Evaluation of Carbon Equivalences in Ethanol Production from Energy Crops in Thailand

Thanakrit Neamhom, Withida Patthanaissaranukool, and Chongchin Polprasert

Abstract— *Main objective of this study is to evaluate carbon equivalences occurring in the production of ethanol from sugarcane and cassava, starting from plant cultivation until production of alcohol. Following the concept of Carbon-Balanced model, carbon emissions from resources and energy consumed were found to be 829.6±8.3, and 1,155.2±22.8 kg CE/ha-y for su garcane and cassava, respectively. However, due to the greater amount of ethanol produced and the use of waste recovery, the production of ethanol from cassava was found to help reduce carbon emission to the atmosphere at the rate of 0.20 kg CE/L ethanol, equivalent to (-) 596.4 kg CE/ha-y. Meanwhile, ethanol produced from molasses still emits carbon of 0.21 kg CE/L ethanol, corresponding to the emission flux of (+) 148.2 kg CE/ha-y. From the finding of this study, it is suggested that molasses-based ethanol production be upgraded so to achieve carbon emission reduction as to help lessen climate change impact.*

Keywords— **Carbon equivalences, ethanol production, sugarcane, cassava.**

1. INTRODUCTION

The world is facing the worst energy crisis as its non-renewable, fossil sources are depleting, although many countries are still use crude petroleum as a fuel for electricity generation and transportation. In Thailand, energy consumption has been rising with the rate of 6.8% per year for the past 20-30 years because of the growth of transportation and industrial sectors [4]. So the government of Thailand and many companies try to find the alternative ways to produce more energy in this country. Therefore, biofuel particularly produced from biomass feed stock (such as ethanol from sugarcane and cassava) would fulfill these needs. Apart from that, the use of ethanol contributes to net zero CO_2 emission because they are derived from plants that fix atmospheric CO_2 for their growth. The use of renewable energy sources is often suggested to be a possible solution to lower the contribution to climate change and the dependency on fossil fuels [5]. Moreover, biofuel productions promote economic development and create employment in rural areas as well as reducing imports of fossil fuels [3].

Sugarcane and cassava are the primary agricultural crops planted in the tropical area. Cassava (*Manihot esculenta*) is the third largest source of carbohydrate food in the tropic after rice and maize [5]. Sugarcane (Saccharum spp.) is the largest crop, by quantity, produced in the world. In 2012, it was cultivated about 26 million hectares in 90 countries. The world demand for sugar is the primary driver of sugarcane agriculture. It can grow in both tropical and subtropical regions.

Because both plants thrive and yield well under conditions of low rainfall and in acidic, marginal soils, and has the continuous harvesting, so the northeast region of Thailand is planting favorability [3]. Sugarcane and cassava are ones of the major crops in Thailand after rice and Para rubber [6]. These two crops can be used as the main materials to produce ethanol. However, the ethanol production could generate a lot of carbon emitted into the atmosphere, thereby aggravating global warming situations [8,9,10].

From the above-mentioned problems of climate change and rising cost of fossil fuel versus bioethanol production process, the objectives of this work are (1) to evaluate carbon equivalences occurring in productions of ethanol from sugarcane and cassava and (2) to develop the sustainability index associated with their productivities.

2. METHODOLOGY

Field survey and data collection

The carbon equivalences from energy crops, sugarcane and cassava, were estimated, using both primary data from field survey and secondary data from literature. In the field survey, questionnaire was used to gather data from sixty-six farmers. The information of energy, fertilizer and herbicide used in sugarcane and cassava plantations were collected. Three sugar mills and five ethanol plants –one fed with cassava chips and four with molasses– were visited to interview with managers to acquire the information of all inputs and outputs; such as production rate, manpower in the factory, quantities of

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chemicals, water and energy consumed in the ethanol production process.

Carbon balanced-model and conversion factors

Data values on materials input and output from the processes were interpreted in terms of carbon equivalences. They were classified into three groups – carbon fixation, emission, and reduction. **Carbon fixation or C_{fix}** is the product of photosynthetic reaction in which CO_2 in the atmosphere is combined with H_2O to form organic carbon. After consumed by humans, it returns to atmosphere, resulting no emission through this pathway. The computation of C_{fix} is shown in Equation (1) where yield is the product from plantation and CE is carbon equivalent coefficient of C in CH_2O, which is equal to 0.4 kg CE/kg harvest. **Carbon emission or C_{em}** is coming from the use of fossil energy, photosynthesized two billion years ago and stored underneath the earth surface. After used by human, it remains in the atmosphere as incremental CO_2 that causes global warming effects. Computation of C_{em} is shown in Equation (2) where A is the amount of resource used, and CE is conversion factor of carbon equivalences from resource used. CE conversion factors of resources used in ethanol production are listed in Table 1. **Carbon reduction or C_{re}** is the amount of carbon associated with recovery or recycling of waste and by-product as is calculated using Equation (3) where biomass is the amount of waste recycled or reused.

$$C_{fix} = Yield \times CE \quad (1)$$

$$C_{em} = \frac{A}{Unit} \times CE \quad (2)$$

$$C_{re} = \frac{biomass}{Unit} \times CE \quad (3)$$

In Equations (2) and (3) above, CE conversion factor of fossil energy compound can be calculated using the stoichiometric ratio of carbon contained in the chemical formula. For materials other than fossil, the CE conversion factors of materials are calculated, using the energy consumption for its production divided by the thermodynamic conversion factor of 39 MJ/kg CE [6,7]. To calculate carbon reduction from the use of ethanol in lieu of gasoline, the equivalent specific energy of both compounds is taken into account. Hence, the use of ethanol is found to help reduce the emission at the rate of 0.47 kg CE per liter of ethanol when replacing fossil gasoline with the same energy content.

Note that carbon emissions from the manufacture of durable items, like heavy machines, are not taken into account in this study as their quantities are much less than those of carbon fixation produced throughout the working lifetime of the machines [6,7]. Also, carbon equivalence of manpower is not determined because human are carbon mobilizers that rely on carbon movement to satisfy their livelihood needs. Their daily consumption of food and other photosynthetic compounds to live already represents a required amount of carbon fixed on land.

3. RESULTS AND DISCUSSION

Identification of carbon pathway

Following the carbon balance model (CBM), schematic flow diagrams of carbon mobilization for cultivation, primary processing and ethanol production from sugarcane and cassava are presented in Figures 1 and 2, respectively.

The sugarcane and cassava plantations are located mostly in northeast region of Thailand. So, a number of both plantations were visited and farm owners were interviewed so as to acquire the information of all input used in the cultivation process. In sugarcane milling, three by-products used as raw materials for other beneficial productions are (1) Bagasse which can be used to generate electricity for internal uses in the mill, (2) Wet cake, which is used for fertilizer production, and (3) Molasses which is used for ethanol production. In fermentation process, molasses is used as raw material to be blended with yeast and chemicals. After that, it undergoes fermentation and distillation to produce 99.5% purified ethanol salable in the market. After distillation process, slurry effluent is used as input material for biogas generation. The biogas produced is used to generate electricity sold to the outside grid. Finally, liquid effluent from the digester is used to combine with wet cake in fertilizer production process.

Table 1. CE conversion factor of resources used in ethanol production

Items	Chemical formula	Unit	CE (kg CE/unit)	Ref.
Organic carbon				
Diesel	$C_{12}H_{23}$	L	0.74	[2]
Gasoline	C_8H_{17}	L	0.60	[2]
Fossil-based materials				
N-fertilizer	N	kg	0.71	[2]
P_2O_5-fertilizr	P_2O_5	kg	0.07	[2]
K_2O fertilizer	K_2O	kg	0.04	[2]
Alachor	-	kg	2.21	[2]
Paraqout	-	kg	0.88	[2]
Diuron	-	kg	1.92	[2]
Antracine	-	kg	1.37	[2]
Glyphosate	-	kg	0.87	[2]
Water	-	m^3		-
Lime	-	kg	0.22	[2]
Enzyme	-	kg	2.43	[2]
Sodium hydroxide		kg	0.67	[2]
Polymers	-	kg	3.08	[1]
Electriity	-	kWh	0.18	[2]
Ethanol	C_2H_5OH	L	0.47	-

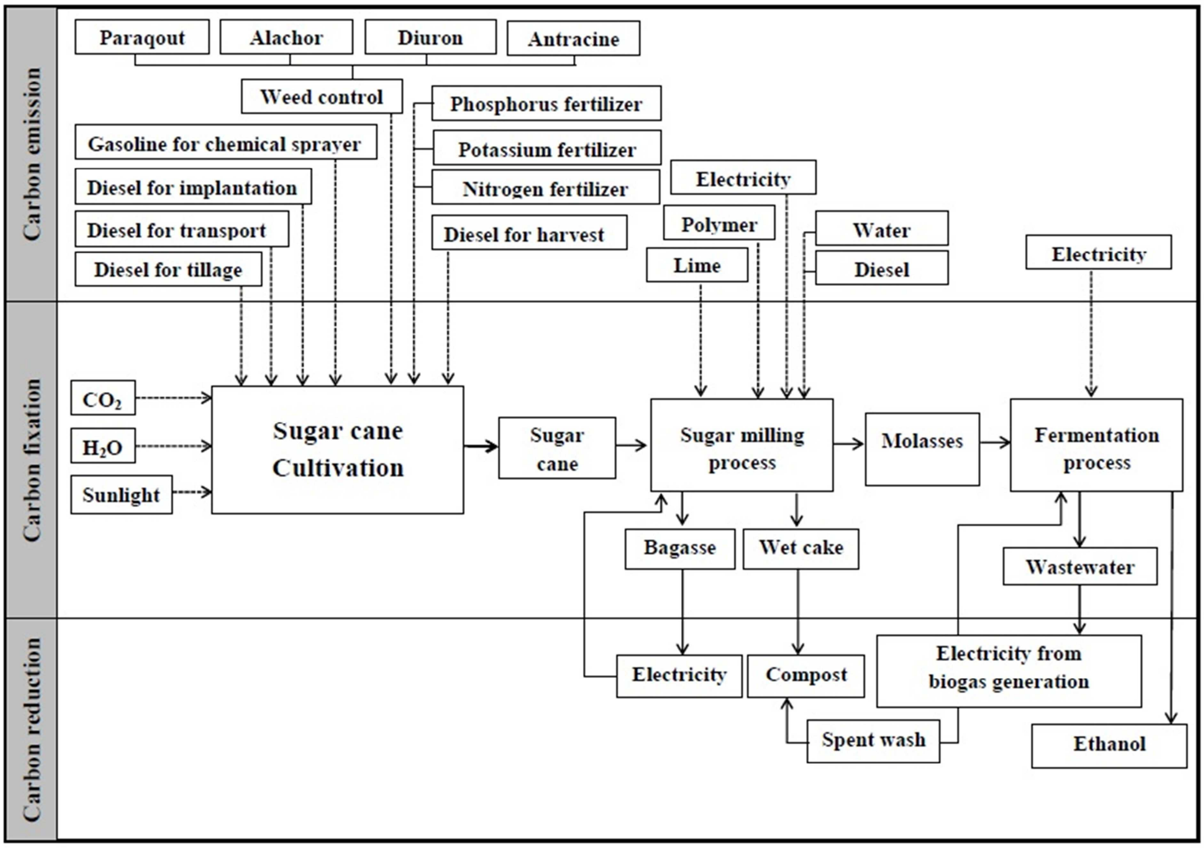

Fig.1. Schematic flow diagram of cultivation, primary processing and ethanol production from sugarcane.

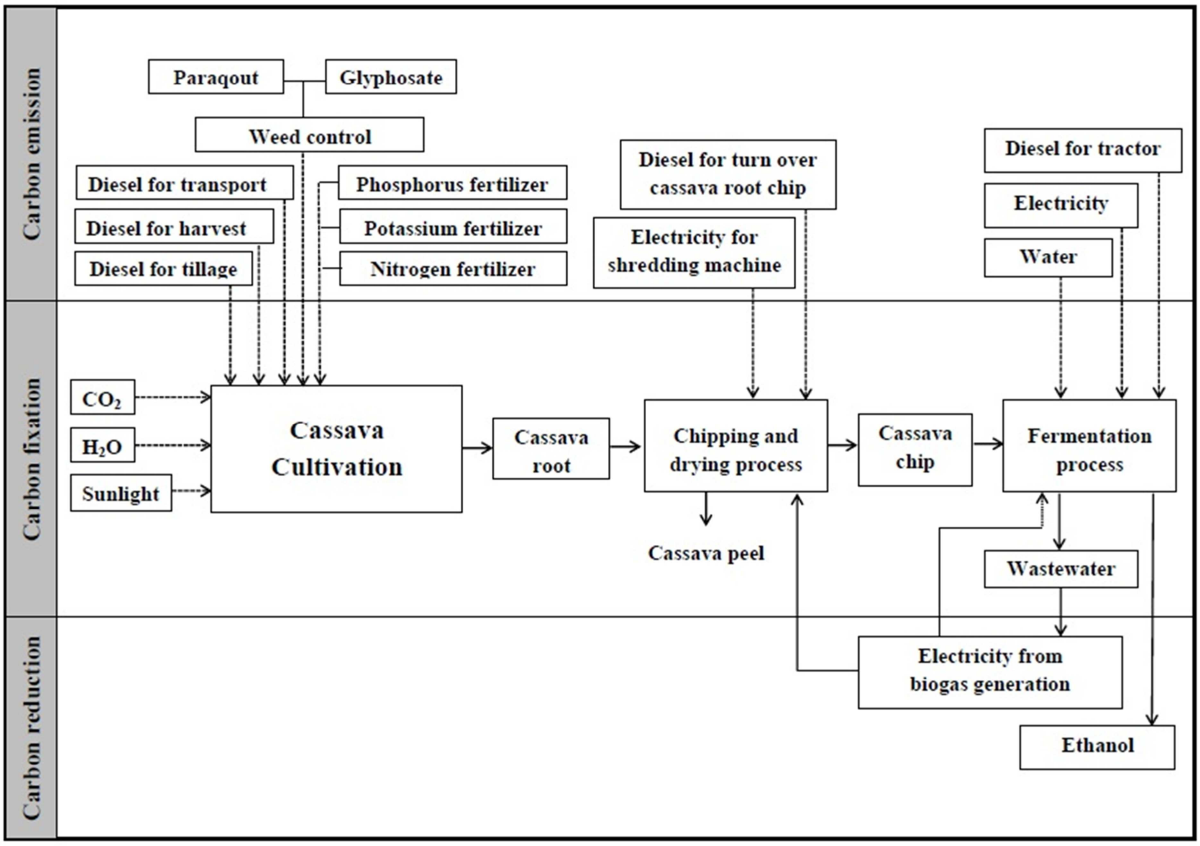

Fig.2. Schematic flow diagram of cultivation, primary processing and ethanol production from cassava.

For cassava, four discrete products produced from cassava root harvested from the plantation include (1) starch, (2) dried chip, (3) pellet, and (4) ethanol. Each one is produced using different milling equipment and methods. In ethanol production, the root is shredded and mixed with enzymes and yeast before being brought to the fermentation vessel. After fermentation reaction, alcohol is separated from the reactor effluent, using distillation unit. The slurry after distillation is discharged to anaerobic digester to produce biogas, which is used to generate electricity spent in the mill and/or sold to outside grid. The digester's liquid is finally used for plant watering while the biosolids is used to produce compost materials.

Evaluation of carbon equivalences in ethanol production

The cultivation activities of sugarcane are similar to those of cassava. Tractor is used for tillage, the Nitrogen-Phosphorus-Potassium (N-P-K) fertilizer is applied 2 times per crop, after tilling and 60 days later. Moreover both plants receive natural rain water for their growth, in general. One difference in the cultivation is tilling frequency. For sugarcane, tillage is carried out once per three crop cycles; while it is every year for cassava. In one hectare, average sugarcane and tapioca's yields are found 70.8 and 21.3 tons/ha-y from diesel fuel consumed at the rate of 119.9 and 35.5 L/ha-y, respectively. The application rate of N-P-K fertilizer is 419.7 and 261.7 kg/ha-y for sugarcane and cassava, respectively. For weed control, Paraqout is applied on sugarcane and cassava cultivation fields with the rates of 4.2 and 9.4 kg/ha-y or 0.06 and 0.44 kg/ton harvest, respectively. Alachor, Diuron, and Antracine are used only in sugarcane cultivation at the rate of 3.5, 6.1, and 5.6 kg/ha-y, respectively. Glyphosate is used only in cassava field at the rate of 4.5 kg/ha-y. Carbon emissions were estimated from the amount of materials used and productivity occurring in the cultivation processes. They are summarized in Table 2. The results show that cultivation process emits carbon to the atmosphere at the rate of 475.2±12.7 and 118.1±23.5 kg CE/ha-y for sugarcane and cassava, respectively.

In ethanol production, process chain of each crop is different in the feed material used for fermentation. The ethanol production from cassava employs dried chips as feed, while that from sugarcane does molasses, which is one of by-products from raw sugar crystal production.

From the resources consumed in both cultivation and ethanol productions, all carbon equivalences occurring in ethanol productions from sugarcane and cassava are summarized in Table 3.

In ethanol production from sugarcane, activities ranging from land preparation, crop planting and maintenance, harvest, sugar and ethanol production processes, result in carbon emission of (+) 819.6 kg CE/ha-y. The amount of reduced carbon is found (-) 671.3 kg CE/ha-y. In this reduction, the highest 329.0 kg CE/ha-y is found to be due to ethanol used to replace fossil gasoline. The second highest 252.8 kg CE/ha-y is due to electricity generated from bagasse. From high-strength BOD in wastewater discharged into anaerobic digester, biogas is generated and further used for electricity generation, resulting in carbon reduction of 61.6 kg CE/ha-y. Finally, spent wash –treated effluent– is blended with ash from power plants to produce composting. The quantities of nutrients (N-P-K) contained in compost applied on sugarcane fields are used to calculate carbon reduction of 27.8 kg CE/ha-y. From the emitted carbon minus carbon reduced, results show that the ethanol production from molasses still emits carbon into the atmosphere at the rate of +148.2 kg CE/ha-y.

Table 2. Carbon emissions in cultivation processes

Consumptions	Carbon emissions (kg CE/ha-y)	
	Sugarcane	**Cassava**
Diesel		
Tillage	50.0±21.5	5.8±4.1
Implantation	18.2±16.2	-
Harvest	136.0±44.3	9.2±0.4
Transport	20.6±2.3	0.9±0.4
Fertilizer		
N-fertilizer	176.5±13.2	82.0±72.4
P_2O5-fertilizr	5.2±0.2	5.1±2.1
K_2O fertilizer	3.8±0.4	2.9±1.2
Weed control		
Alachor	7.7±3.5	-
Paraqout	3.7±1.8	8.2±7.4
Diuron	11.7±7.5	-
Antracine	7.7±3.8	-
Glyphosate	-	3.9±1.4
Gasoline		
Chemicals sprayer	34.0±0.1	-
Total	**475.2±12.7**	**118.1±23.5**

In the ethanol production from cassava, the use of BOD to produce biogas for electrical energy production and nutrients recycled from final effluent result in carbon reduction of 348.5 kg CE/ha-y. High consumption of fossil fuel and fossil-based materials such as diesel fuel, electricity, and chemical fertilizers produces carbon emission of (+) 1,155 kg CE/ha-y. Meanwhile carbon reduction from greater amount of ethanol produced from cassava, electricity generated from biogas, and nutrients recycled from final effluent are found to help offset the emissions, resulting in net emission of -596.4 kg CE/ha-y. The negative sign reveals that consumption of cassava-based bioethanol helps reduce carbon emission, thereby contributing to climate change mitigation.

Table 3. Carbon Equivalences in cultivation and ethanol production

Carbon equivalences/Processes	Unit	Quantity (Unit/ha-y)		Carbon equivalences (kg CE/ha-y)	
		Sugarcane	Cassava	Sugarcane	Cassava
1.Carbon fixations					
- Raw sugar crystal	ton	7.4±0.0	-	2,916.0±0.0	-
- Ethanol	L	700.0±0.0	3,000.0±0.0	220.9±0.0	940.5±0.0
2.Carbon emissions					
2.1 Cultivation process					
- Diesel for tillage	L	67.6±20.3	7.8±5.6	50.0±21.5	5.8±4.1
- Diesel for implantation	L	24.6±21.9	-	18.2±16.2	-
- Diesel for harvest	L	12.4±0.5	12.4±0.5	136.0±44.3	9.2±0.4
- Diesel for transport to mill	L	15.3±10.0	15.3±10.0	20.6±2.3	0.9±0.4
- Nitrogen fertilizer [N]	kg	248.6±18.6	115.5±102.0	176.5±13.2	82.0±72.4
- Phosphorus fertilizer [P_2O_5]	kg	74.9±2.2	73.1±30.6	5.2±0.2	5.1±2.1
- Potassium fertilizer [K_2O]	kg	96.2±9.0	73.1±30.6	3.8±0.4	2.9±1.2
- Alachor consumption	kg	3.5±1.6	-	7.7±3.5	-
- Paraqout consumption	kg	4.2±2.0	9.4±8.4	3.7±1.8	8.2±7.4
- Diuron consumption	kg	6.1±3.9	-	11.7±7.5	-
- Antracine consumption	kg	5.6±2.8	-	7.7±3.8	-
- Glyphosate consumption	kg	-	4.5±1.6	-	3.9±1.4
- Gasoline for chemical sprayer	L	56.6±0.1	-	34.0±0.1	-
2.2 Sugar milling process					
- Lime	kg	40.6±9.4	-	8.9±2.1	-
- Polymer	kg	0.4±0.0	-	1.4±0.0	-
- Enzyme/yeast	kg	40.0±6.0	-	97.2±14.6	-
- Electricity	kWh	1,536.0±0.0	-	230.4±0.0	-
- Diesel	L	8.5±0.0	-	6.0±0.1	-
- Water	m^3	50.0±25.0	-	0.4±0.2	-
2.3 Chipping and drying process					
- Electricity for shredding machine	kWh	-	1,480.7±926.0	-	222.1±138.9
- Diesel for turn over root chipped	L	-	936.8±0.0	-	666.1±0.0
2.4 Fermentation process					
- Enzyme/yeast	kg	-	40.0±6.0	-	97.2±14.6
- Sodium hydroxide	kg	-	72.1±0.0	-	48.3±0.0
- Water	m^3	-	44.0±0.0	-	3.5±0.2
3.Carbon reduction					
- Electricity generation from biogas	kWh	410.7±0.0	2,320.0±0.0	61.6±0.0	348.0±0.0
- Electricity generation from bagasse	kWh	1,685.3±0.0	-	252.8±0.0	-
- Nitrogen from composting	kg	33.8±0.0	-	24.0±0.0	-
- Phosphorus from composting	kg	47.1±0.0	1.4±0.0	3.3±0.0	0.1±0.0
- Potassium from composting	kg	12.5±0.0	10.0±0.0	0.5±0.0	0.4±0.0
- Ethanol	L	700.0±0.0	3,000.0±0.0	329.0±0.0	1,400.6±0.0
4.Total Carbon emissions (+) [2.1+2.2+2.3+2.4]				**819.6±8.3**	**1,155.2±22.8**
5.Total carbon reductions (-) [3]				**671.3±0.0**	**1,751.6±0.0**
Total carbon fixation [(1)]				**3,136.9±0.0**	**940.5±0.0**
Net carbon emission [(4) + (5)]				**(+) 148.2**	**(-) 596.4**

4. CONCLUSION

From average yields of sugarcane (70.8 tons/ha-y) and cassava root (21.3 tons/ha-y), bioethanol can be produced of 700 and 3,000 L/ha-y, respectively. Carbon equivalences occurring in the cultivation, milling, and fermentation are estimated from energy and materials used in the processes. The cultivations of sugarcane and cassava were found to emit 475.2±12.7 and 118.1±23.5 kg CE/ha-y, respectively.

Overall, from cultivation to ethanol production, cassava is found to help reduce carbon emission at the rate of 0.20 kg CE/L ethanol or equivalent to the reduction flux of 596.4 kg CE/ha-y. In molasses-based ethanol production, net emission is found 0.21 kg CE/L ethanol, which is equivalent to the emission flux of 148.2 kg CE/ha-y. Findings found in this study suggest that molasses-based ethanol production process, at present, be renovated so to minimize emission as to help alleviate global warming.

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