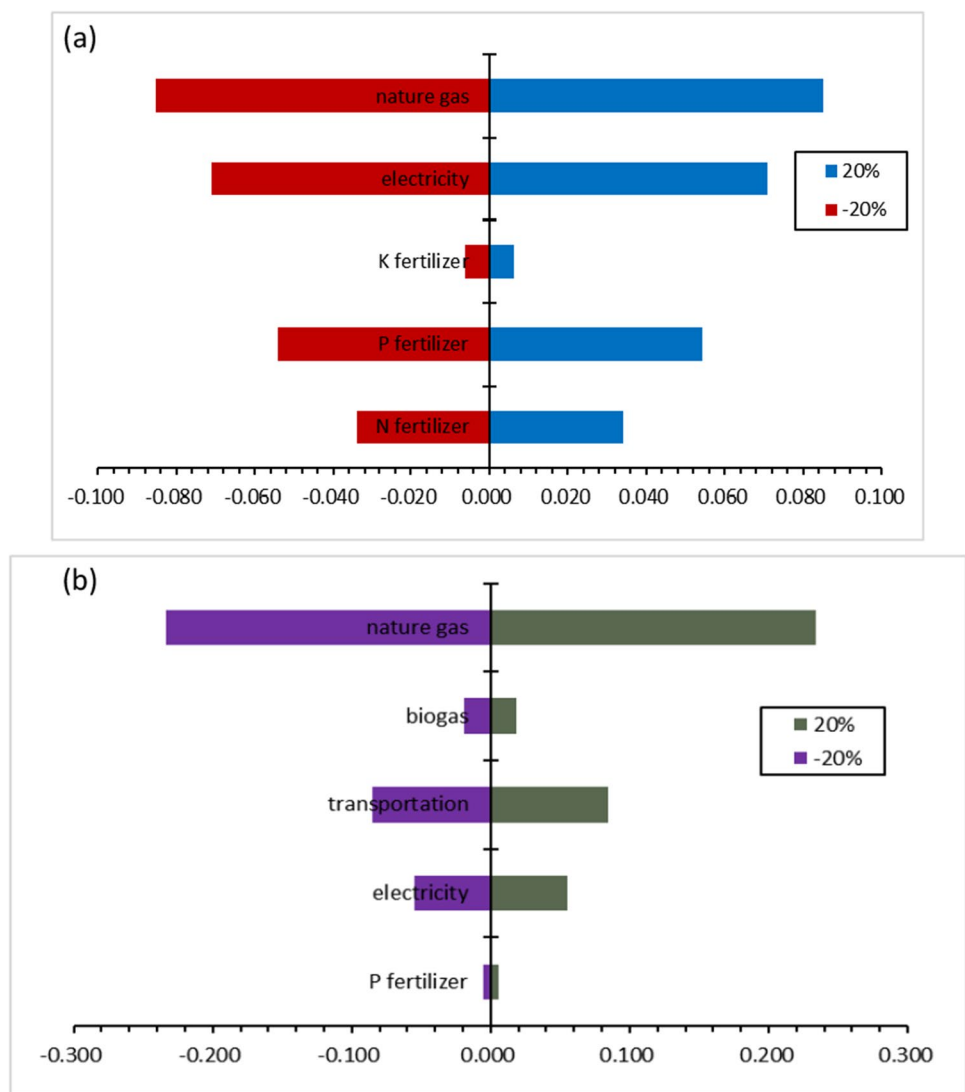
Therefore, it is a good choice to reduce the consumption of natural gas or use other clean energy sources instead. Reducing energy consumption has always been an excellent strategy to reduce environmental pollution.

4 Conclusion

In this research, the biomass ethanol production system of RMF and CF technology is calculated and simulated. The net energy analysis and environmental impact assessment of the cassava ethanol production process in different scenarios were carried out, and a model conforming to the product consumption data of the factory was established. The liquefaction stage and the distillation stage with the largest energy consumption in the ethanol production stage were analyzed to find the key points.

The basic model established through factory data verification showed that the error between the simulated data and the average value of the 3-year factory data was only 1.53%. Further studies found that increasing the alcohol concentration of the fermentation broth was beneficial in reducing production energy consumption and emissions. Comparison of the environmental impact of the raw material fermentation (RMF) and clinker fermentation (CF) production processes showed that the RMF production process had an advantage over the CF production process in terms of energy savings, saving 633 MJ/ton of ethanol. All cassava ethanol production models showed a competitive net energy ratio of no less than 2.74. However, CO₂ emissions were reduced through CO₂ capture and storage technology, making all systems become net GHG-negative systems. Among them, the 15% RMF showed the most competitive net energy ratio of 2.97 and the highest renewability of 4.52 with the lowest environmental emissions. The carbon footprint of the CF and RMF systems was 730.89 kg CO₂ and 693.5 kg CO₂, respectively. The planting stage contributed more than 50% of the carbon emissions. In addition, through sensitivity analysis, the

Fig. 11 **a** Sensitivity analysis on GWP. **b** Sensitivity analysis on AP



impact of different material consumption on GWP and AP within a certain fluctuation is determined. The model used to study can also be used in the study of ethanol production from other different raw materials and promote the establishment of a more abundant biomass ethanol LCA database.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13399-022-03442-9>.

Author contribution All the authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Lulu Zhan, Xi Zhang, Yizhen Zeng, Rui Li, Xianliang Song, and Bin Chen. The first draft of the manuscript was written by Lulu Zhan, and all the authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

Funding The authors would like to thank National Natural Science Foundation of China for their support of this project (No:52100210).

Data availability Not applicable.

Declarations

Ethical approval Not applicable.

Competing interests The authors declare no competing interests.

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