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Long-Term Bioethanol System and Its Implications on GHG Emissions: A Case Study of Thailand

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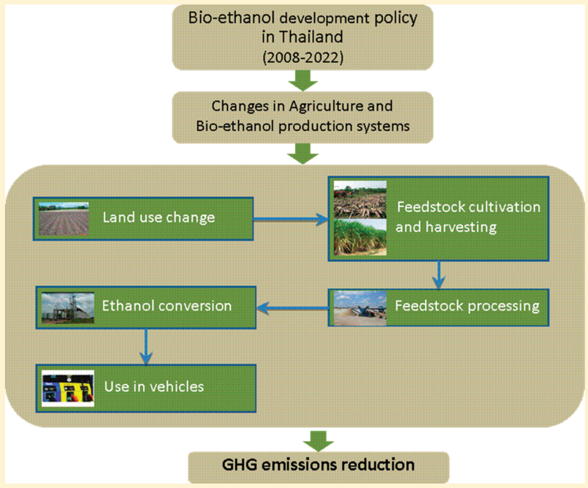
S *Supporting Information*

ABSTRACT: The study evaluates greenhouse gas (GHG) emissions performance of future bioethanol systems in Thailand to ascertain whether bioethanol for transport could help the country mitigate a global warming impact. GHG emission factors of bioethanol derived from cassava, molasses, and sugar cane are analyzed using 12 scenarios covering the critical variables possibly affecting the GHG performance, i.e., (1) the possible direct land use change caused by expanding feedstock cultivation areas; (2) types of energy carriers used in ethanol plants; and (3) waste utilization, e.g., biogas recovery and dry distillers grains with solubles (DDGS) production. The assessment reveals that GHG performance of a Thai bioethanol system is inclined to decrease in the long run due to the effects from the expansion of plantation areas to satisfy the deficit of cassava and molasses. Therefore, bioethanol will contribute to the country's strategic plan on GHG mitigation in the transportation sector only if the production systems are sustainably managed, i.e., coal replaced by biomass in ethanol plants, biogas recovery, and adoption of improved agricultural practices to increase crop productivity without intensification of chemical fertilizers. Achieving the year 2022 government policy targets for bioethanol with recommended measures would help mitigate GHG emissions up to 4.6 Gg CO_2-eq per year.



1. INTRODUCTION

Biofuels have been attached significance as alternative fuels for transportation to mitigate the dependency on petroleum derivatives which have several constraints in their long-term utilization, e.g., volatile prices, insecurity of supply, and especially the environmental concerns over climate change.[1] The expectations with respect to biofuels are multidimensional; for example, many countries encourage biofuels derived from indigenous feedstocks in order to enhance rural development through increasing employment and stabilizing income to farmers. The emissions of greenhouse gases (GHGs), in particular carbon dioxide, are expected to decrease when replacing fossil fuels with biofuels because the latter are derived from plant materials. Currently, bioethanol and biodiesel are the two main liquid biofuels being used worldwide to partially substitute petroleum based gasoline and diesel, respectively. The current blending rates are often in the range 5−20% for ethanol with gasoline and 2−5% for biodiesel with conventional diesel.[2,3] The rising interest in biofuels can be seen in many countries that have established ambitious goals for substituting petroleum fuels with biofuels; for example, the United States proposed a target of increased bioethanol production to 36 billion L by 2022, and the European Union expects 10% of transportation fuels to be replaced by biofuels by 2020. China, the emerging giant of the world economy and international energy markets, has also promoted biofuels by setting goals at 10 M ton/year for bioethanol and 12 M ton/year for biodiesel by 2020; meanwhile, India announced a target of 20% biofuels in the transport mix by 2017.[3−5]

Increased demand for these first generation biofuels might cause drawbacks to ecosystems and society in the foreseeable years if the biofuel systems are not sustainably managed. For instance, the nonenvironmental aspects related to biofuels such as food and fuel competition and impact on food availability at affordable prices are side effects widely being discussed today.[6−8] In addition, as compared to petroleum fuels, biofuels may result in an adverse impact on net energy and GHG balance when considering their entire life cycle. In the past, the variations mainly focused on the fossil fuel inputs into cultivating and downstream processing that reduced net GHG savings as well as

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the nitrous oxide emissions from fertilizer application during the cultivation of the feedstock which could partially offset CO_2 emission reductions.[9−12] However, recently several studies have shown that land-use changes and management caused by increased growing demand for feedstocks could substantially increase GHG emissions from the changes of carbon stock and may contribute to the loss of biodiversity and ecosystem services especially in the case of deforestation.[13−16] Therefore, to guarantee that biofuels and bioenergy could help mitigate global warming impact when replacing petroleum fuels, the GHG emissions reduction is set as one of the principal criteria for sustainable biofuels.[17−20]

The Royal Thai Government (RTG) has promoted biofuels for road transport to reduce oil imports by utilizing the abundance of energy crops in the country as feedstocks. At present, liquid biofuels for transport are bioethanol produced from sugar cane, molasses, and cassava, while biodiesel is produced from palm oil, animal fat, and used cooking oil. Though the demand for diesel in transportation in Thailand is greater than that for gasoline, the RTG has set the ambitious goals for bioethanol development at a higher level than biodiesel, i.e., 9 M liter/day for bioethanol and 6 M liter/day for biodiesel in 2022 because the estimated availability of feedstocks such as sugar cane and/or cassava are greater than palm oil. Bioethanol is playing an important role as alternative fuel for passenger cars in Thailand, and today there are three gasohol blends in the market, i.e., E10 (a 10% blend of bioethanol with 90% gasoline), the 20% ethanol blend (E20), and the 85% ethanol blend (E85). The production of bioethanol has rapidly increased from 0.4 M liter per day in 2006 to 1 M liter a day in 2009 or 60% annual growth, and the boom will continue for achieving the long-term government policy target of bioethanol development in Thailand.[21]

This study aims to evaluate the GHG emission implications on the future (long-term) bioethanol system in Thailand based on the government's recent 15 years policy target for bioethanol development.[22] The obtained results are not only to examine the net GHG performance of a future bioethanol system in Thailand when the goals are implemented but also to discuss the key factors in the entire the life cycle which can affect the GHG emissions. The paper is organized as follows: Section 2 provides an overview of the modeling of the future bioethanol system in Thailand, the methodology used, the scope of life cycle analysis, and data sources used to assess GHG performances of the modeled bioethanol system. The 12 possible systems for bioethanol derived from molasses, cassava, and sugar cane are also defined in this section. The results and discussion on the GHG emissions and performance of future bioethanol production systems in Thailand are presented in Section 3. This includes the analyses of the key factors in the bioethanol production system that can affect the GHG emissions, i.e., direct land use change, crop yield improvement, and crop residue removal, as well as their effect on GHG emissions and the conclusion about GHG performance of future bioethanol production systems in Thailand.

2. METHODOLOGY

2.1. Modeling of the Future (Long-Term) Bioethanol System in Thailand. Thailand, well-known as an agro-industry based country, has a variety of raw materials which can be used for producing bioethanol; however, cane molasses, cassava, and sugar cane juice are the three major feedstocks being promoted by the RTG due to the proven conversion technologies and their estimated availability in the future for fuel after accounting for domestic consumption for food and animal feed as well as export.[23] In the beginning stage of biofuel promotion in Thailand, ethanol fuel was primarily derived from cane molasses. However, both cassava and sugar cane are inclined to play an important role as the major feedstocks in the foreseeable years due to a significant increase in the cassava and sugar cane based ethanol plants that have been approved by the government, and several plants are under construction (Table S1 of the Supporting Information).

The government has high expectations from bioethanol as alternative energy to help the country reduce oil imports and help farmers have more income stability from selling crops. An example is the case of cassava in Thailand; the cassava starch industry is not expected to grow rapidly, and the chips/pellets industry has begun declining. Therefore, there is definitely a possibility of having surplus cassava for bioethanol in the future. This is especially true if cassava yields are improved in accordance with the policies on high-yield varieties development and good agricultural management promotion.[24] Otherwise, the oversupply of cassava as compared to the market demand could push down crop prices. Therefore, the targets of producing bioethanol in the country as mentioned in the renewable energy development plan (2008−2022) were set quite high, i.e., 3 M liter ethanol/day for short-term (by 2011), 6 M liter/day for the medium-term (by 2016), and 9.0 M liter/day for the long-term (by 2022).[22] According to these targets, the future (long-term) bioethanol in Thailand can be modeled by using several assumptions. Only molasses, cassava, and sugar cane juice are considered as possible feedstocks in the future. All 47 ethanol plants licensed by the government can start operation in accordance with the proposed schedule (as updated in September 2009) and be fully operational by year 2016. The ratios of feedstocks used for the multifeedstocks bioethanol plants are assumed as shown in Table S1. Projections reveal that the Thai bioethanol system in 2022 will be 19% from molasses, 72% from cassava, and 9% from sugar cane. Detailed projections are shown in the Supporting Information (SI).

2.2. Life Cycle Assessment and GHG Indicators. Life cycle assessment (LCA) is an environmental sustainability assessment tool which has been widely used to assess environmental performance of renewable technologies and also bioenergy systems such as bioethanol[9,12,25−27] and biodiesel.[13,28−30] The crucial advantage of a life cycle approach is that all burdens from raw material extraction through production, to use and disposal, will be accounted for. Even though focusing only on GHG emissions is not the complete LCA as described in the ISO standards,[31,32] it is especially useful for evaluating the GHG performance of transportation biofuels by a fair comparison with conventional petroleum fuels because it focuses on the entire life cycle of the biofuels rather than just the combustion in vehicles.[17,33] Even though a variety of research on LCA and GHG analysis of bioenergy and biofuels has been conducted, diverse results have been obtained even for the same kind of bioenergy. The reasons can be categorized into two groups, i.e., the variations due to the differences in production environment of bioenergy systems such as type of biomass sources, conversion technologies, conversion efficiency, etc.,[9,34] and the variations due to the different approaches used to address methodological issues in LCA such as the treatment of multi-functional processes, the determination of system boundaries, and the handling of biogenic carbon balances.[33,35,36]

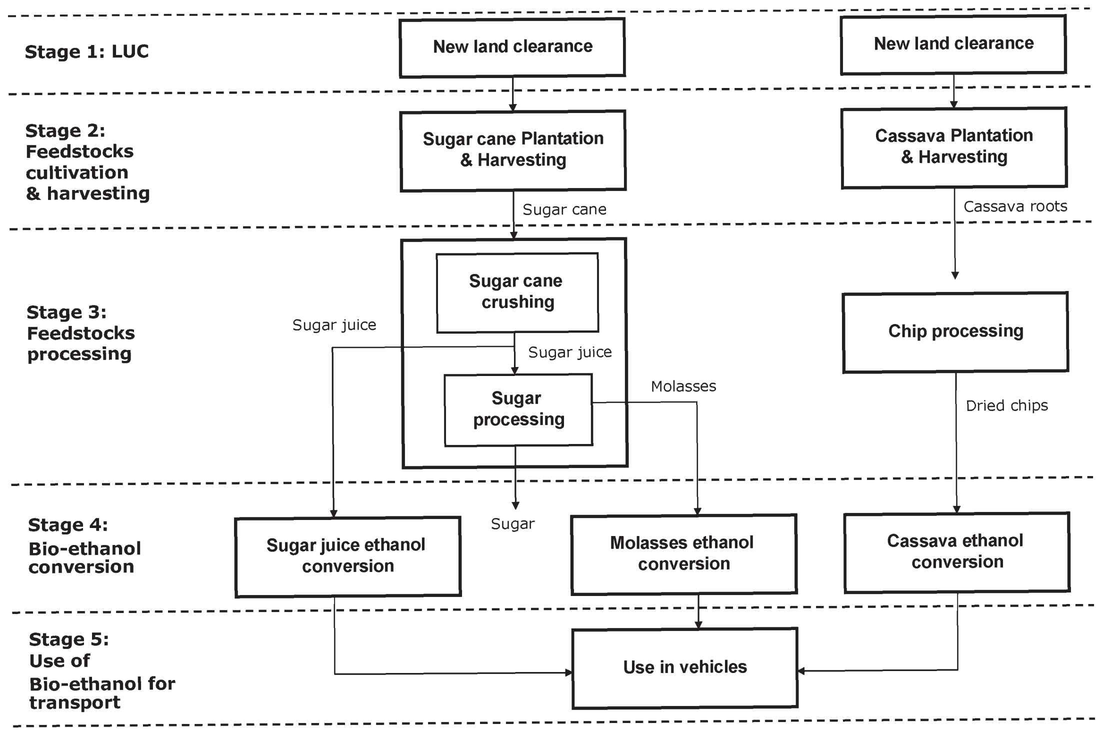

Figure 1. Life cycle stages associated with the future bioethanol systems in Thailand.

In this study, life cycle GHG emissions of cassava, molasses, and sugar cane ethanol are assessed for the individual pathways of bioethanol production. However, to evaluate the overall GHG performance of the future bioethanol system in Thailand, three GHG indicators including the average GHG emission factor of bioethanol system, the percentage in GHG emissions reduction, and the net avoided GHG emissions as compared to petroleum fuels at the same performance will also be determined. The average GHG emission factor is an indicator to determine the overall GHG emissions per functional unit of bioethanol system. The percentage in GHG emissions reduction and net avoided GHG emission are the two indicators used to evaluate the performance in GHG reduction of a bioethanol system. Whereas the percentage is just for comparison with the fossil equivalent, the absolute value gives the actual reduction for the entire system. Equations and parameters for these three indicators are defined in the SI.

2.2.1. Functional Unit. The study defines the functional unit as 1 MJ to determine the GHG performance of a bioethanol system when comparing with the conventional petroleum fuel system. This energy basis would result in a fair comparison as the differences in the energy contents are accounted for.[34] As the energy content of bioethanol is 21.2 MJ/liter ethanol whereas that of gasoline is 32.4 MJ/liter gasoline,[37] a liter of ethanol therefore produces the same performance as 0.65 L of gasoline.

2.2.2. Scope of GHG Emissions. The life cycles of various bioethanol pathways in Thailand are shown in Figure 1. The system is divided into five main stages including land use change (LUC) for new plantation areas, feedstocks cultivation and harvesting, feedstocks processing, bioethanol conversion, and use of bioethanol in vehicles. The analyses focus on the three most important GHGs of the bioenergy system, i.e., carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O),[34] and the global warming potential factors used are 1, 25, and 298 kg CO_2-eq/kg substance, respectively.[38] The total GHG emissions are from the various life cycle stages such as land use change and management, cultivation and harvesting, feedstock processing, bioethanol conversion, use in vehicles, and extraction of input materials throughout the life cycle. Credits are provided for biogas recovery, excess electricity from cogeneration, etc. Additional details on the scope of analyses on GHG emissions, formula, and parameters used in each life cycle stage of bioethanol systems as shown in Figure 1 can be found in the SI.

2.3. Scenarios and Data Sources. *2.3.1. Scenarios Definition.* The possible systems for bioethanol derived from molasses, cassava, and sugar cane are divided into 12 scenarios including 6 scenarios for cassava ethanol, 4 for molasses ethanol, and 2 for sugar cane ethanol. Base case scenarios represent the most common practice of the existing commercial bioethanol production chains in Thailand.[12,25,26] The others are modeled by varying the key factors in their production systems that may significantly affect the GHG emissions, i.e., (1) types of fuel used for steam and power generation in ethanol plant, and (2) waste utilization and their consequent GHG emissions credits. Moreover, the probable direct LUC caused by expanding cultivation areas for cassava and/or sugar cane are also considered in the analysis. Descriptions of the scenarios are summarized in Table 1.

2.3.2. Data Sources. Data sources and key parameters used for base case scenarios of bioethanol systems in Thailand are shown in the SI (Table S3).

3. RESULTS AND DISCUSSION

3.1. GHG Emissions of Bioethanol in Thailand. GHG emissions per MJ of bioethanol used for transport in various scenarios are examined (details shown in the SI), and the results are summarized in Table 2. The assessment reveals that there are wide ranges of GHG emissions especially when direct LUC is

Table 1. Scenarios for Bioethanol Systems in Thailand

scenario	description
1. CE_BC or base case scenario of cassava ethanol system	Existing cassava ethanol system where cassava ethanol plant uses imported coal as fuel to produce steam and electricity is supplied from the national grid system. Distillery spent wash, the high organic wastewater discharged from ethanol conversion stage, is sent to aerobic ponds without waste recycling systems.
2. CE_S1	Adding the upflow anaerobic sludge blanket (UASB) system for biogas recovery from spent wash to the base case CE_BC. This biogas is used in the boiler to substitute imported coal. The GHG emission credits from coal displacement are accounted for in the GHG balance.
3. CE_S2	Adding the dry distillers grains with solubles (DDGS) production from spent wash to the base case CE_S1. Animal feed (soybean meal) is the product substituted by DDGS. Each kilogram of DDGS is considered to substitute 0.78 kg of soybean meal.[39,40]
4. CE_S3	Using rice husk as fuel in place of imported coal in the base case CE_BC.
5. CE_S4	Combination of scenarios CE_S1 and CE_S3.
6. CE_S5	Combination of scenarios CE_S2 and CE_S3.
7. MoE_BC or base case scenario of molasses ethanol system	Existing molasses ethanol system where the molasses ethanol plant uses steam and electricity produced from bagasse supplied from a sugar mill. Surplus electricity at sugar mills is sold to the national grid. The GHG emission credits from this reduction of grid power generation are included and allocated to molasses on an energy basis. Spent wash is sent to aerobic ponds without recovery of biogas.
8. MoE_S1	Adding biogas recovery to the base case MoE_BC. Credits are provided for the displaced conventional electricity from the excess electricity from surplus bagasse not used by the system.
9. MoE_S2	Same as base case MoE_BC but using imported coal in ethanol conversion instead of bagasse.
10. MoE_S3	Combination of scenarios MoE_S1 and MoE_S2. Biogas energy is considered to substitute imported coal.
11. SC_BC or base case scenario of sugar cane ethanol system	Representing a sugar cane ethanol system where the ethanol will be produced directly from sugar cane juice without producing sugar. Bagasse is used as fuel to produce steam and electricity. Surplus electricity from bagasse is supplied to the grid system, and credits are provided for displaced GHG emissions from conventional electricity production. Spent wash is sent to aerobic ponds without biogas recovery.
12. SC_S1	Adding biogas recovery to the base case SC_BC. Credits are provided for the displaced conventional electricity from the excess electricity from surplus bagasse and biogas not used by the system.

Table 2. GHG Emissions (g CO_2-eq per MJ of Bioethanol) for Various Bioethanol Systems in Thailand

		including LUC	
scenarios	excluding LUC	FL-CL	GL-CL
Cassava			
CE_BC: use coal as fuel	91	313	127
CE_S1: CE_BC + biogas	82	304	118
CE_S2: CE_S1 + DDGS	81	303	117
CE_S3: use biomass as fuel	37	258	73
CE_S4: CE_S1 + CE_S3	28	250	64
CE_S5: CE_S2 + CE_S3	27	249	63
Molasses			
MoE_BC: use biomass as fuel	31	295	74
MoE_S1: MoE_BC + biogas	28	292	71
MoE_S2: use coal as fuel	119	380	158
MoE_S3: MoE_S2 + biogas	100	361	140
Sugar Cane			
SC_BC: use bagasse as fuel	27	157	48
SC_S1: SC_BC + biogas	23	154	44

included in the system boundary. As the changes of tropical forest land and/or grassland to cropland are included in the analyses, the GHG emissions can possibly increase from 1 to 10 times compared to the cases where LUC is excluded. Conversion of tropical forest land to cropland results in the highest GHG emissions due to the CO_2 emissions from the loss of carbon stock in above- and below-ground biomass (AGB and BGB) and non-CO_2 emissions from burning biomass as part of the first clearance of land (as shown in the SI), totalling about 14.5 ton CO_2-eq ha^{-1} yr^{-1}. In addition, soil carbon stock change from this direct LUC also creates GHG emissions of about 2.1 ton CO_2-eq ha^{-1} yr^{-1}. This is in contrast to the case of converting grassland to cropland for which GHG emissions originate mainly from soil carbon stock changes, i.e., 1.9 ton CO_2-eq ha^{-1} yr^{-1}, and the losses of carbon stocks in AGB and BGB are just about 0.8 ton CO_2-eq ha^{-1} yr^{-1}. The GHG performance of bioethanol can be measured as the payback period by dividing the carbon debt from LUC with the GHG credits of bioethanol compared to gasoline. For example, as the life cycle GHG emission factor of conventional gasoline system is about 2.92 kg CO_2-eq per liter gasoline or 90 g CO_2-eq per MJ,[37] the carbon debt from converting grassland to cropland can be paid off by the GHG credits of bioethanol within 4 years for sugar cane ethanol, 8 years for molasses ethanol, and 10 years for cassava ethanol for the base case scenarios. This payback period obtained for sugar cane ethanol is relatively low as compared to molasses and cassava ethanol and is consistent with the results of another study where the payback time is not more than 7.5 years.[41] Nevertheless, there are a number of variables in real agricultural practices that can affect GHG emissions, e.g., the effects of different tillage methods and other crops management measures, such as growing cover crops to improve soil organic carbon or no-tillage cultivation, and these variables need further investigation.[11]

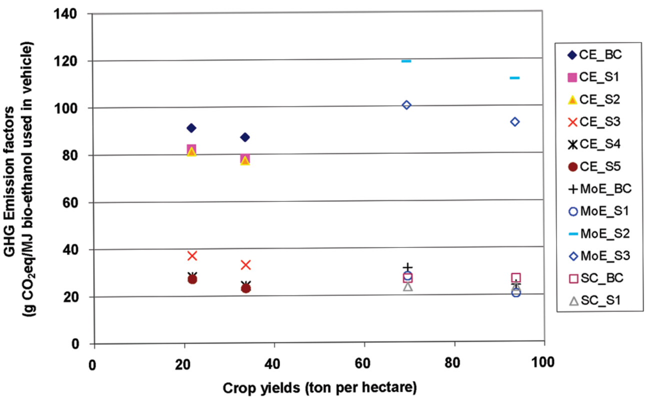

Figure 2. GHG emissions of bioethanol systems after adjusting crop yields (by adopting high yield varieties and good agricultural practices).

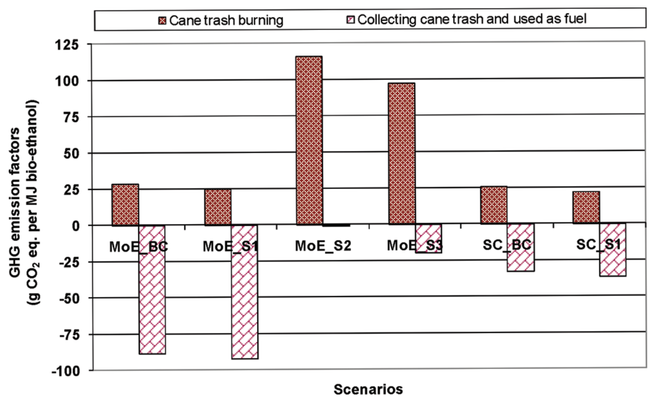

Figure 3. Comparison of GHG emission factors for molasses and sugar cane ethanol when 50% of cane trash has been collected and used as fuel.

So far LUC induced by domestic demand for bioethanol in Thailand has not been much of a focus as bioethanol production mainly relied on the surplus feedstocks obtained from the existing plantation areas. However, it would need to be considered if the approved ethanol plants were operated and the government target of 9 M liter ethanol per day was achieved. The government policy emphasizes increasing feedstocks production by improving yields instead of expanding plantation areas. However, the demand-supply of feedstocks estimated by the Department of Alternative Energy Development and Efficiency (DEDE) shows that there are 2.6 M ton of surplus cassava for producing ethanol in 2011 equivalent to 1.2 M liter of ethanol per day; however, the total installed capacity of cassava ethanol plants in Thailand is expected to be much higher at 4 M liter per day.[42] Thus, LUC for feedstock production, particularly cassava, will become an important factor in the long run.

The comparison among three feedstocks shows that sugar cane ethanol gives the lowest GHG emission at around 23−27 g CO_2-eq per MJ ethanol (excluding LUC). GHG emissions for cassava and molasses ethanol are in the ranges 27−91 and 28−100 g CO_2-eq per MJ ethanol, respectively. The wide ranges in GHG emissions stem from the differences in the production environment. For example, bioethanol conversion is an energy intensive process; therefore, using fossil fuels such as coal to produce steam and electricity will cause significantly higher GHG emissions than systems which use biomass. Bioethanol systems which have wastes and residues recycling such as biogas used for energy or using spent-wash to produce DDGS yield the lowest GHG emissions.

3.1.1. Effect of Crop Yield Improvement on GHG Emissions. Crop yield improvement is an important measure to maximize benefits of biofuels chain in the long run because arable land and other input resources during cultivation and harvesting are used efficiently. Thailand currently has an average cassava yield of 22 ton/ha. This is the second highest cassava yield in the world only after India and is nearly double the average yield in the world.[43] Sugar cane yield is about 70 ton/ha, lower than in other sugar exporting countries such as Brazil and Australia.[43] The Thai government has been promoting good agricultural practices and high yield varieties to farmers nationwide in order to achieve the policy goals on crop productivity improvement, i.e., 34 ton/ha for cassava and 94 ton/ha for sugar cane by year 2012.[22] The effects of crop yields on the GHG emission factors of cassava, molasses, and sugar cane ethanol with the yields of cassava and sugar cane improved as per policy targets are also evaluated. The assessment is divided into two approaches, i.e., (1) yield improvement by increased fertilizer requirements, and (2) yield improvement by adopting appropriate and high-yield varieties nationwide.

Intensification of chemical fertilizers is one of the factors to increase crop yields; however, this must be traded off with the consequential impacts on GHG emissions caused by the additional fertilizer input. The foreground data reveals that farmers generally apply less fertilizer than recommended by good agricultural practices for cost reduction. This, nevertheless, depends on the attractiveness of crop prices at any particular time. The additional fertilizer requirement for cassava is around 4.2 kg N (based on the optimum fertilizer requirement i.e. 100 kg N, 50 kg P_2O_5 and 100 kg K_2O per ha[44,45]); while for sugar cane it is 1−1.5 kg N per ton cane.[46,47] If both conditions of the additional fertilizers input for cassava and sugar cane were applied to achieve the target yields of the government, the results show that GHG emissions per liter of bioethanol for all systems would be increased by around 3−8% even taking into account the increased yield.

However, this GHG emission caused by an intensification of chemical fertilizers may not be a serious issue if appropriate and high-yield varieties were adopted nationwide as this would also be reflected in the reduced requirement for LUC resulting in GHG benefits. Due to the continual development of high yield varieties, the current varieties of cassava (e.g., Kasetsart 50, Rayong 5, Rayong 72, and Rayong 9) and sugar cane (e.g., K 84−200, U thong 3, and K 90−54) being recommended to Thai farmers have the potential to yield about 31−50 ton/ha for cassava and 94−112 ton/ha for sugar cane with improved soil quality using organic fertilizers and good practices in land preparation, plantation, harvesting, and regular weed control.[46−48] Figure 2 shows that minimum GHG emissions of bioethanol derived from cassava, molasses, and sugar cane would be 24, 20, and 23 g CO_2 eq per MJ bioethanol, respectively.

3.1.2. Effect of Crop Residue Removal on GHG Emissions. The practice to handle crop residues is another essential factor contributing to the GHG performance of bioethanol production in Thailand. This is especially true for bioethanol derived from sugar cane where cane trash (leaves and tops) is currently disposed of by burning in the fields during harvesting. As the average production data of all the 46 Thai sugar mills in 2008 revealed that around 50% of the cane supplied to sugar mills was burnt cane,[49] this value can be implied as the percentage of cane trash burnt in the fields during harvesting. This open burning of

Table 3. Percentage GHG Emissions Reduction for Different Bioethanol Systems in Thailand

	% net avoided GHG emissions when comparing with gasoline			
	excluding LUC		including LUC	
feedstocks	base case	range	FL − CL	GL − CL
cassava	(−2%)	73%[a]−(−2%)	(−178%) − (−249%)	30% − (−42%)
molasses	65%	77%[b]−(−33%)	(−222%) − (−320%)	25% − (−73%)
sugar cane	70%	70%−74%[c]	(−70%) − (−74%)	48% − 52%

[a] Referring to cassava ethanol system in which ethanol plant uses biomass as fuel and recovered biogas is utilized (based on cassava yield = 34 ton/ha as policy target). [b] Referring to molasses ethanol system in which ethanol plant uses biomass as fuel and recovered biogas is utilized (based on sugar cane yield = 94 ton/ha as policy target). [c] Referring to sugar cane ethanol system in which ethanol plant uses biomass as fuel and recovered biogas is utilized (based on sugar cane yield = 94 ton/ha as policy target).

Table 4. Future Bioethanol Production in Thailand Classified by Types of Feedstocks and Plantation Areas

	plantation areas	2011	2016	2022
molasses ethanol (M liter/day)	existing	0.72	1.19	1.67
	new			0.05
cassava ethanol (M liter/day)	existing	1.95	1.04	
	new		3.43	6.48
sugar cane ethanol (M liter/day)	existing	0.33	0.55	0.80
	new			

trash not only causes emissions of non-CO_2 GHGs such as CH_4 and N_2O during the smoldering phase but the heat also reduces the value of commercial cane sugar (CCS) from cane juice.[48] In addition, trash burning also has an effect on soil quality resulting in poor growth and lower yields of the ratoon crops.[50] To mitigate GHG impact during this stage, a proposed measure has been to leave 50% trash in fields in order to return soil organic matter and moisture and another 50% utilized for energy in sugar mills.[41,51] In order to get the net GHG benefits of this measure, the avoided GHG emissions from cane trash burning will be combined with the credits of electricity (about 97 kWh per ton cane) obtained from surplus cane trash[41] as described in Table S3. The results of sensitivity analyses on GHG emission factors of molasses and sugar cane ethanol in Thailand are shown in Figure 3. GHG emissions of molasses and sugar cane ethanol could be minimized to (−92) and (−36) g CO_2 eq per MJ bioethanol, respectively. Even though cane trash that is retained on the soil surface after harvest has the potential to supply nitrogen (N) to crops which might help farmers decrease N-fertilizer input, several studies have shown that trash supplies N to sugar cane quite slowly; i.e., it could increase soil N by 3−23% depending on soil and climatic factors, but this would take 10−35 years for the soils to approach this equilibrium.[52,53] Thus, this benefit is not useful in the short term and hence not included in the calculations.

3.1.3. Percentage GHG Emissions Reduction. The percentage GHG emissions reductions of various possible bioethanol systems in Thailand are summarized in Table 3. The results indicate that bioethanol derived from molasses and sugar cane in the base case scenario already provide the GHG emissions reduction compared to conventional gasoline if we do not consider LUC emissions. In contrast, base case scenario of the cassava ethanol system does not provide GHG emissions reduction compared to gasoline. This is because the existing cassava ethanol plant in Thailand uses imported coal as fuel and the primary data used in the analysis is site-specific. In fact, GHG emissions reduction benefits would also have a wide range and could vary depending on the essential factors such as LUC, types of fuel used in ethanol plants, crop productivity, and approaches to manage the crop residues.

3.2. GHG Performance of Future Bioethanol Production Systems in Thailand. The projections of future bioethanol production systems as shown in Figure S1 reveal that the bioethanol production per day in 2022 will consist of 6.5 M liter of casssava ethanol, 1.7 M liter of molasses ethanol, and 0.8 M liter of sugar cane ethanol requiring 9.5 M ton cassava, 2.5 M ton molasses, and 5.2 M ton sugar cane per year. To satisfy the increased demand for molasses, cassava, and sugar cane for food, feed, and biofuels in the future, the RTG has set policy targets on crops yields improvement instead of expanding cultivation areas. The plantation areas are expected to be maintained at the current levels, i.e., 1.2 M ha for cassava and 1.1 M ha for sugar cane. The assessment results reveal that the future GHG performance of bioethanol systems varies significantly depending upon the factors such as crop yield improvement, direct LUC caused by expanding cultivation areas, type of fuel used, and waste utilization; therefore, several assumptions for those production factors need to be defined to evaluate the GHG performance of future bioethanol systems in Thailand.

Silalertruksa and Gheewala in 2010 assessed the future security of feedstocks supply for bioethanol production in Thailand.[23] The results showed that, even though the cassava and sugar cane yields were improved as per the ambitious goals of the government, the feedstocks after accounting for both domestic and export demand fell short: cassava in 2016 and molasses in 2022. Therefore, expansion of cultivation areas for cassava and sugar cane are still required in order to avoid reducing export of molasses and cassava product such as dried chips and pellets that could bring about indirect effects when the additional molasses and cassava must be produced elsewhere. The amounts of bioethanol that will be produced in the future classified by existing and new plantation areas are shown in Table 4.

To satisfy bioethanol production as shown in Table 4, five possible cases for future bioethanol systems are developed as follows:

(Case 1) Base case scenarios of cassava, molasses, and sugar cane ethanol systems as defined in section 2.3.1 are referred, and the new plantation areas for both cassava and sugar cane will take place on grassland.

Table 5. Projected Net GHG Emissions and the Average GHG Emission Factors of Future Bioethanol Production System in Thailand[a]

year	case 1	case 2	case 3	case 4	case 5
		Average GHG Emission Factors of Bioethanol (kg CO_2 eq/L Ethanol)			
2011	1.39	1.39	0.48	0.48	0.48
2016	1.75	3.16	0.76	2.18	0.49
2022	1.84	3.7	0.85	2.71	0.49
		Net Avoided GHGs Emission Compared to Gasoline (M tons CO_2 eq/year)			
2011	0.56	0.56	1.55	1.55	1.55
2016	0.33	−2.86	2.57	−0.63	3.19
2022	0.2	−5.91	3.45	−2.68	4.63
		GHGs Emissions Reduction Compared to Gasoline (%)			
2011	27%	27%	74%	74%	74%
2016	8%	−67%	60%	−15%	74%
2022	3%	−95%	55%	−43%	74%

[a] Negative values (−) mean bioethanol system does not provide GHG emission benefit as compared to gasoline.

(Case 2) Case 1 is changed by assuming that the new plantation areas for cassava and sugar cane will take place on forest land.

(Case 3) Ethanol systems widely adopt the sustainability measures, e.g., waste utilization and replacement of coal by biomass in ethanol plants as defined in section 2.3.1, i.e., scenario 4, CE_S3 for cassava ethanol; scenario 8, MoE_S1 for molasses ethanol; and scenario 12, SC_S1 for sugar cane ethanol. The new plantation areas for both cassava and sugar cane take place on grassland.

(Case 4) Case 3 is changed by assuming that the new plantation areas for cassava and sugar cane take place on forest land.

(Case 5) Case 4 is changed by assuming that cassava and sugar cane yields are projected to increase to reach the genetic potentials of the current varieties, i.e., 50 and 125 tons/hectare, respectively, by adopting good quality varieties nationwide.[48] Therefore, expansion of new cultivated areas will not be required.

Table 5 shows the results of the average GHG emissions of the overall bioethanol system in Thailand and the possible GHG emissions reduction as compared to the displaced amounts of gasoline from using bioethanol for transport during 2011−2022. The average GHG emission factor of an overall future bioethanol system in Thailand in 2022 would possibly be 0.49−3.7 kg CO_2 eq per liter ethanol. This wide range in the GHG emission factor of future bioethanol systems is due to the variations of production factors as mentioned in cases 1−5. Nevertheless, the overview of the results shows that GHG performances of a Thai bioethanol system are likely to decrease in the long run from the effects of expansion of plantation areas to satisfy the deficits of cassava and molasses (cases 1−4). Therefore, improvements of cassava and sugar cane yields as in case 5 through the development of high yield varieties and adoption of good and appropriate varieties nationwide would be a vital measure to avoid direct LUC and its consequential impact on GHG emissions.

At the long-term target (year 2022) of 9 M.liter ethanol per day, 4.6 M ton CO_2 eq per year could be avoided which is a 74% reduction as compared to gasoline only if the conditions defined in case 5 were successfully adopted nationwide. Therefore, to succeed in the long term environmental sustainability of bioethanol in Thailand, policy makers need to encourage measures for improving efficiency across the entire life cycle of ethanol production. Particularly, the substitution of fuel used in ethanol plants from imported coal to bioenergy, both biomass and biogas, is strongly recommended. In addition, the good practices for agricultural sector such as selection of good quality varieties and cane trash utilization, and for ethanol conversion sectors such as byproduct utilization, should be rapidly introduced to all relevant stakeholders. In fact, the benefits on GHG emission reduction as determined in this study can be used as the basis for policy promotion, e.g., granting subsidies to stimulate the use of biofuel when this amount of avoided GHGs emission is monetized. However, as the results are quite sensitive to the production environment, this will be a problem for providing a sound basis for granting subsidies.

ASSOCIATED CONTENT

Supporting Information. Detailed information on the modeling of future bioethanol production, GHG indicators used, scope, and parameters used for evaluating GHG emissions over the entire life cycle of bioethanol production systems. This material is available free of charge via the Internet at http://pubs.acs.org.

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