CHAPTER 4

RESULTS AND DISCUSSION

This chapter discusses the study results which will be presented in the following order: 1) the data from the literature and GIS concerning the selected areas for the field data collection, 2) carbon footprints of sugarcane-based and cassava-based bioethanol, 3) water footprints of sugarcane, cassava, sugarcane-based and cassava-based bioethanol, and 4) scenario analysis.

4.1 The data from the literature and GIS concerning the selected areas for the filed data collection

4.1.1 Harvested areas, products and yields of sugarcane and cassava

According to the 2008-2012 statistical data from Thailand’s Office of Agricultural Economics, Ministry of Agriculture and Cooperatives (2011), the harvested areas, products and yields of sugarcane and cassava in northern Thailand are as shown in Table 4.1.

The harvested area of sugarcane in northern Thailand covered 12 provinces with a total harvested area of 307,668 ha/year. Total sugarcane production was 23,574,225 ton/year and average yield was 68.85 ton/ha. For cassava, the harvested area covered 13 provinces with a total harvested area of 219,305 ha/year. Total production was 4,420,865 ton/year and average yield was 19.47 ton/ha.

Table 4.1 Harvested areas, production and yields of sugarcane and cassava.

Province	Sugarcane			Cassava		
	Harvested area (ha)	Production (ton/year)	Yield (ton/ha)	Harvested area (ha)	Production (ton/year)	Yield (ton/ha)
Chiang Rai	0	0	0	2,224	43,029	19.17
Phayao	0	0	0	836	16,645	19.55
Lampang	5,230	258,093	49.29	313	5,694	17.92
Chiang Mai	401	22,602	56.29	0	0	0
Tak	1,422	86,423	60.80	4,228	89,740	20.69
Kamphaeng Phet	65,439	5,170,994	78.99	87,254	1,772,127	20.39
Sukhothai	25,485	1,777,301	69.48	2,566	48,424	19.28
Phrae	325	21,807	67.08	320	5,960	18.50
Uttaradit	14,657	1,029,488	70.10	2,645	48,528	18.45
Phitsanulok	20,954	1,477,655	70.41	28,461	596,412	20.94
Phichit	7,467	514,285	68.63	726	14,128	19.45
Nakhon Sawan	90,287	7,246,550	79.95	47,142	949,416	20.18
Uthai Thani	35,856	2,703,343	74.48	30,809	607,747	19.50
Phetchabun	40,145	3,265,684	80.64	11,781	223,015	19.10
Average	25,639	1,964,519	68.85	16,870	340,067	19.47

Source: The Office of Agricultural Economics, 2011

4.1.2 The study of harvested areas of sugarcane and cassava by geological information system

With the land use information in northern Thailand in 2008 and the information of soil series with the overlay analysis by GIS, the density of the spread of sugarcane and cassava harvested areas as well as the soil series information of each area can be determined.

From Figure 4.1, the most densely harvested areas of sugarcane in northern Thailand in descending order are the provinces of Nakorn Sawan, Kamphaengphet, Sukhothai, Utaithani, Petchaboon, Lampang, Uttraradit and Phichit. The other provinces have few densely harvested areas of sugarcane, so they are not suitable to be used as the information in choosing the study area. However, when the overlay analysis of sugarcane harvested areas and soil series was performed, it was found that most of the sugarcane harvested areas are in highlands. Nevertheless, in some provinces, such as Nakorn Sawan, Sukhothai and Phichit, the sugarcane harvested areas are rice fields with poor draining system. The soil series in most of the harvested areas have shallow soil surface with good draining. The soil texture is sandy, gray and light brown. The subsoil is sandy loams or sandy clay with pH 5.5-7.0. The soil series information for the provinces with many harvested areas is shown in Appendix A.

The densely harvested areas of cassava in descending order are the provinces of Kampaengpetch, Nakorn Sawan, Utaithani, Petchaboon, Uttraradit, Sukhothai and Chiang Rai, as presented in Figure 4.1. The remaining provinces show few densely harvested areas and thus are excluded in choosing the study area. The overlay analysis of cassava harvested areas and soil series reveals that most of the sugarcane harvested areas are in highlands and that the soil series in most of the harvested areas have shallow soil surface with good draining. The soil texture is sandy, gray and light brown. The subsoil is sandy loams or sandy clay with pH 5.5-7.0. The soil series information for the provinces with many harvested areas of cassava is presented in Appendix A.

4.1.3 General survey data of sugarcane and cassava plantations in northern Thailand

From the data of harvested areas and the spread of the areas, this research study has selected 3 provinces, i.e. Nakorn Sawan, Kampaengpetch and Utai Thani, for field data collection. The data in this study were collected by field surveys and interviews during the 2011 crop year. A total of 1,200 questionnaires were used in the interview whereby 600 each of sugarcane growers and cassava growers were interviewed with the questionnaire. The summary of important survey data is presented in Appendix B. The questionnaire results show the total growing areas of sugarcane and cassava in this region of 122,450 ha and 73,638 ha, respectively. With respect to sugarcane, it was planted during January and February, and the sugarcane growers used tractors to prepare soil by which diesel fuel of 15.93 ± 6.07 L/ha was used (mean ± standard deviation from the 600 sugarcane respondents).

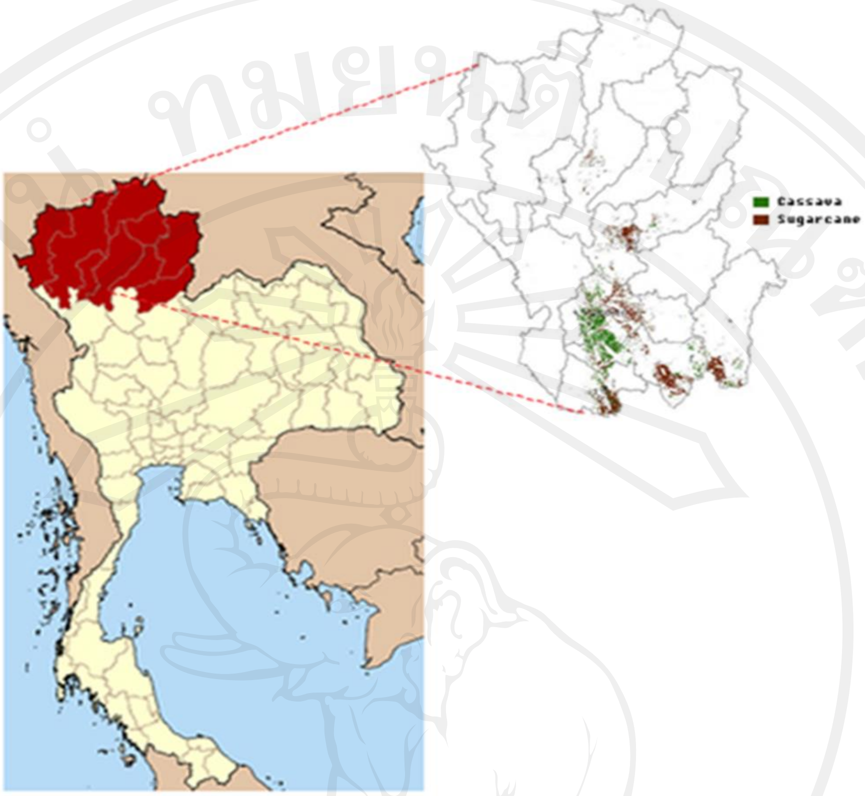


Figure 4.1 The density of the spread of sugarcane and cassava harvested areas in northern Thailand.

Diesel for planting, harvesting and transport to truck were 13.46 ± 6.97 L/ha, 12.31 ± 5.00 L/ha and 14.05 ± 5.28 L/ha, respectively. Applications of fertilizers during the period of land preparation were 76.68 ± 45.27 kg N/ha, 36.23 ± 32.84 kg P /ha and 39.55 ± 38.07 kg K/ha while those during crop maintenance were 69.71 ± 47.96 kg N/ha, 40.20 ± 35.65 kg P/ha, 50.51 ± 41.86 kg K/ha. Herbicide use to control weeds or inhibit their normal growth was 8.09 ± 5.72 kg/ha. A majority of the sugarcane growers in the survey were found to rely mainly on precipitation. Typically, sugarcane was harvested in October to November with the average yield of 78.91 ± 14.53 ton/ha. In addition, the interviews reveal that the sugarcane growers in this region practiced both burning and un-burning pre-harvests.

In this region, cassava was planted during March and April and harvested the following year during February and March. The cassava growers used tractors for plowing, the practice which required diesel fuel of 18.00 ± 7.29 L/ha. Diesel fuels for harvesting and transport to truck were 17.41 ± 6.60 L/ha and 9.47 ± 6.35 L/ha. Applications of fertilizers during the period of land preparation were 61.86 ± 42.09 kg N/ha, 31.04 ± 29.22 kg P/ha and 33.71 ± 30.80 kg K/ha, and those during crop maintenance were 56.26 ± 38.17 kg N/ha, 39.27 ± 34.58 kg P/ha, 41.61 ± 36.47 kg K/ha. Herbicides use to get rid of weeds or inhibit their normal growth was 17.42 ± 12.18 kg/ha. Like the sugarcane growers, most of the cassava growers in this region depended heavily on precipitation. The average yield was 22.90 ± 6.62 ton/ha.

4.2 Carbon footprint

4.2.1 Data collection results

4.2.1.1 Sugarcane-based bioethanol

The life cycle of sugarcane–based bioethanol production encompasses sugarcane cultivation, sugar milling, bioethanol production and transportation as shown in Figure 4.2. The results from LCI data collection in each process are as follows:

i) Cultivation of sugarcane

The study of sugarcane (sugarcane virgin) cultivation process covers land preparation, planting, crop maintenance and harvesting. The data on the use of important resources, such as fuel oil, chemical fertilizers, chemical substances and water, are collected. The questionnaire results are calculated for the weighted means, which subsequently are used as the average for northern Thailand in this study. The inventory data per 1 hectare of sugarcane cultivation are presented in Table 4.2.

In Table 4.2 are weighted averages of data from the questionnaires. The cultivation phase was subdivided into two basic processes: use of agrochemicals and of machinery. In the case of sugarcane, the data on fertilizer use from the field surveys show that the sugarcane growers used a variety of chemical fertilizers which were applied 2 – 3 times throughout the entire crop year. The types of chemical fertilizers applied as the composite formula varied, ranging from high to low nitrogen contents of 46-0-0, 27-8-8, 27-12-6, 25-7-7, 21-7-18, 16-8-8, 16-20-0, 16-8-16, 15-15-15, 15-7-18, 15-7-7, 13-13-27 and 6-3-3, and the LCI data expressed in terms of N-P-K were 170 kg N/ha, 101.88 kg P/ha and 126.25 kg K/ha. The herbicide used was paraquat (5.44 kg/ha) or ametryn (4.19 kg/ha). The machinery phase included the use of all machinery in the field from planting to harvesting. The total diesel fuel used was 63.44 L/ha, and the average yield of sugarcane in this region was 78,912.50 kg /ha. For sugarcane tops and leaves, the growers would adopt either the burning or un-burning practice, the products of which are used as natural fertilizers.

Table 4.2 The inventory data for 1 hectare of sugarcane cultivation.

Activity	Unit	Quantity
Input		
Fertilizers		
N	kg	170.00
P	kg	101.88
K	kg	126.25
Herbicides		
Paraquat	kg	5.44
Ametine	kg	4.19
Diesel	L	63.44
Output		
Sugarcane	kg	78912.50
Tops and leaves	kg	22095.50

ii) The transportation of sugarcane to sugar milling

Transportation data collected consist of the sources of sugarcane, distance, type of truck and weight of truck. This research has gathered the primary data of sugarcane transportation from the agriculturists in the three provinces and from sampled sugar factories. However, in CF calculation, only the data from the sampled sugar factories are considered.

iii) Sugar milling (molasses generation)

The survey on the production of primary materials to be used as the raw materials by bioethanol factories requires collection of sugar milling data in order to find CF from molasses generation. The research covers sugarcane acquisition (sugarcane is divided into two types: burned and unburned sugarcane) to enter the milling, filtering, evaporation, crystallization and centrifugation processes. It also considers support systems, e.g. the production of soft water, water, steam, electricity, and waste management.

This study collects the primary data from two sugar factories, i.e. factory S1 and factory S2. The data are used in finding the weighted mean for this study. The inventory data for 1 kg of molasses are presented in Table 4.3. Since molasses is a by-product of sugar production, GHG emission from sugar production processes is the total emission for sugar and molasses production. According to the LCA principle, for any production processes that give more than one product, or in the other words, have any by-products that can be used for other purposes, the allocation is required. In this research, the allocation by mass and economic value as shown in Table 4.4 has been conducted.

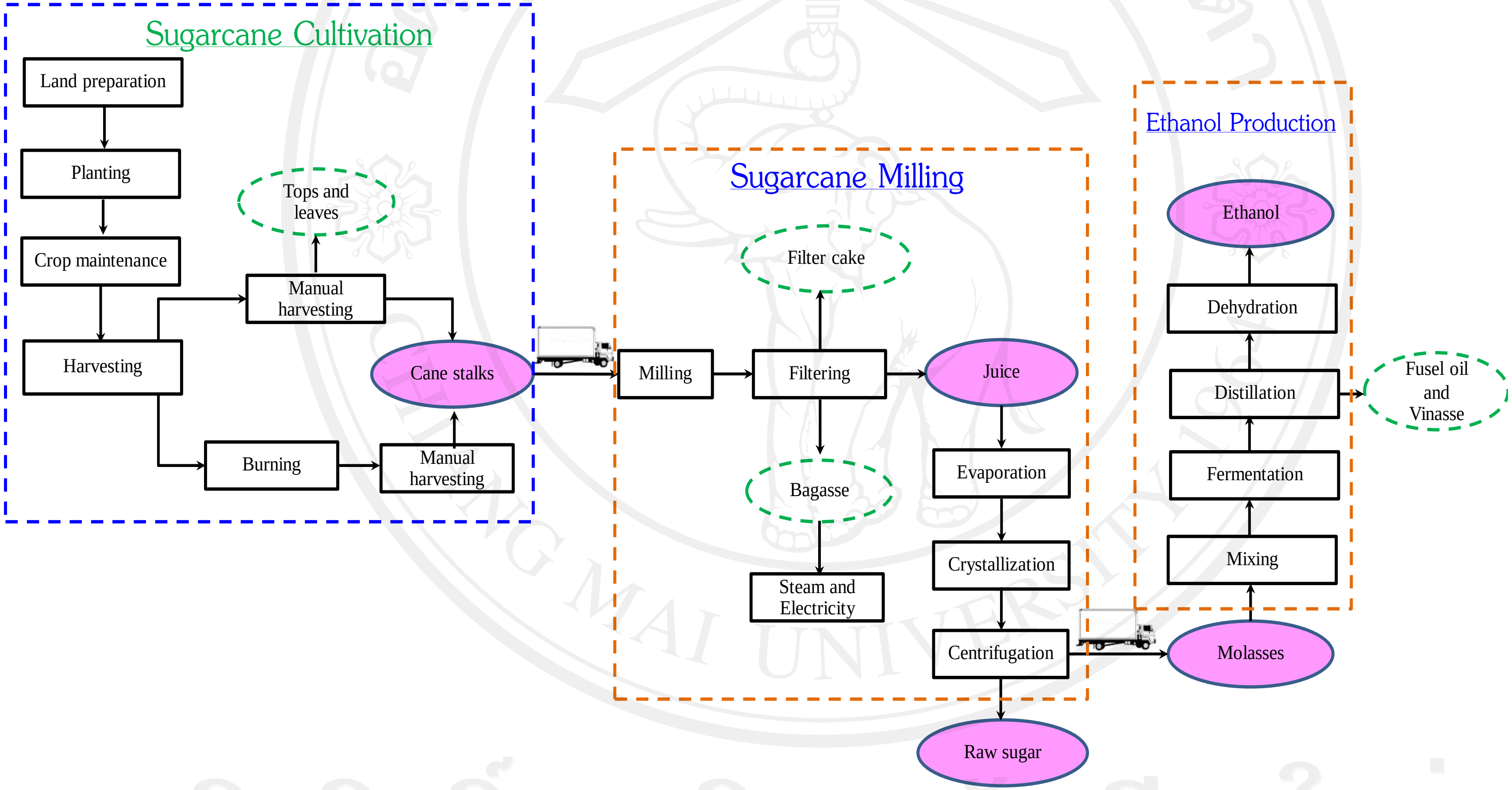


Figure 4.2 The life cycle of sugarcane-based bioethanol.

Table 4.3 The inventory data for 1 kilogram of molasses.

Activity	Unit	Quantity
Input		
Unburned sugarcane	kg	9.0366
Burned sugarcane	kg	13.9503
Calcium hydroxide	kg	0.0371
Biocide	kg	0.0001
Precipitating agents	kg	0.0001
Sanitizer	kg	0.00002
Waterlock	kg	0.0001
Scale inhibitor	kg	0.0004
Enzyme (Amylase)	kg	0.0002
Sodium hydroxide	kg	0.0040
Butanedioic Acid	kg	0.00002
Water	L	2.3440
Steam	kg	6.3311
Electricity	kWh	0.2668
Diesel	L	0.00002
Output		
Molasses	kg	1.0000
Bagasse	kg	6.8604
Sugar	kg	2.7234
Filter cake	kg	0.9377
Waste water	L	2.3440

Table 4.4 Allocation by economics of sugar and molasses.

Activity	Value (Bath/kg)	Quantity (kg)	Allocation by mass (%)	Allocation by economics (%)
Sugar	12.91	2.7234	73	92
Molasses	2.95	1.0000	27	8
Total		3.7234	100	100

Table 4.4 shows the molasses acquisitions allocated by mass and economic value of 27% and 8% of the total. Thus, when calculating GHG emission from sugar production, the allocation to molasses 27% and 8% of the total for allocation by mass and economic value must be applied.

iv) The transportation of molasses to bioethanol factory

As this study does not have the data of the molasses transportation from sugar factory to bioethanol factory, the calculation will use, if there are no transportation data specified in the National Guideline of Carbon Footprint of Product, a 32-ton 22-wheeled semi-trailer with the transporting distance of 700 kilometers back and forth. The departing trip is calculated as the transportation of all products and the return trip is calculated as the empty trailer.

v) Bioethanol production

The study of bioethanol production processes covers mixing, fermentation, distillation and dehydration. The data collected from this study include primary and secondary data. The primary data are from a factory and the secondary data are from Thai language public journals and technical reports which collect inventory data per 1 liter of sugarcane-based bioethanol as shown in Table 4.5.

Table 4.5 The inventory data for 1 liter of sugarcane-based bioethanol.

Activity	Unit	Quantity
Input		
Molasses	kg	4.2553
Yeast	L	0.00003
Phosphoric acid	kg	0.00004
Ammonium sulfate	kg	0.0012
Diammonium sulfate	kg	0.00001
Sulfuric acid	kg	0.0132
Water	m^3	0.0101
Steam	ton	0.0029
Electricity	kWh	0.3095

Table 4.5 (Continued)

Activity	Unit	Quantity
Output		
Ethanol	L	1.0000
Vinasse	m^3	0.0116
Fusel oil	kg	0.0004

4.2.1.2 Cassava-based bioethanol

The life cycle of cassava–based bioethanol production encompasses cassava cultivation, cassava processing and bioethanol production as shown in Figure 4.3.

i) Cultivation of cassava

The study of cassava cultivation covers land preparation, planting, crop maintenance and harvesting. The data collection has been undertaken on use of major resources such as fuel oil, chemical fertilizers, chemical substances and water. The data are used to compute the weighted means of northern Thailand for this study. The inventory data for 1 hectare of cassava are presented in Table 4.6.In the case of cassava, the data on fertilizer use from the field indicate that the cassava growers applied a variety of chemical fertilizers to their plantations. The growers typically applied the chemical fertilizers 1 – 2 times throughout the entire crop year. The types of chemical fertilizers applied as the composite formula varied, ranging from high to low nitrogen contents of 46-0-0, 27-12-6, 27-12-8, 26-20-20, 21-4-21, 16-8-8, 16-8-16, 16-20-0, 16-16-8, 15-15-15, 15-7-18, 15-15-22, 10-0-60, 6-3-3, and 0-0-60. The LCI data expressed in terms of N-P-K were 160.00 kg N/ha, 125.63 kg P/ha, and 131.25 kg K/ha. The herbicide use was paraquat (7.94 kg /ha) or glyphosate (7.00 kg /ha). The machinery phase included the use all machinery in the field from planting to harvesting, and the total consumption of diesel fuel was 45.63 L/ha. The average yield of cassava in this region was 22,906.25 kg/ha, while cassava leaves and other remaining parts after harvest are used as natural fertilizers.

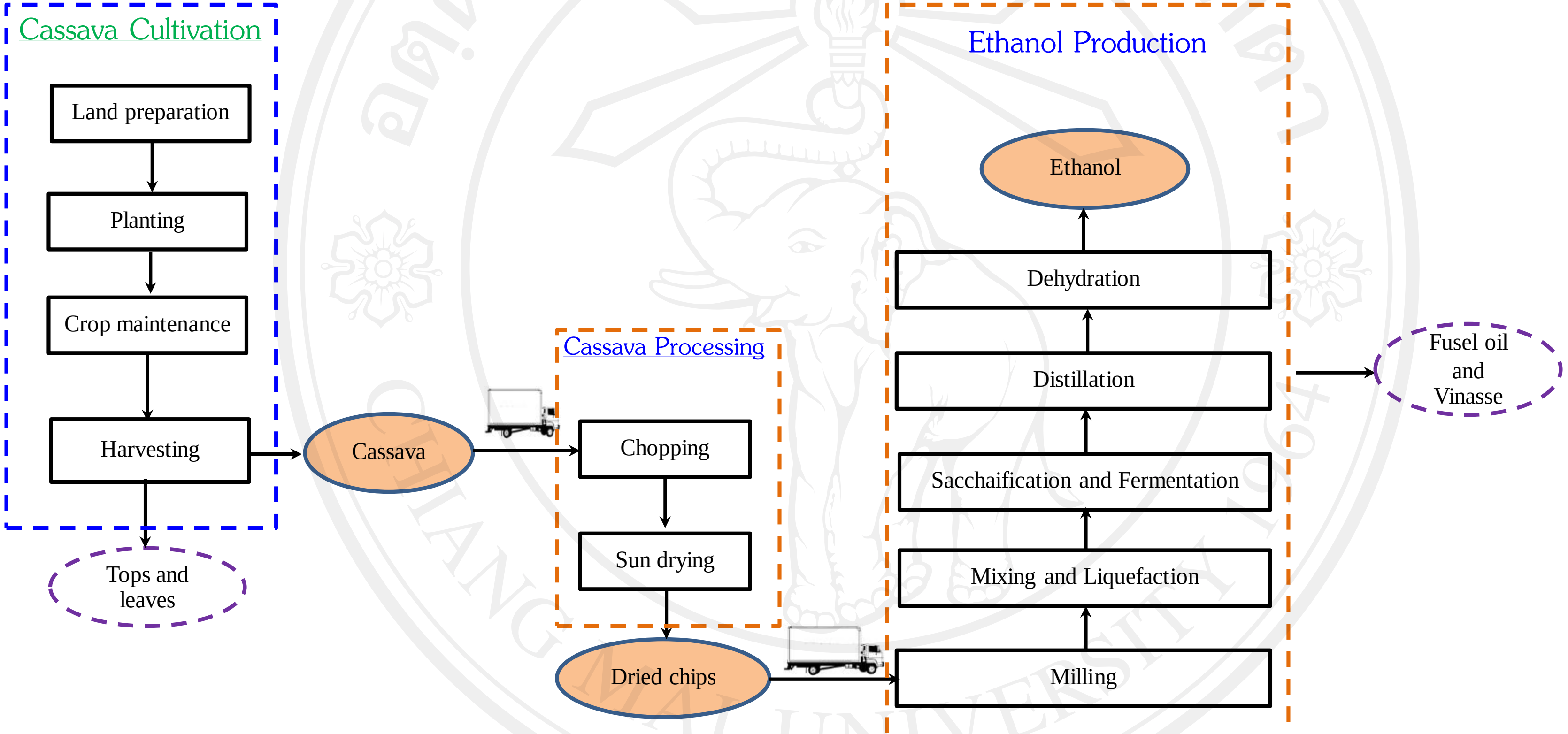


Figure 4.3 The life cycle of cassava-based ethanol bioethanol

Table 4.6 The inventory data for 1 hectare of cassava cultivation.

Activity	Unit	Quantity
Input		
Fertilizers		
N	kg	160.00
P	kg	125.63
K	kg	131.25
Herbicides		
Paraquat	kg	7.94
Ametine	kg	7.00
Diesel	L	45.63
Output		
Cassava	kg	22,906.25

ii) The transportation of cassava to cassava processing

In this study, since no data on transporting cassava from the field to cassava processing exist, the calculation will be based on, if there are no transportation data specified in the National Guideline of Carbon Footprint of Product, a 32-ton, 22-wheeled semi-trailer with the transporting distance of 700 kilometers back and forth. The departing trip is calculated as the transportation of all products and the return trip is calculated as the empty trailer.

iii) Cassava processing and bioethanol production

The data collection of cassava processing and bioethanol production is undertaken at a bioethanol factory. The collection of the data starts from transportation of cassava from the field to the chopping and sun drying process, the latter of which gives dried chips which are the raw materials to be sent to bioethanol factory. The production processes include milling and mixing, liquefaction, fermentation, distillation, and dehydration. The inventory data of important inputs/outputs of 1 liter of cassava-based bioethanol are depicted in Table 4.7.

Table 4.7 The inventory data for 1 liter of cassava-based bioethanol.

Activity	Unit	Quantity
Input		
Fresh cassava	kg	7.6091
Enzyme (Amylase)	kg	0.0004
Sodium hydroxide	kg	0.0085
Yeast	kg	0.0008
Diesel	L	0.0133
Steam	ton	0.0034
Soft water	m^3	0.0101
Electricity	kWh	0.4441
Output		
Ethanol	L	1.0000
Vinasse	m^3	0.0100
Fusel Oil	kg	0.0040

4.2.2 Carbon footprint calculations and interpretation

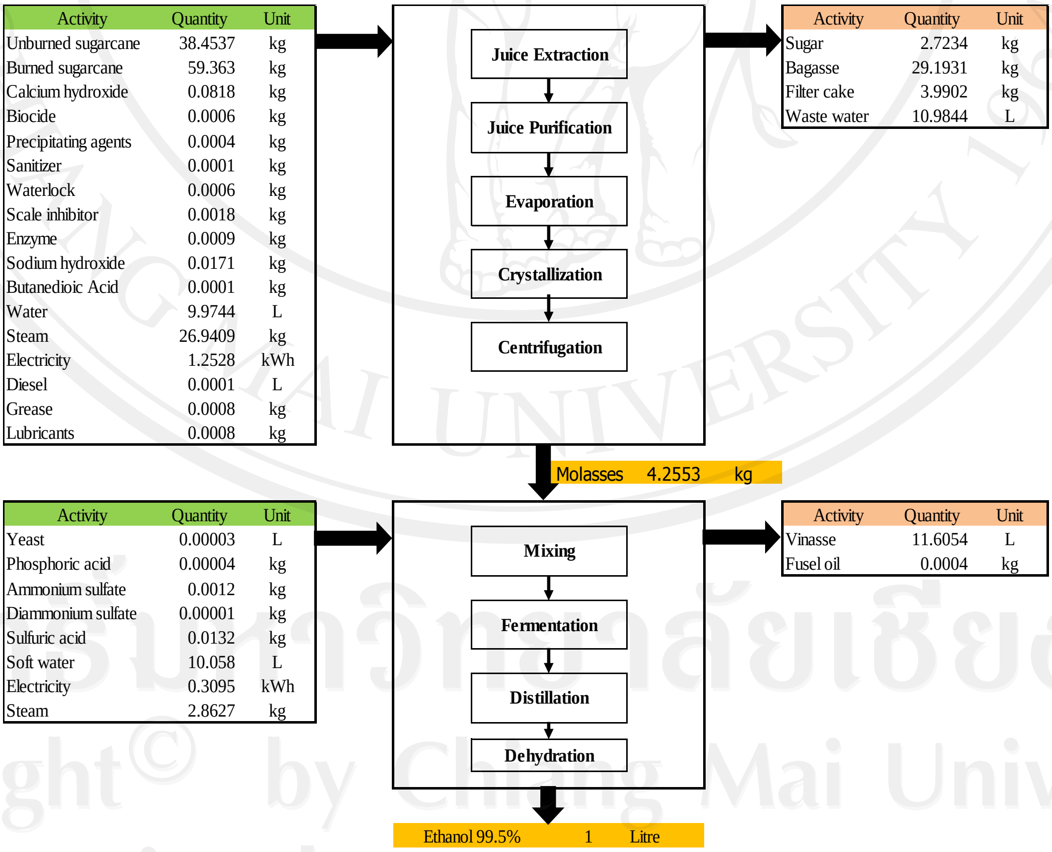
Normally, LCI data received from data collection will be in two separate sections: agricultural section and production process section. The data will be converted to mass and energy balances per functional unit before using in calculating CF of interested product by considering GHG emission in carbon dioxide equivalent per functional unit. In this study, it can be concluded that:

4.2.2.1 Sugarcane-based bioethanol

The calculation of CF of sugarcane-based bioethanol starts from converting data of raw materials, resources and energy use to mass balance per 1 liter of bioethanol as shown in Figure 4.4. Then, it is multiplied by the emission factor of each activity data. CF is the sum of GHG emission of every activity. In this study, GHG emissions of sugarcane cultivation, sugar milling and bioethanol production will be considered.

The assessment of GHG emission of sugarcane cultivation is based on 1 kilogram of sugarcane. Therefore, the data in Table 4.2 will be converted to mass balance so that the value can be multiplied by the emission factor of each activity data in Table 3.3. This will give GHG emissions for 1 kilogram of unburned and burned sugarcane, the values of which are respectively shown in Tables 4.8 and 4.9, which can be used as emission factors for CF calculation.

The calculation of GHG emission for 1 liter of sugarcane-based bioethanol can be divided into two parts. The first part is raw material, energy and resource acquisition. The calculations of allocation by mass and economic value are presented in Appendix C. The second part is raw material, energy and resource transportation from the sources to producers. In this case, the calculation of GHG emission of transportation will use distance. The emission factor used is from TGO (2013). The calculation is again presented in Appendix C.



Activity	Quantity	Unit
Unburned sugarcane	38.4537	kg
Burned sugarcane	59.363	kg
Calcium hydroxide	0.0818	kg
Biocide	0.0006	kg
Precipitating agents	0.0004	kg
Sanitizer	0.0001	kg
Waterlock	0.0006	kg
Scale inhibitor	0.0018	kg
Enzyme	0.0009	kg
Sodium hydroxide	0.0171	kg
Butanedioic Acid	0.0001	kg
Water	9.9744	L
Steam	26.9409	kg
Electricity	1.2528	kWh
Diesel	0.0001	L
Grease	0.0008	kg
Lubricants	0.0008	kg

Activity	Quantity	Unit
Sugar	2.7234	kg
Bagasse	29.1931	kg
Filter cake	3.9902	kg
Waste water	10.9844	L

Activity	Quantity	Unit
Yeast	0.00003	L
Phosphoric acid	0.00004	kg
Ammonium sulfate	0.0012	kg
Diammonium sulfate	0.00001	kg
Sulfuric acid	0.0132	kg
Soft water	10.058	L
Electricity	0.3095	kWh
Steam	2.8627	kg

Activity	Quantity	Unit
Vinasse	11.6054	L
Fusel oil	0.0004	kg

Figure 4.4 Mass balance of 1 liter of sugarcane-based bioethanol.

Table 4.8 GHG emission of 1 kilogram of unburned sugarcane.

Activity	Unit	Quantity (per FU)	GHG emissions ($kgCO_2e$)
Fertilizers			
N	kg	0.0022	0.0056
N_2O direct from fertilizer use	kg	0.0022	0.0101
P	kg	0.0013	0.0003
K	kg	0.0016	0.0003
Herbicides			
Paraquat	kg	0.0001	0.0002
Ametine	kg	0.0001	0.0005
Diesel (Production)	kg	0.0007	0.0002
Diesel (combustion)	L	0.0008	0.0022
		Total	**0.0194**

Table 4.9 GHG emission of 1 kilogram of burned sugarcane.

Activity	Unit	Quantity (per FU)	GHG emissions ($kgCO_2eq$)
Fertilizers			
N	kg	0.0022	0.0056
N_2O direct from fertilizer use	kg	0.0022	0.0101
P	kg	0.0013	0.0003
K	kg	0.0016	0.0003
Herbicides		0.0000	
Paraquat	kg	0.0001	0.0002
Glyphosate	kg	0.0001	0.0005
Diesel (Production)	kg	0.0007	0.0002
Diesel (Combustion)	L	0.0008	0.0022
Top and leaves burning	kg	0.2800	0.0377
		Total	**0.0571**

As shown in Table 4.10, the sum of CFs of 1 liter of sugarcane-based bioethanol allocated by mass, in light of the B2B assessment scope, is 3.21 kgCO$_2$-eq, while that by economics is 1.62 kgCO$_2$-eq (Table 4.11).

Table 4.10 Carbon footprint results for 1 liter of sugarcane-based bioethanol (Allocation by mass)

Life cycle stage	GHG emission of raw material, energy and resource acquisition and utilization (kgCO$_{2\ eq.}$)	GHG emission of raw material, energy and resource transportation (kgCO2 eq.)	Total (kgCO2 eq.)	Percentage
Raw materials acquisition	1.2751	1.0773	*2.3524*	*73.2584*
Manufacturing	*0.8587*	*0.0000*	*0.8587*	*22.7416*
Total	***2.13***	***1.08***	***3.21***	***100.00***

Table 4.11 Carbon footprint results for 1 liter of sugarcane-based bioethanol (Allocation by economics)

Life cycle stage	GHG emission of raw material, energy and resource acquisition and utilization (kgCO$_{2\ eq.}$)	GHG emission of raw material, energy and resource transportation (kgCO2 eq.)	Total (kgCO2 eq.)	Percentage
Raw materials acquisition	*0.3813*	*0.3763*	*0.7576*	*46.7654*
Manufacturing	*0.8587*	*0.0000*	*0.8587*	*53.2346*
Total	***1.24***	***0.38***	***1.62***	***100.00***

The analysis result of CF of sugarcane-based bioethanol shows that the raw material, energy and resource acquisition process produces the highest GHG emissions. In comparing between the CFs of allocation by mass and economics, it was found that the allocation by mass has higher GHG emission. When considering the acquisition and the utilization of raw materials, energy and resources, most of the GHG emission is caused by burned sugarcane (more than 70%), followed by unburned sugarcane (more than 15%). For GHG emission from manufacturing, it was found that the production of steam gives out the highest GHG at 78%, followed by that of electricity at 22% of total CF.

4.2.2.2 Cassava-based bioethanol

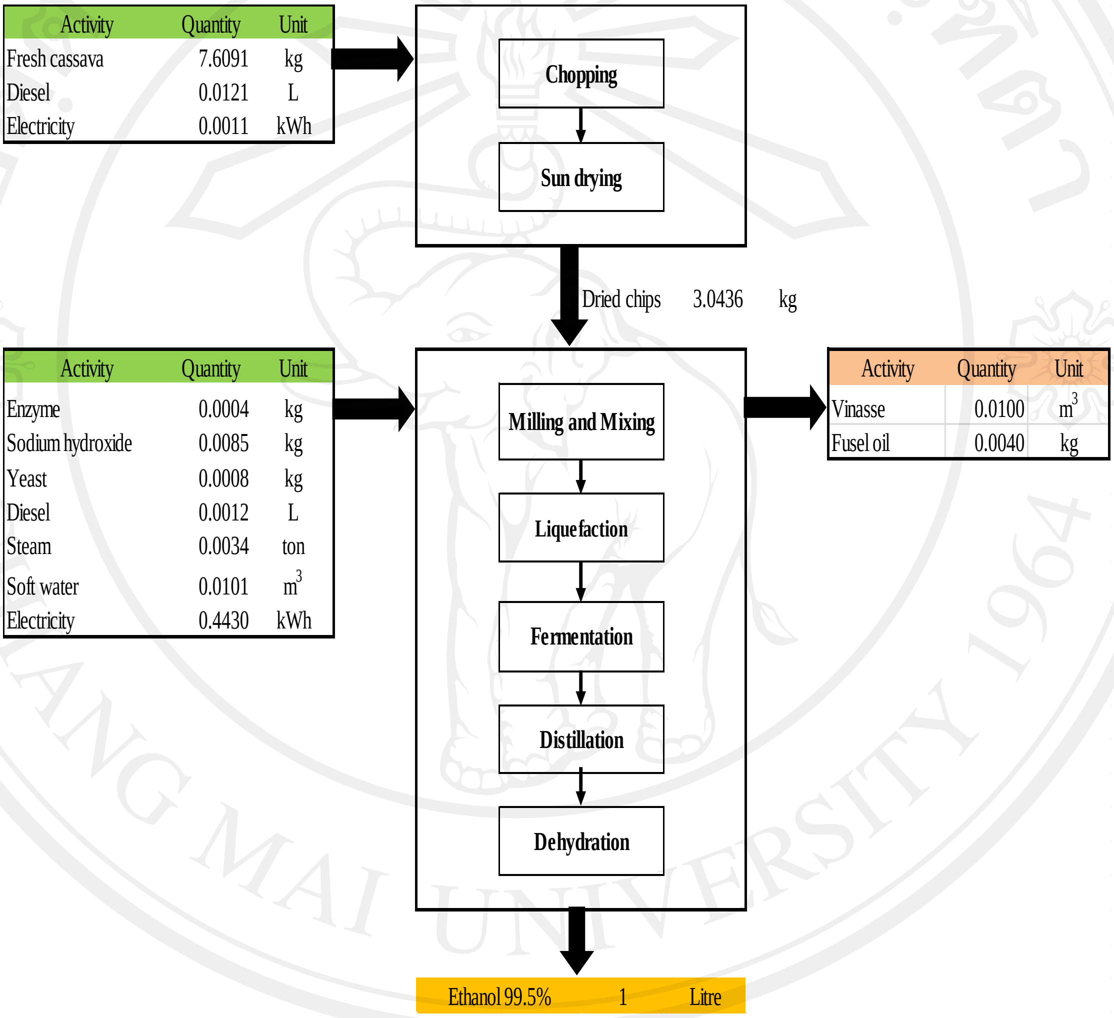
The calculation of CF of cassava-based bioethanol starts from converting data of raw materials, resources and energy use to mass balance per 1 liter of bioethanol. Then, it is multiplied by the emission factor of each activity data. CF is the sum of GHG emission of every activity. In this study, GHG emissions of cassava cultivation, dried chips processing and bioethanol production will be considered.

The assessment of GHG emission of cassava cultivation is based on 1 kilogram of cassava. Therefore, the data in Table 4.6 will be converted to mass balance so that the value can be multiplied by the emission factor of each activity data in Table 3.3. This will give GHG emission for 1 kilogram of cassava as shown in Table 4.12.

The data collected will be converted to mass balance as in Figure 4.5 so that it can be used in calculating GHG emission for 1 liter of cassava-based bioethanol. The data are divided into 2 parts. The first part is raw material, energy and resource acquisition. The second part is raw material, energy and resource transportation from the sources to producers. The calculation is shown in Appendix C. In this case, the calculation of GHG emission of transportation will use distance. The emission factor used is from TGO (2013). The calculation is presented in Appendix C.

Therefore, the sum of CFs of 1 liter of cassava-based bioethanol, given the B2B assessment scope, is 1.02 kgCO_2-eq. The assessment results of each process in the life cycle are shown in Table 4.13 and Figure 4.6.

The results of CF analysis of cassava-based bioethanol show that raw material acquisition has the highest GHG emissions. When comparing raw material, energy and resource acquisition and utilization with raw material, energy and resource transportation, it was found that the acquisition and utilization has higher GHG emission. Most of the GHG emission is from cassava cultivation process, 90.90% of 0.5451 $kgCO_2eq$. For the GHG emission of manufacturing, it was found that electricity has the highest, 86.65% of 0.3115 kgCO2eq.



Activity	Quantity	Unit
Fresh cassava	7.6091	kg
Diesel	0.0121	L
Electricity	0.0011	kWh

Activity	Quantity	Unit
Enzyme	0.0004	kg
Sodium hydroxide	0.0085	kg
Yeast	0.0008	kg
Diesel	0.0012	L
Steam	0.0034	ton
Soft water	0.0101	m^3
Electricity	0.4430	kWh

Activity	Quantity	Unit
Vinasse	0.0100	m^3
Fusel oil	0.0040	kg

Figure 4.5 Mass balance of 1 liter of cassava-based bioethanol.

Table 4.12 GHG emission of 1 kilogram of cassava.

Activity	Unit	Quantity (per FU)	GHG emissions ($kgCO_2e$)
Fertilizers			
N	kg	0.0070	0.0182
N_2O direct from fertilizer use	kg	0.0070	0.0327
P	kg	0.0055	0.0014
K	kg	0.0057	0.0009
Herbicides			
Paraquat	kg	0.0003	0.0011
Glyphosate	kg	0.0003	0.0049
Diesel (Production)	kg	0.0017	0.0005
Diesel (Combustion)	L	0.0020	0.0054
		Total	**0.0651**

Table 4.13 Carbon footprint results for 1 liter of cassava-based bioethanol

Life cycle stage	GHG emission of raw material, energy and resource acquisition and utilization ($kgCO_2$ eq.)	GHG emission of raw material, energy and resource transportation (kgCO2 eq.)	Total (kgCO2 eq.)	Percentage
Raw materials acquisition	*0.5451*	*0.1650*	*0.7101*	*69.51*
Manufacturing	*0.3115*	*0.0000*	*0.3115*	*30.49*
Total	***0.86***	***0.17***	***1.02***	***100.00***

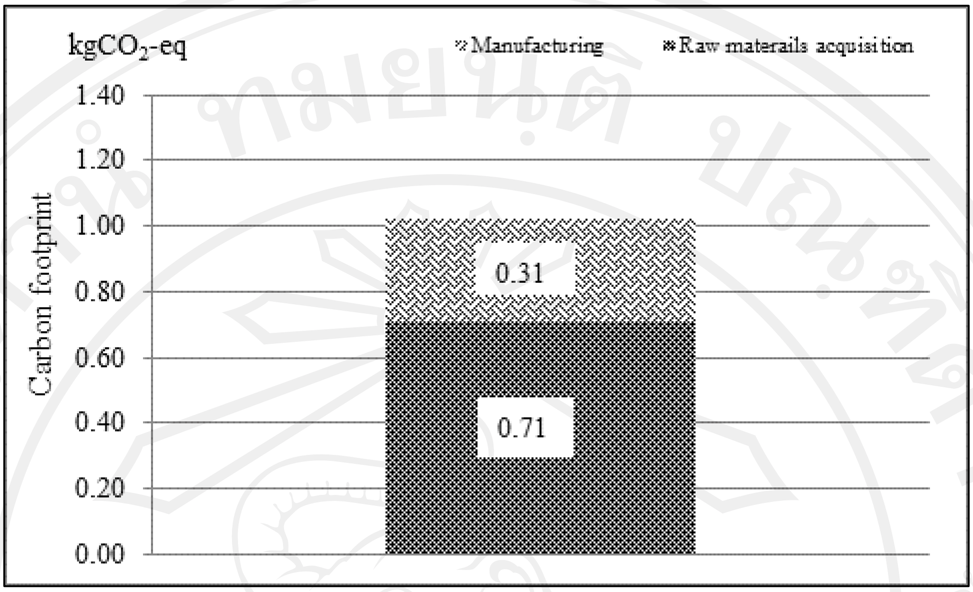


Figure 4.6 CF calculation results during the life cycle of cassava-based bioethanol

4.3 Water footprint

4.3.1 The green and blue evapotranspiration of sugarcane and cassava

From the field surveys and interviews with the growers, it was found that they relied chiefly on rain water for their sugarcane and cassava cultivation. Rain-fed conditions can be simulated with the model by choosing to apply no irrigation. In the rain-fed scenario, the ET_{green} is equal to the total evapotranspiration as simulated by the model and the ET_{blue} is zero. The results are shown in Table 4.14 for sugarcane and cassava in northern Thailand. Figures 4.7 and 4.8 show yield production under rain-fed condition for sugarcane and cassava respectively in which evapotranspiration, total rainfall, and effective rainfall (ET_a) are the results from running the CROPWAT model while yield is from Table 4. In the case of sugarcane, the effective rainfall of all the provinces was sufficient for growth except in Phare and Pichit provinces, while in the case of cassava the effective rainfall of all the provinces was insufficient for cassava growth due to lower rain use efficiency. The rain use efficiency is subject to climatic factors, crop characteristics and soil conditions. However, under the rain-fed condition, water stress will adversely affect crop growth and ultimately crop yield. As water stress is a factor limiting yield production, irrigation programming is essential in order to maximize production per cubic meter of irrigation water. The effects of the magnitude and the timing of water deficit on crop growth and yield are of major importance in scheduling available but limited water supply over growing periods of the crops and in determining the priority of water supply among crops during the growing season, and thereby the efficient irrigation schedule is one way of maximizing water use efficiency.

Table 4.14 The ET_a, ET_{green} and ET_{blue} of sugarcane and cassava.

Province	**Sugarcane**			**Cassava**		
	ET_a	**ET_{green}**	**ET_{blue}**	**ET_a**	**ET_{green}**	**ET_{blue}**
	mm/growing period			**mm/growing period**		
Chiang Rai	-	-	-	578.0	578.0	0
Phayao	-	-	-	592.8	592.8	0
Lampang	1,006.5	1,006.5	0	491.4	491.4	0
Chiang Mai	988.8	988.8	0	-	-	-
Tak	1,002.0	1,002.0	0	569.5	569.5	0
Kamphaeng Phet	1,073.0	1,073.0	0	551.4	551.4	0
Sukhothai	1,130.7	1,130.7	0	568.3	568.3	0
Phrae	1,042.5	1,042.5	0	604.0	604.0	0
Uttaradit	1,076.4	1,076.4	0	526.7	526.7	0
Phitsanulok	974.9	974.9	0	552.6	552.6	0
Phichit	1,035.7	1,035.7	0	513.4	513.4	0
Nakhon Sawan	1,013.7	1,013.7	0	564.1	564.1	0
Uthai Thani	1,105.8	1,105.8	0	528.9	528.9	0
Phetchabun	1,019.0	1,019.0	0	600.5	600.5	0
Average	**1039.1**	**1039.1**	**0**	**557**	**557**	**0**

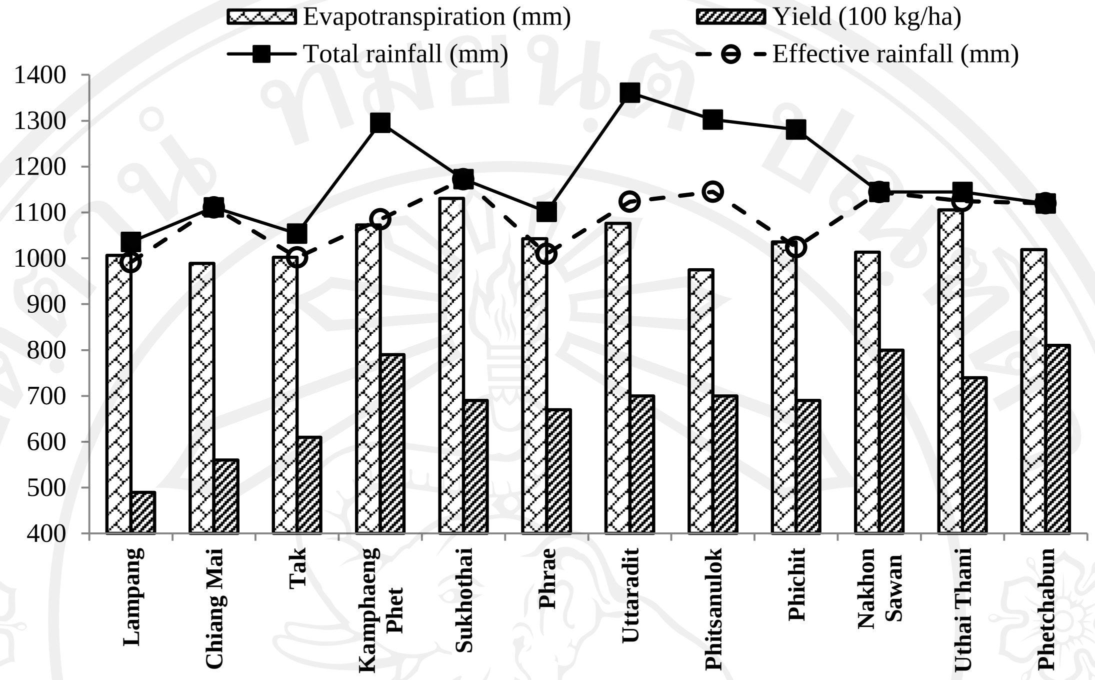


Fig. 4.7 Evapotranspiration, yield, total rainfall and effective rainfall in case of sugarcane

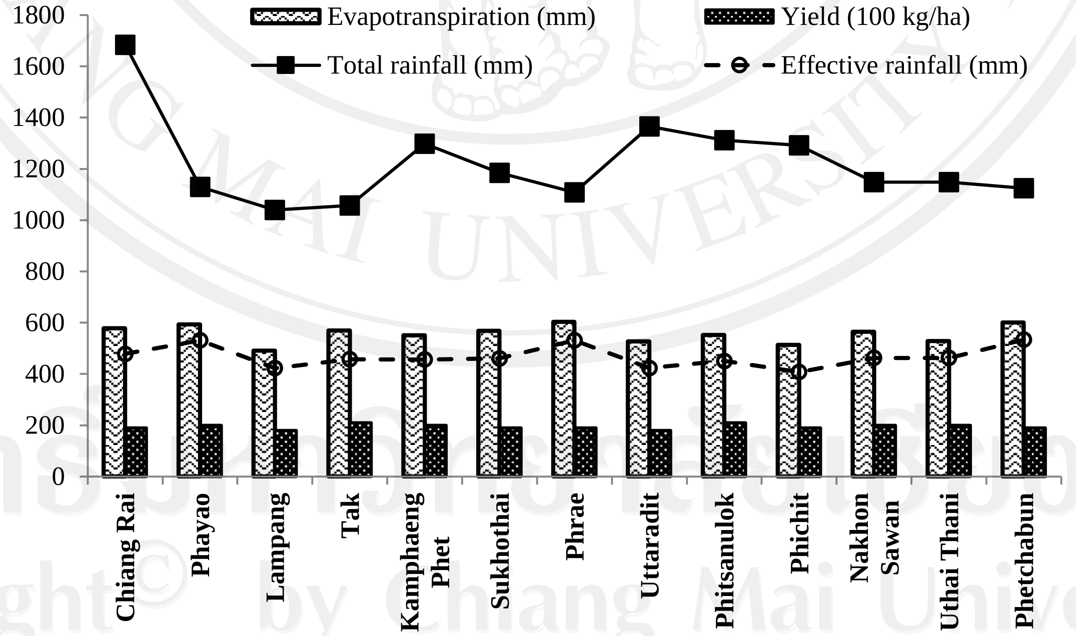


Fig. 4.8 Evapotranspiration, yield, total rainfall and effective rainfall in case of cassava

Since water is an important factor in plant growth and when a plant lacks water for a period of time during its growth, it might affect the production. Figures 4.9 and 4.10 show that if a plant is not in dehydration condition, the yield will increase. The production data in Table 4.1 are yield under rain-fed condition. If a plant has sufficient water under irrigation condition, yield will be increased. As a result, this research predicts yield under irrigation condition by the linear crop-water production function equation (Equation 3.4).

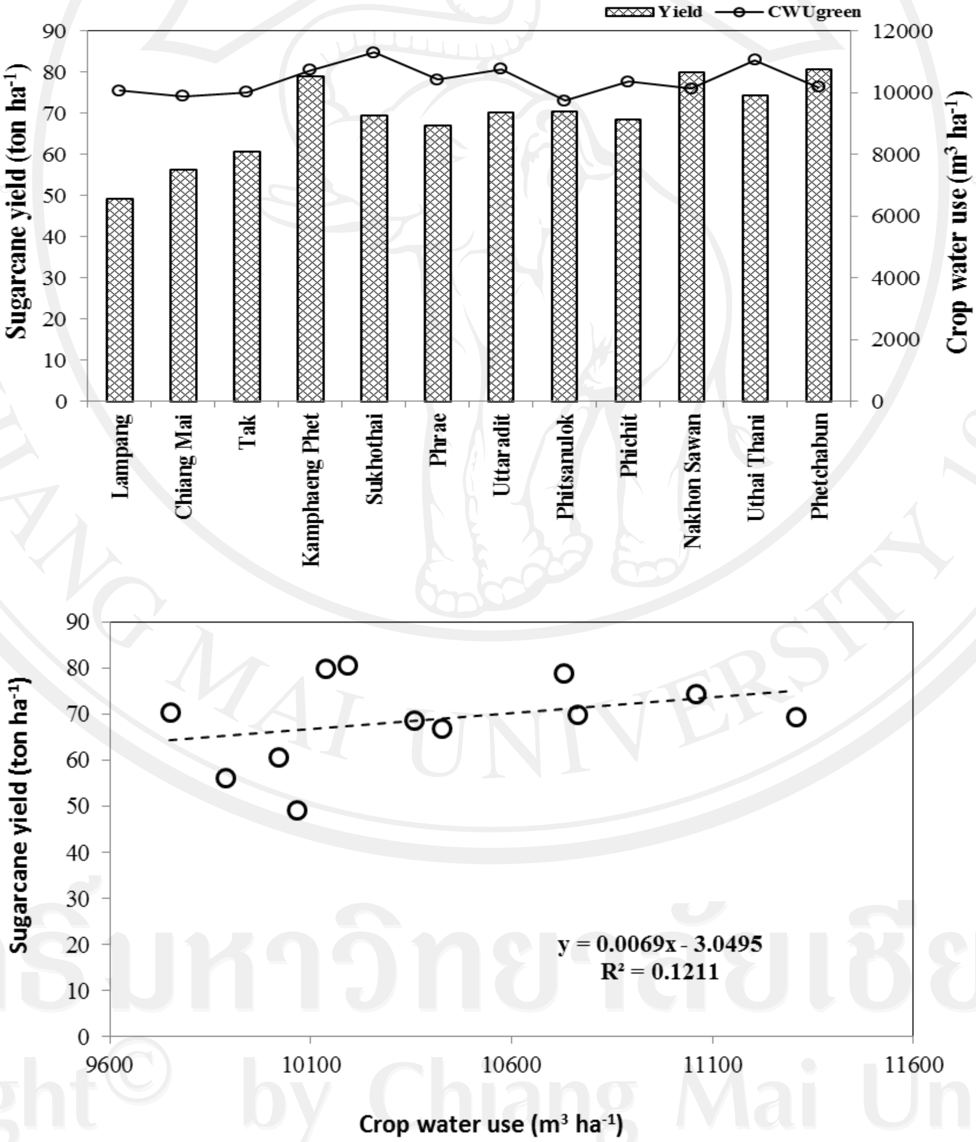
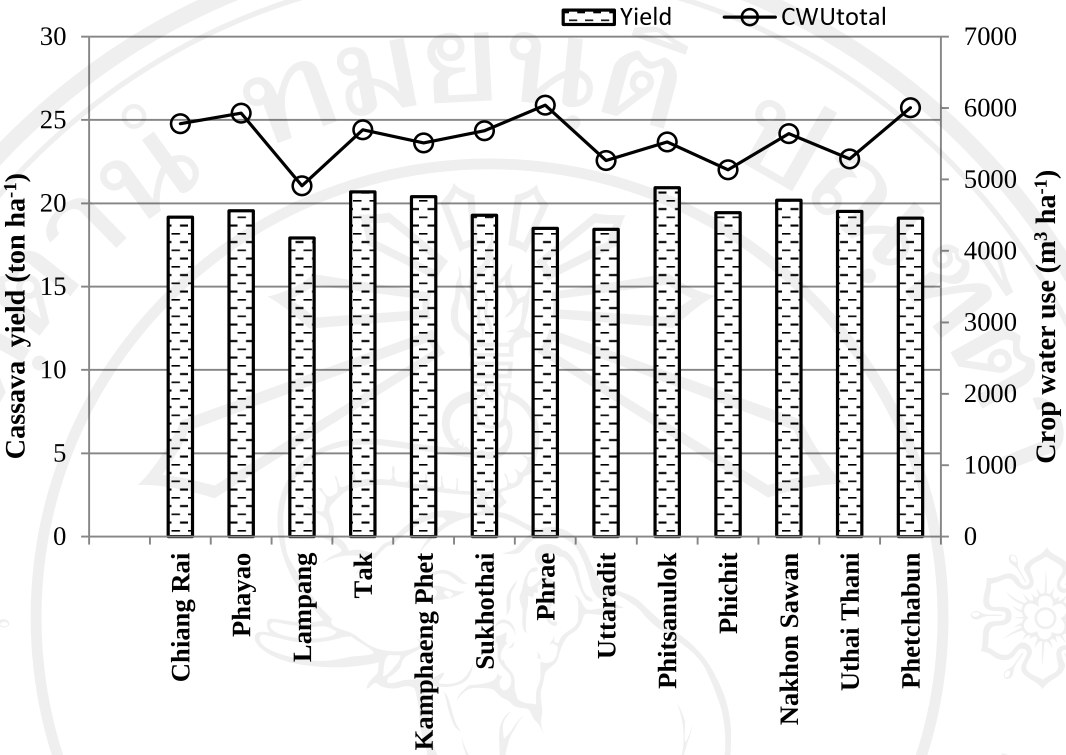


Fig. 4.9 Total crop water use and sugarcane yield of each province in northern Thailand.



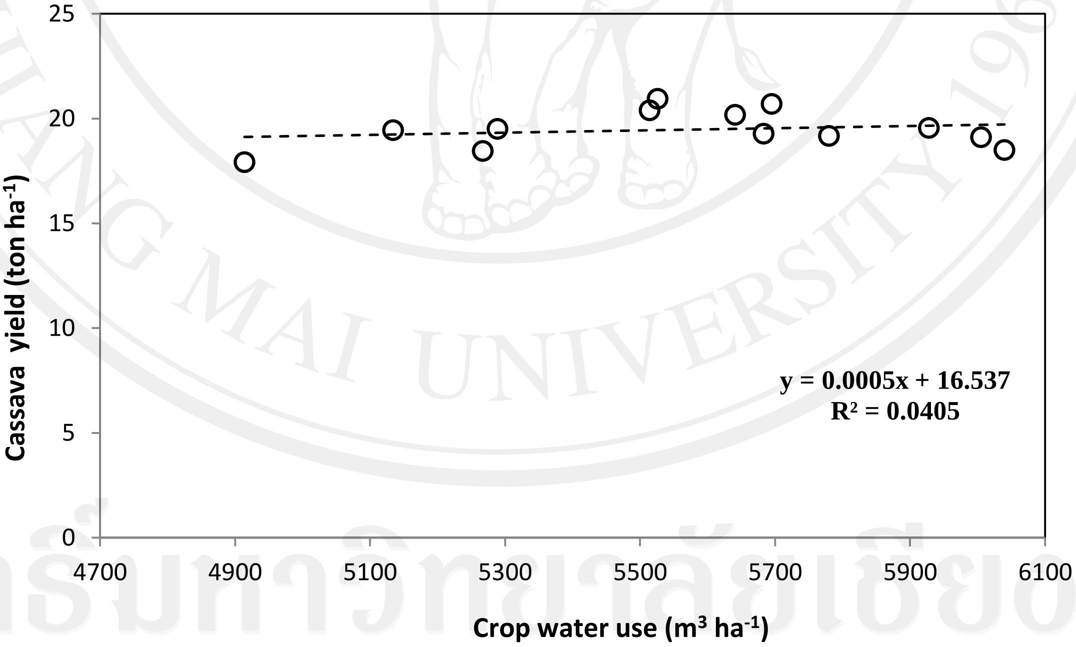


Fig. 4.10 Total crop water use and cassava yield of each province in northern Thailand.

The results of forecast yield under irrigation condition are shown in Table 4.15. When comparing yields under rain-fed and irrigation condition, it was found that yield under irrigation condition increases in every province for both sugarcane and cassava, as shown in Figures 4.11 and 4.12.

Table 4.15 Evapotranspiration and forecast yield under irrigation condition

Province	**Sugarcane**				**Cassava**			
	ET_a	**ET_{blue}**	**ET_{green}**	**Yield**	**ET_a**	**ET_{blue}**	**ET_{green}**	**Yield**
	mm/growing period			**ton/ha**	**mm/growing period**			**ton/ha**
Chiang Rai	-	-	-	-	768.1	295.1	473	25.47
Phayao	-	-	-	-	746.9	318.6	428.3	24.63
Lampang	1160.9	197.3	963.6	58.65	778.2	362.8	415.4	28.38
Chiang Mai	1308.3	360.4	947.9	79.62	-	-	-	-
Tak	1238.4	237.8	1000.6	78.87	821.5	345.5	476	29.85
Kamphaeng Phet	1141.5	142.2	999.3	85.12	791.4	297.3	494.1	29.26
Sukhothai	1276.9	277	999.9	80.55	849.2	346.4	502.8	28.81
Phrae	1140.3	195.8	944.5	74.78	768.1	355.3	412.8	23.53
Uttaradit	1141.5	118.8	1022.7	75.25	799.1	342.3	456.8	27.99
Phitsanulok	1188.7	228.4	960.3	89.79	814.9	348.9	466	30.88
Phichit	1103.6	138.4	965.2	74.10	779.9	345	434.9	29.55
Nakhon Sawan	1296.5	220.1	1076.4	108.30	893.9	400.9	493	31.98
Uthai Thani	1296.5	280.7	1015.8	90.44	893.9	410	483.9	32.96
Phetchabun	1165.1	99.6	1065.5	94.92	835.9	417.2	418.7	26.59
Average	**1204.9**	**208.0**	**996.8**	**82.53**	**810.8**	**352.7**	**458.1**	**28.45**

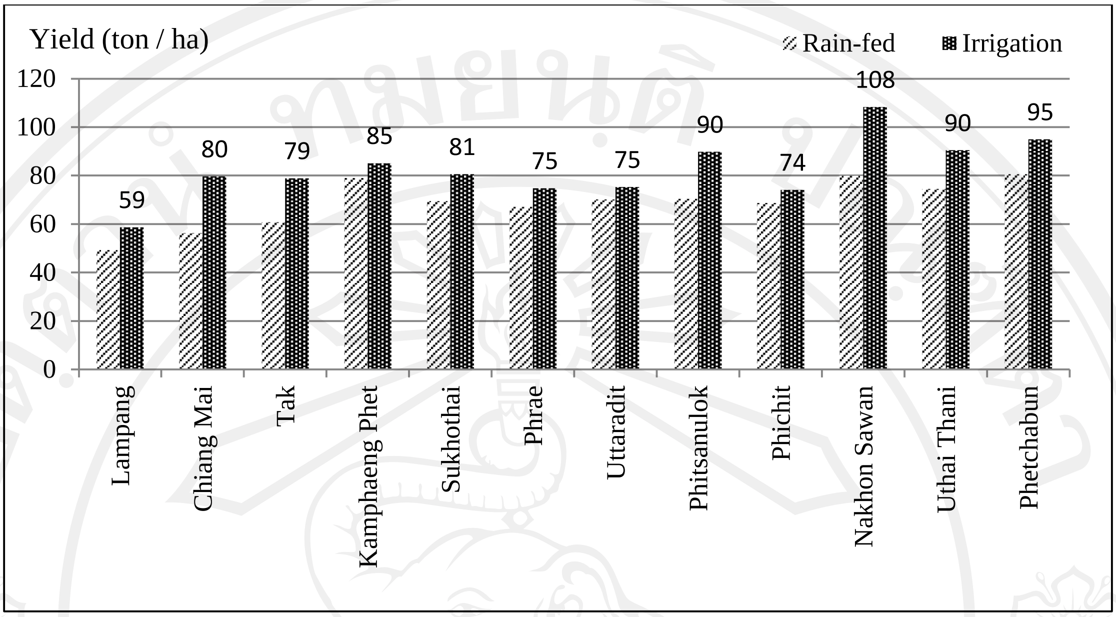


Figure 4.11 Yield of sugarcane under rain-fed and irrigation conditions

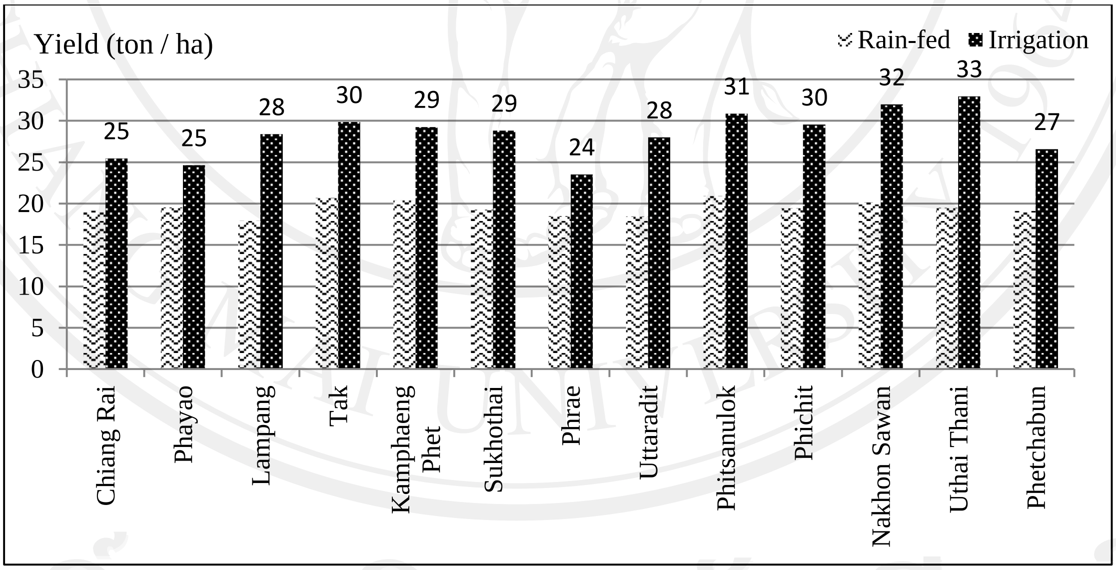


Figure 4.12 Yield of cassava under rain-fed and irrigation conditions

4.3.2 WFs of sugarcane and cassava

With ET_{green} and ET_{blue}, WFs of sugarcane and cassava can be calculated. In this research, WF of each province under rain-fed and irrigation conditions can be calculated as shown in Tables 4.16 and 4.17 for sugarcane and Tables 4.18 and 4.19

for cassava. For irrigation condition, yield from Table 4.15 will be used. The amounts of nitrogen fertilizer used in calculating grey WFs of sugarcane and cassava are 170 kg /ha and 160 kg/ha, respectively. They are the average data from the field survey. From the study, it was found that the average WF of sugarcane under rain-fed in northern Thailand is 205 m^3/ton, with WF_{green} and WF_{grey} accounting for 154 and 51 m^3/ton respectively. WF of sugarcane under irrigation condition is 191 m^3/ton, with WF_{green}, WF_{blue} and WF_{grey} accounting for 123, 26 and 42 m^3/ton, respectively.

Table 4.16 Water footprint of sugarcane under rain-fed condition (m^3/ton).

Province	WF_{green}	WF_{blue}	WF_{grey}	WF_{total}
Lampang	204	0	69	273
Chiang Mai	176	0	60	236
Tak	165	0	56	221
Kamphaeng Phet	136	0	43	179
Sukhothai	163	0	49	212
Phrae	155	0	51	206
Uttaradit	154	0	49	203
Phitsanulok	138	0	48	186
Phichit	151	0	50	201
Nakhon Sawan	127	0	43	170
Uthai Thani	148	0	46	194
Phetchabun	126	0	42	168
Average	**154**	**0**	**51**	**205**

Table 4.17 Water footprint of sugarcane under irrigation condition **(**m^3/ton)**.**

Province	WF_{green}	WF_{blue}	WF_{grey}	WF_{total}
Lampang	164	34	58	256
Chiang Mai	119	45	43	207
Tak	127	30	43	200
Kamphaeng Phet	117	17	40	174
Sukhothai	124	34	42	200

Table 4.17 (Continued)

Province	WF$_{green}$	WF$_{blue}$	WF$_{grey}$	WF$_{total}$
Phrae	126	26	45	197
Uttaradit	136	16	45	197
Phitsanulok	107	25	38	170
Phichit	130	19	46	195
Nakhon Sawan	99	20	31	150
Uthai Thani	112	31	38	181
Phetchabun	112	10	36	158
Average	**123**	**26**	**42**	**191**

In Figure 4.13 which shows WFs of this study and sugarcane producer countries (W.Scholten, 2009), The WFs of sugarcane in this study, for both rain-fed and irrigation, are lower than WFs of Thailand as reported by W. Scholten (2009). They are also lower than WFs of global average and Brazil, a major world’s producer of sugarcane.

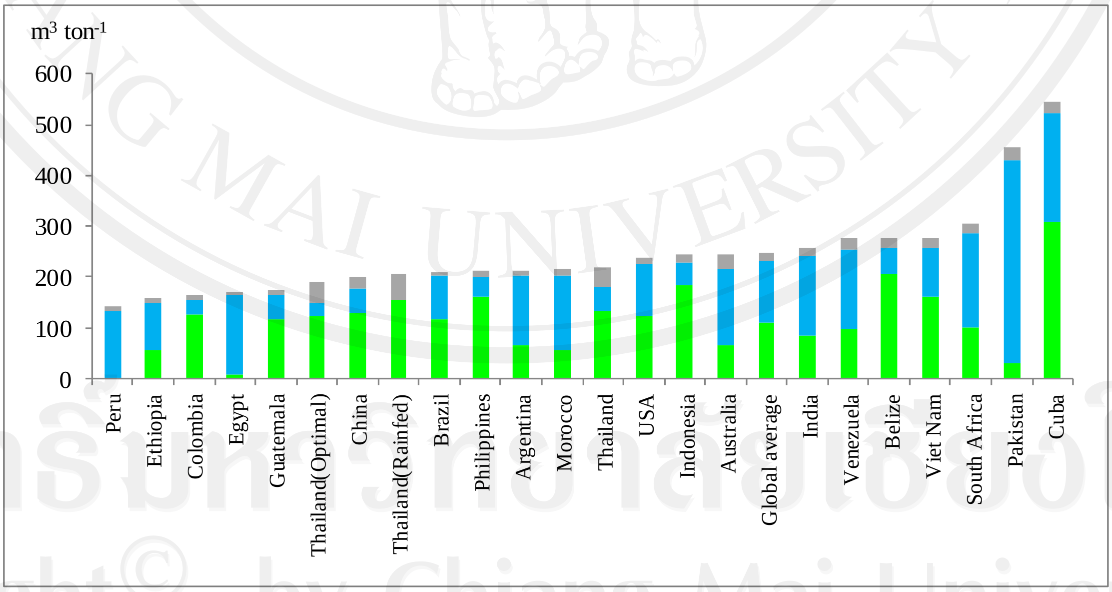


Figure 4.13 The WFs of sugarcane producer countries

In addition, the average WF of cassava under rain-fed in northern Thailand is 449 m^3/ton, dividing into 284 and 165 m^3/ton for WF_{green} and WF_{grey}, respectively. WF of sugarcane under irrigation condition is 400 m^3/ton, dividing into 162, 125 and 113 m^3/ton for WF_{green}, WF_{blue} and WF_{grey} respectively. The result of the study is greater than that of Brazil, which is 156 m^3/ton (Gerbens-Leenes, P. W., 2009), but less than the world averages (Mekonnen, M. M., and Hoekstra, A. Y.,2011), Nigeria (O.Adeti) and Zimbubwe (Gerbens-Leenes, P. W., 2009), which are respectively 564, 992 and 1,074 m^3/ton as shown in Figure 4.14. It can be seen from this study that when sugarcane and cassava are grown under the irrigation condition, they will have full production. Therefore, WF is lower than that of sugarcane and cassava growing under rain-fed condition.

Table 4.18 Water footprint of cassava under rain-fed condition (m^3/ton).

Province	**WF_{green}**	**WF_{blue}**	**WF_{grey}**	**WF_{total}**
Chiang Rai	302	0	167	469
Phayao	303	0	164	467
Lampang	274	0	179	453
Tak	275	0	155	430
Kamphaeng Phet	270	0	157	427
Sukhothai	295	0	166	461
Phrae	326	0	173	499
Uttaradit	286	0	173	459
Phitsanulok	264	0	153	417
Phichit	264	0	165	429
Nakhon Sawan	280	0	159	439
Uthai Thani	271	0	164	435
Phetchabun	284	0	168	452
Average	**284**	**0**	**165**	**449**

Table 4.19 Water footprint of cassava under irrigation condition (m^3/ton).

Province	WF$_{green}$	WF$_{blue}$	WF$_{grey}$	WF$_{total}$
Chiang Rai	186	116	126	428
Phayao	174	129	130	433
Lampang	146	128	113	387
Tak	159	116	107	382
Kamphaeng Phet	169	102	109	380
Sukhothai	175	120	111	406
Phrae	175	151	136	462
Uttaradit	163	122	114	399
Phitsanulok	151	113	104	368
Phichit	147	117	108	372
Nakhon Sawan	154	125	100	379
Uthai Thani	147	124	97	368
Phetchabun	157	157	120	435
Average	**162**	**125**	**113**	**400**

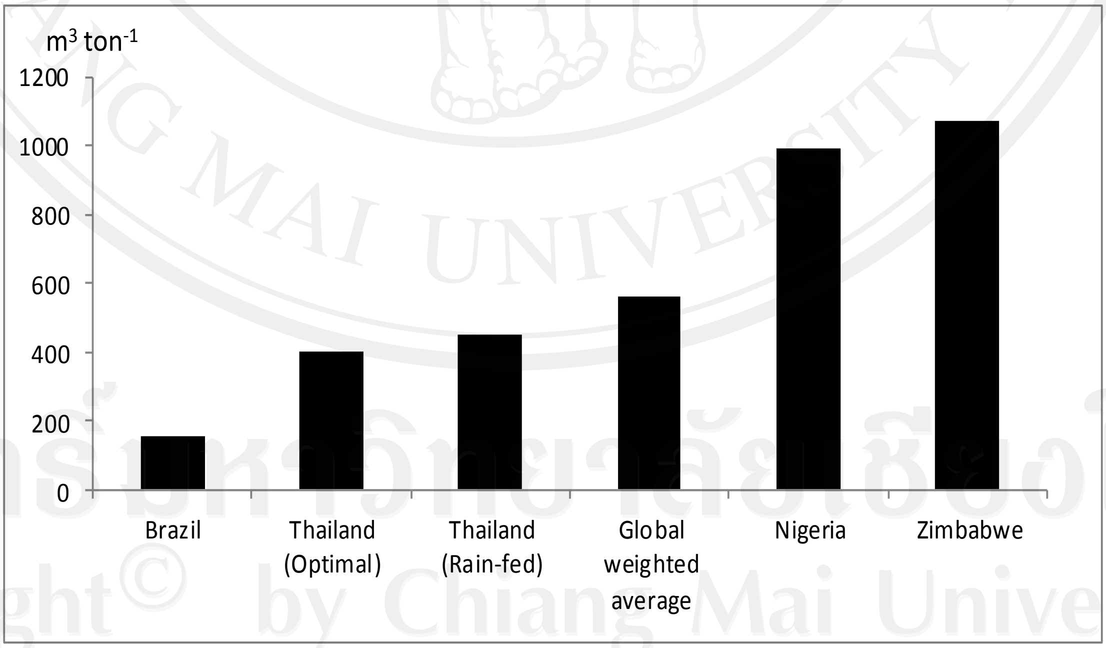


Figure 4.14 The WFs of cassava producer countries

4.3.3 WFs of sugarcane-based bioethanol

The life cycle of bioethanol production from sugarcane as presented in Figure 4.15 can be divided into three stages: sugarcane cultivation, sugar milling to product molasses, and bioethanol production. Each stage needs water. In the sugar milling stage, there are four processes that need water: juice extraction, juice purification, evaporation, and cystallization. The amounts of water use are 0.275, 0.107, 0.046, and 0.046 m^3/ton, respectively. The bioethanol production stage encompasses the mixing, fermentation, distillation and dehydration processes, and the amounts of water use are 0.081, 0.056, 0.039 and 0.008 m^3/ton respectively. The production fraction will change according to the percentages of input and output weights in each process. If the process does not lose weight, f_p is equal to 1 and value fraction will change according to the percentage of the price of all products gained. If there is only one product, f_v is equal to 1.

The results of the analysis on WFs of sugarcane-based bioethanol are divided into bioethanol production from sugarcane under rain-fed and irrigation condition as shown in Figures 4.16 and 4.17. They show WFs of all steps including sugarcane, molasses and bioethanol. For sugarcane under rain-fed condition, WF of bioethanol is 3,372.859 m^3/ton or 2,661.185 L_{water} /$L_{ethanol}$, while WF of bioethanol for sugarcane under irrigation condition is 3,143.068 m^3/ton or 2,479.881 L_{water}/$L_{ethanol}$, the calculation of which is presented in Appendix D. The comparison of the results of this study with those of W. Scholten’s study, which focused on WFs of 19 sugarcane-based ethanol producer countries including Thailand, is as shown in Figure 4.18.

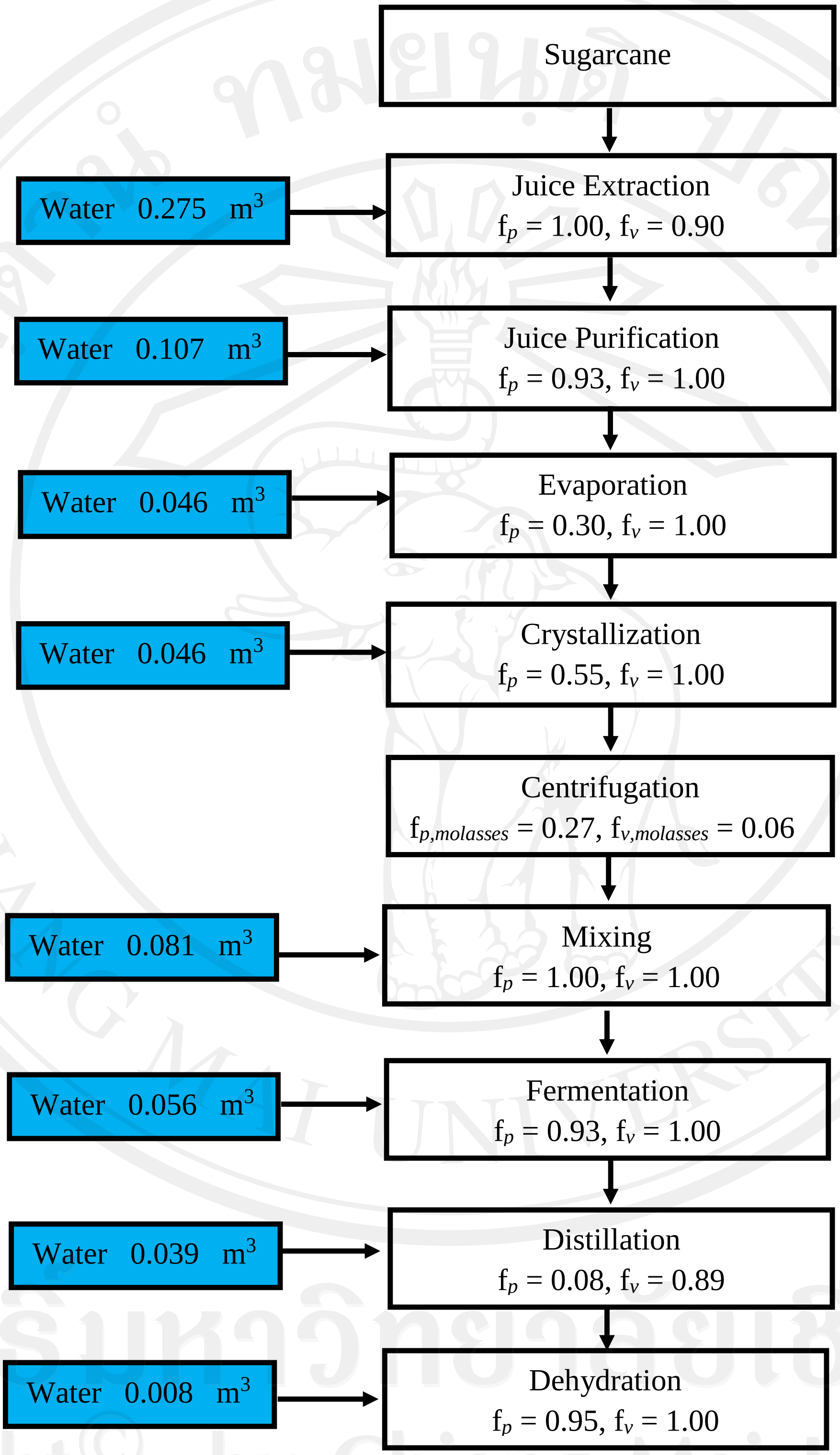


Figure 4.15 The water use for sugarcane-based bioethanol, showing the product fraction and value fraction in each processing step.

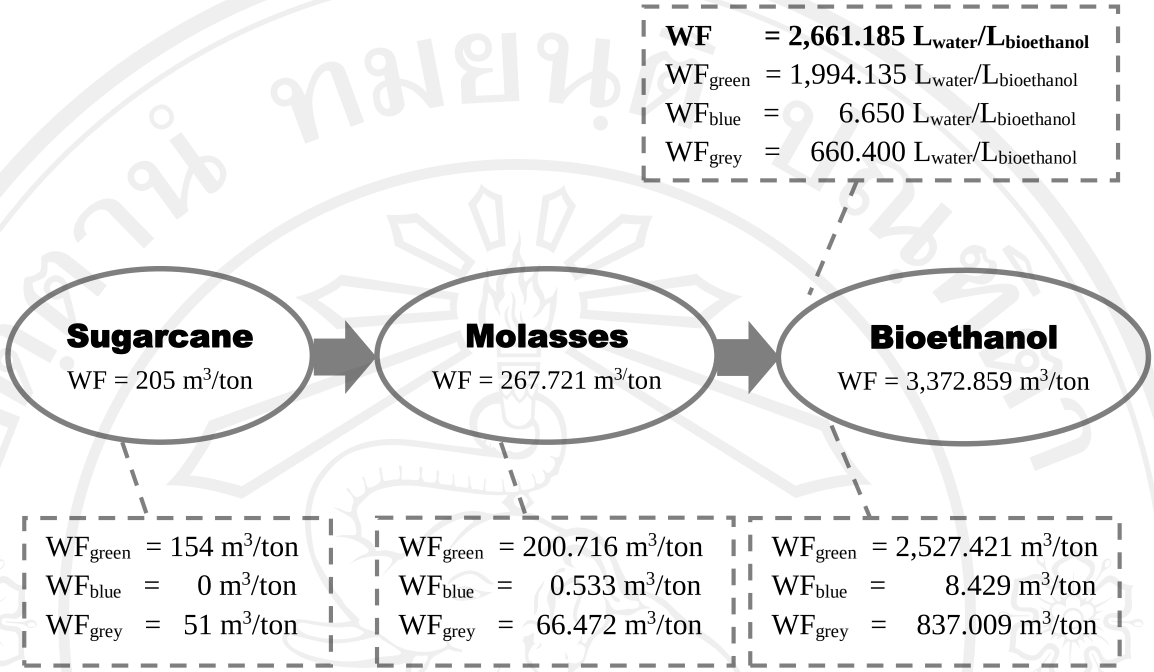


Figure 4.16 The WFs of sugarcane, molasses and bioethanol steps for sugarcane cultivated under rain-fed condition

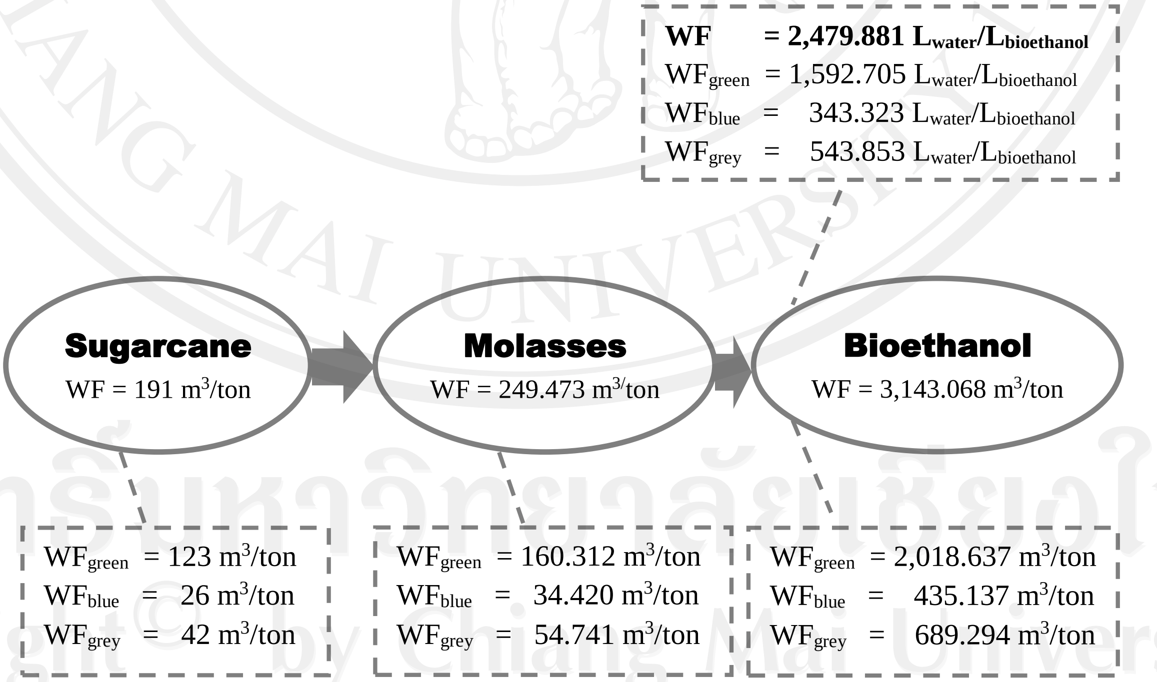


Figure 4.17 The WFs of sugarcane, molasses and bioethanol steps for sugarcane cultivated under irrigation condition

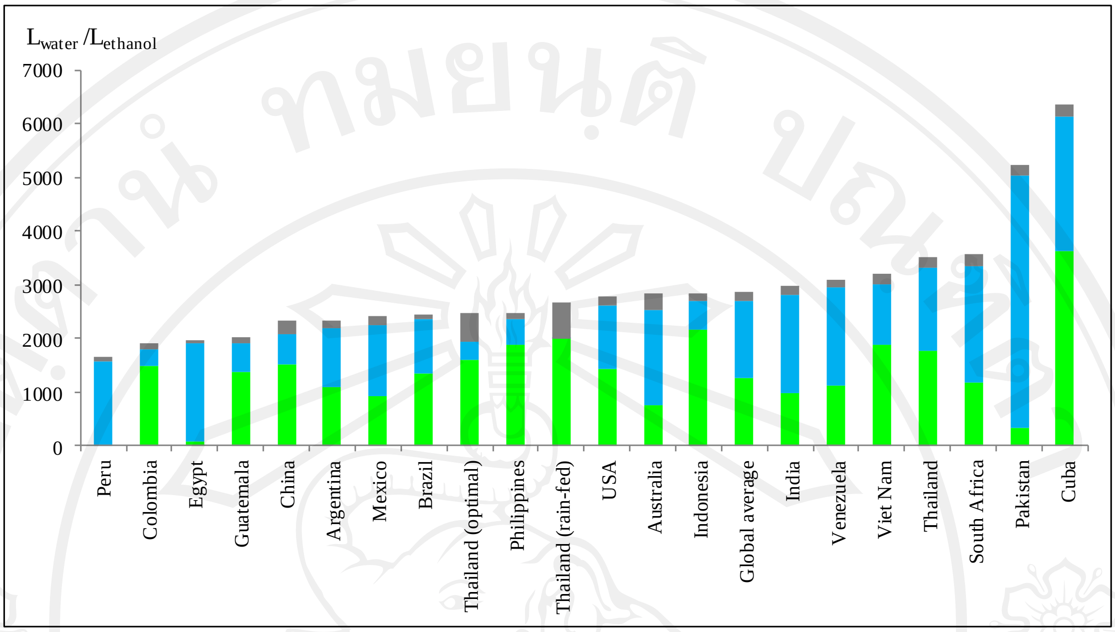


Figure 4.18 The WFs of country producer sugarcane-based bioethanol

From Figure 4.18, it was found that WF of Thailand, as studied by W. Scholten (2009), is ranked fourth, and the value is higher than WFs in this study in both rain-fed and irrigation conditions. WFs in this study are lower than the world average but higher than those of China and Brazil, both of which are the world's leading producers of ethanol. However, they are less than the WFs of Indonesia and Vietnam, both of which are the countries in Southeast Asia like Thailand.

4.3.4 WFs of cassava-based bioethanol

In Figure 4.19, it can be seen that water has been used from cassava cultivation until processing cassava to bioethanol. The production process starts from cassava plantation and harvesting to cassava chips processing. In this process, the weight of cassava after the drying process decreases by 60 percent (f_p = 0.4). Then, it will go through milling and mixing, liquefaction, fermentation, distillation and dehydration with f_p of 0.98, 1.00, 0.97, 0.10 and 0.95 respectively. For distillation, f_v of bioethanol equals 0.89. Water is used in the milling and mixing, liquefaction, distillation and dehydration processes in the amounts of 1.049, 0.003, 0.197 and 0.085 m^3/ton, respectively.

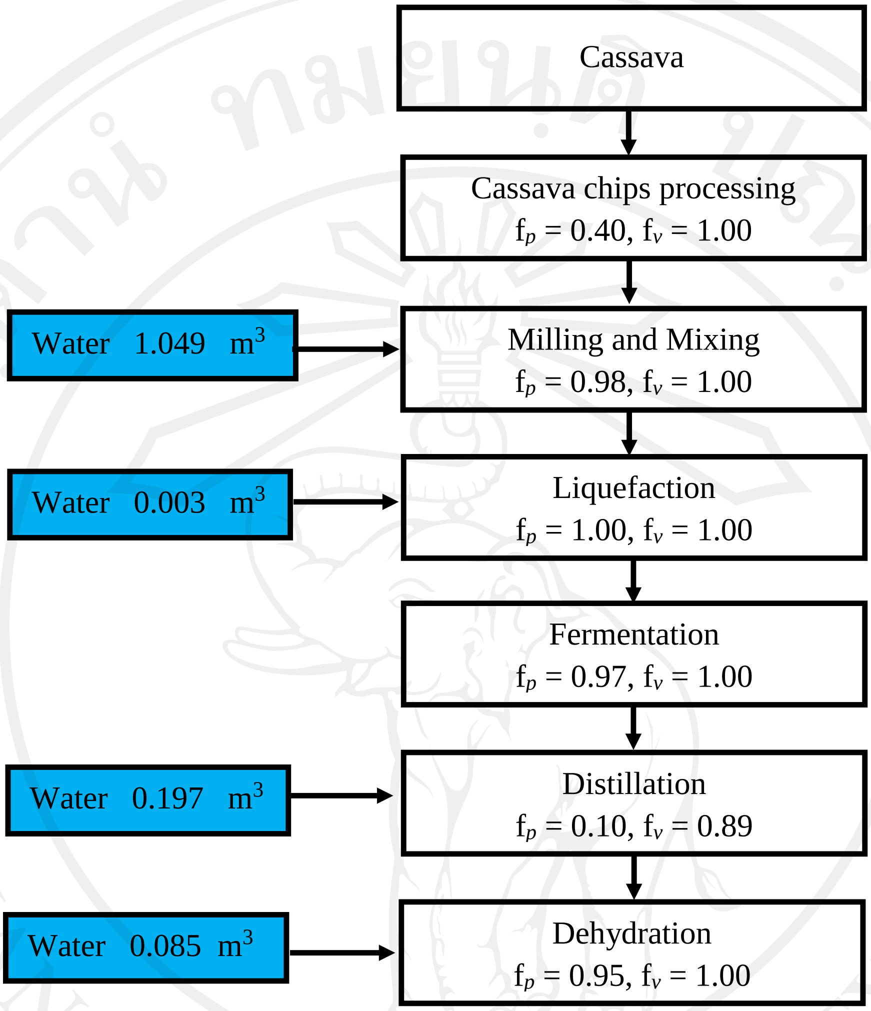


Figure 4.19 The water use for cassava-based bioethanol, showing the product fraction and value fraction in each processing step.

The results of WFs of cassava-based bioethanol analysis are divided into bioethanol production from cassava cultivation under rain-fed and irrigation condition as shown in Figures 4.20 and 4.21. For cassava under rain-fed condition, WF of bioethanol equals 11,072.974 m^3/ton or 8,736.576 Lwater/Lethanol land while WF of bioethanol for cassava under irrigation condition 9,865.694 m^3/ton or 7,784.032 L_{water} /$L_{ethanol}$, the calculation of which is presented in Appendix D. Both figures (i.e., 11,072.974 and 9,865.694 m^3/ton) are lower than WFs of Nigeria (12,626 m^3/ton) (O.Adeoti, 2010) and of Thailand (12,175.246 m^3/ton) (Pongpinyopap, S. and Mungcharoen, T., 2011).

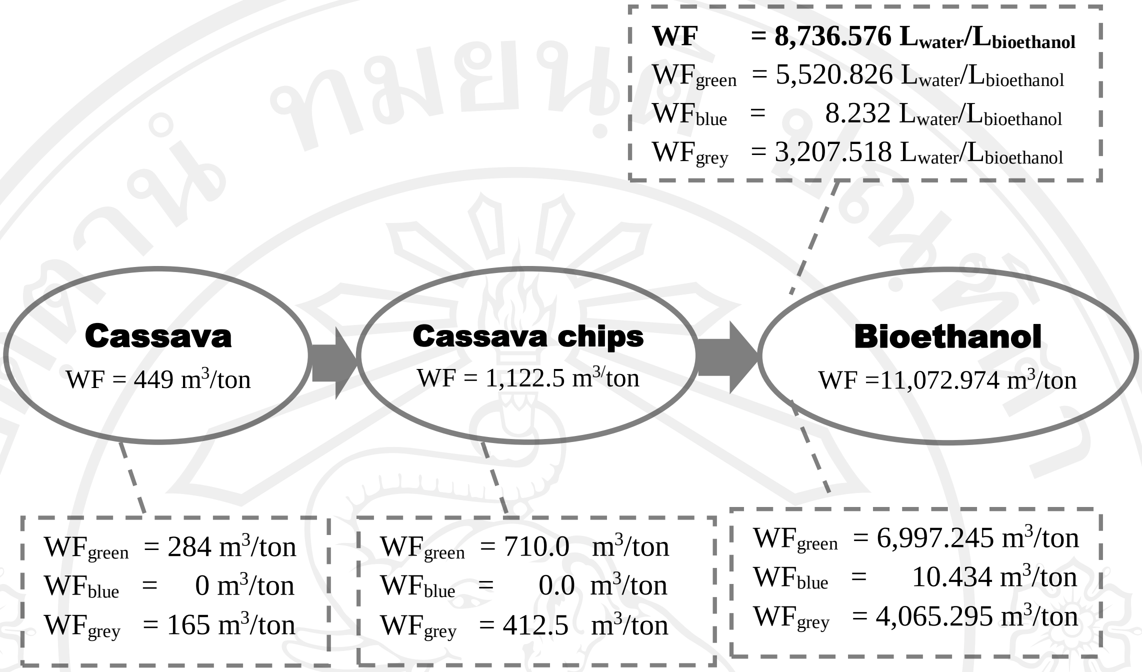


Figure 4.20 The WFs of cassava, cassava chips and bioethanol steps for cassava cultivated under rain-fed condition

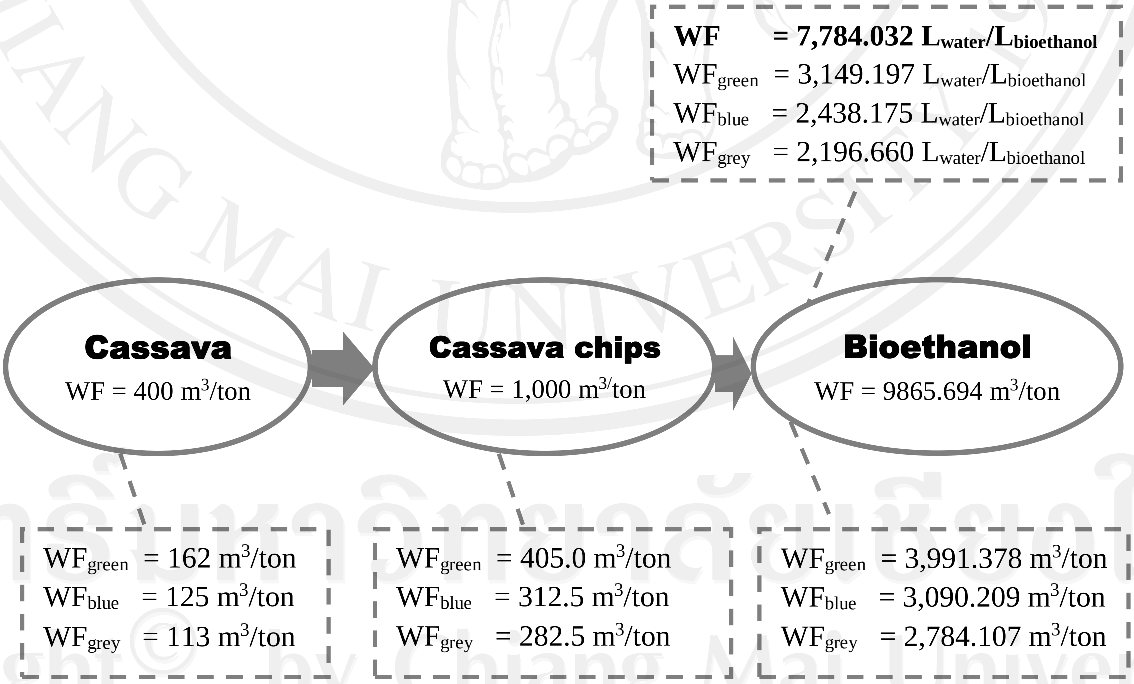


Figure 4.21 The WFs of cassava, cassava chips and bioethanol steps for cassava cultivated under irrigation condition

4.3.5 The reduction of carbon and water footprints

From the study, it is possible to establish guidelines for CF and WF reduction by sector. One set of guidelines is for agricultural sector and the other for industrial sector. The details are as follows:

4.3.5.1 Agricultural sector

The first issue of CF and WF reduction of agricultural product is increasing yield per area by developing watering system in the cultivation. At present, agriculturists harvest sugarcane and cassava using only rainwater. If the watering system is sufficient for the plant's need during its growing period, the yield tends to increase. For example, this study has compared yields of sugarcane and cassava cultivated under rain-fed and irrigation conditions. It was found that sugarcane cultivated under rain-fed condition has the average yield of 68.85 ton/ha while irrigation condition has the average yield of 82.53 ton/ha, or 20 percent more than that under rain-fed condition. Likewise, cassava cultivation under rain-fed condition has the average yield of 19.47 ton/ha while cassava cultivated under irrigation condition has the average yield of 28.45 ton/ha , a 46 percent increase. As water stress is a factor limiting yield production, irrigation programming is essential in order to maximize production per cubic meter of irrigation water. The effects of the magnitude and the timing of water deficit on crop growth and yield are of major importance in scheduling available but limited water supply over growing periods of the crops and in determining the priority of water supply among crops during the growing season, and thereby the efficient irrigation schedule is one way of maximizing water use efficiency.

The second point is chemical fertilizer use reduction, especially Nitrogen fertilizer. From the study of CFs of sugarcane and cassava, it was found that Nitrogen fertilizer use and production process produce most GHG emission. For WF, the grey WF will be reduced when nitrogen fertilizer use is reduced.

4.3.5.2 Industrial sector

The reduction of CF and WF in the production process can be achieved by improving production process to increase yield while the raw material, resource, and energy use are not much different from the normal process, as well as developing technologies that help reduce water use in the production process or reusing water and improving the efficiency of waste management so that waste can be used in other ways, such as using bagasse as fertilizer and producing biogas from wastewater to decrease the use of electricity.

4.4 The results of scenario analysis

This section investigates the effects of the land use, carbon and water footprints of various scenarios and the results are used to establish a set of guidelines for production of ethanol and gasohol.

4.4.1 Scenario I: Comparison among gasoline 95, E10, E20 and E85

Scenario I compares among gasoline 95, E10, E20 and E85, using 1 MJ as the functional unit, considering the entire life cycle from cultivation, raw material production, ethanol production, crude oil extraction, crude oil refining, blending, usage to transportation. As shown in Figure 4.22, the production of 1 MJ of E85 required the most space of land to grow sugarcane and cassava at 0.00004 ha/MJ , followed by E20, E10 and gasoline 95 at 0.000007, 0.000003, and 0.00 ha/MJ, respectively. If Thailand has a policy to promote more use of ethanol in a sequence of ascending doses from gasoline 95 to E10, there would be no incremental in land use as gasoline 95 requires no land to grow crops. However, a transition from E10 to E20 and from E20 to E85, the demand for land to grow crops would increase by 107% and by 450%, respectively.

When considering greenhouse gas emissions of the entire cycle starting from cultivation, raw material production, ethanol production, crude oil extraction, crude oil refining, blending, usage to transportation, gasoline 95 produced the lowest emission of greenhouse gases at 92.4 gCO2eq/MJ, followed by E10, E20 and E85 at 93.3, 94.5 and 116.1 gCO2eq, respectively. Moreover, in percentage terms, a transition from gasoline 95 to E10 increases greenhouse gas emissions by 0.89%, from E10 to E20 by 1.31%, and from E20 to E85 by 22.87%, as shown in Figure 4.23.

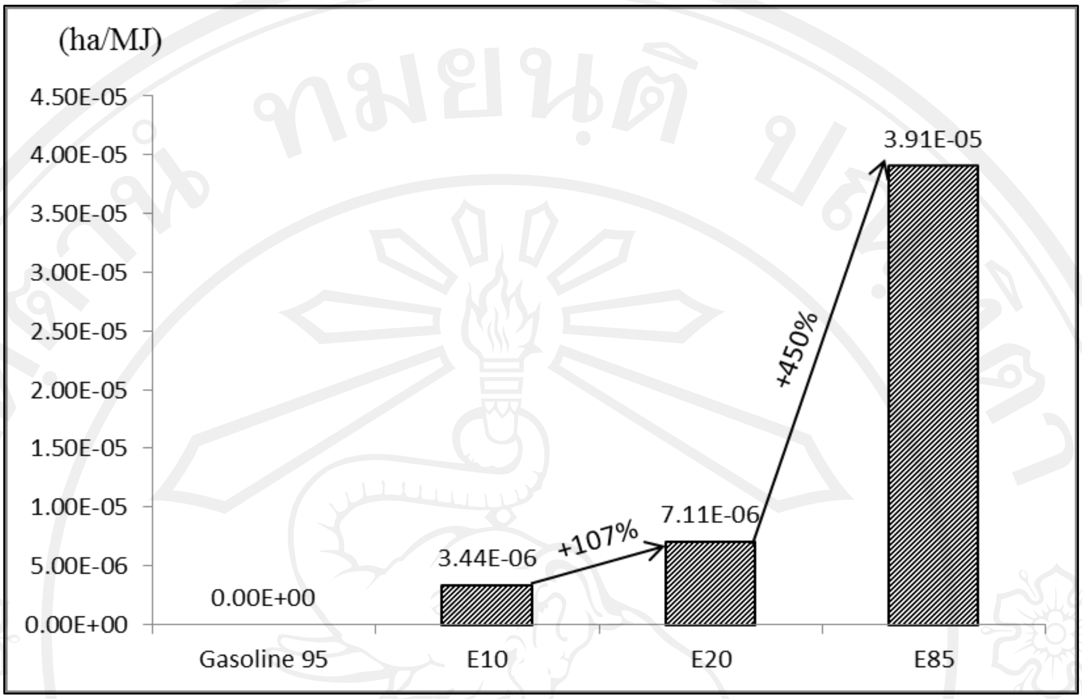


Figure 4.22 Land use for different types of fuels

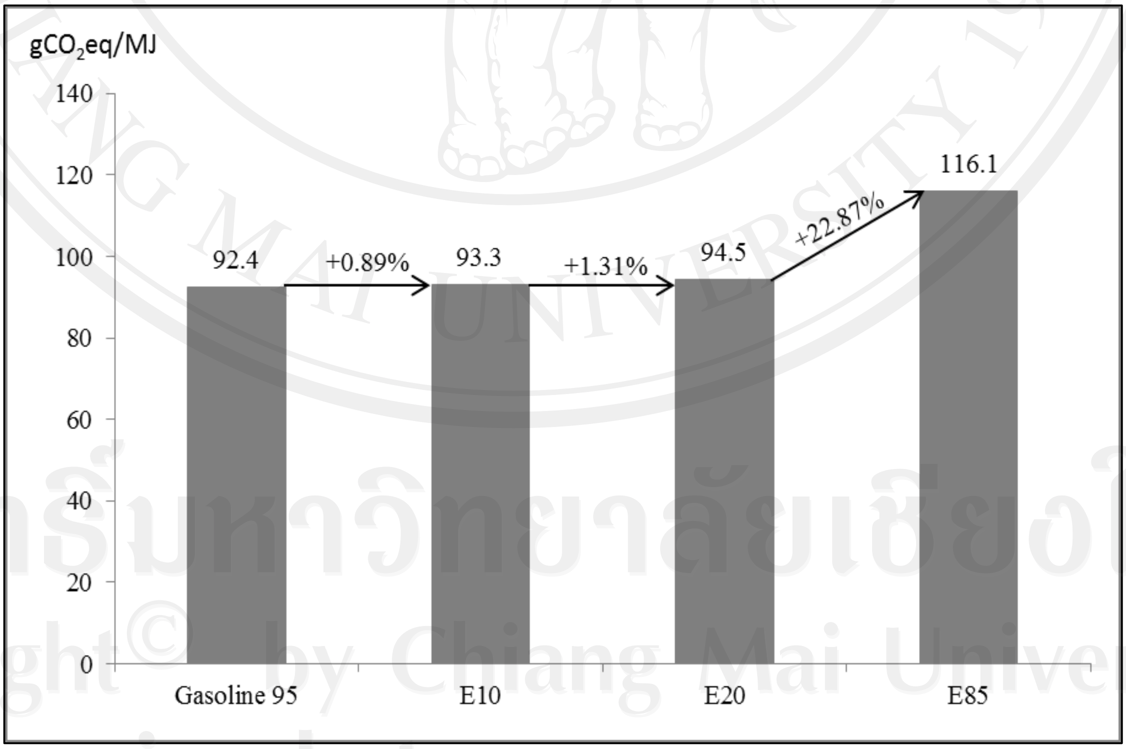


Figure 4.23 Greenhouse gas emissions of different fuel types

This scenario focused on water use for agriculture only because worldwide agriculture accounts for 70% of all water consumption compared to 20% for industry and 10% for domestic use. In addition, demand for water varies according to the amount of ethanol produced. As depicted in Figure 4.24, E85 fuel consumed the most water up to 86.6 m^3/MJ, followed by E20 at 15.8 m^3/MJ and E10 at 7.6 m^3/MJ. However, gasoline 95 required no water for agriculture. Therefore, a switch from gasoline 95 to E10 would increase water usage by 7.6 m^3/MJ, from E10 to E20 by 8.1 m^3/MJ or 106%, and from E20 to E85 by 70.9 m^3/MJ or 450%.

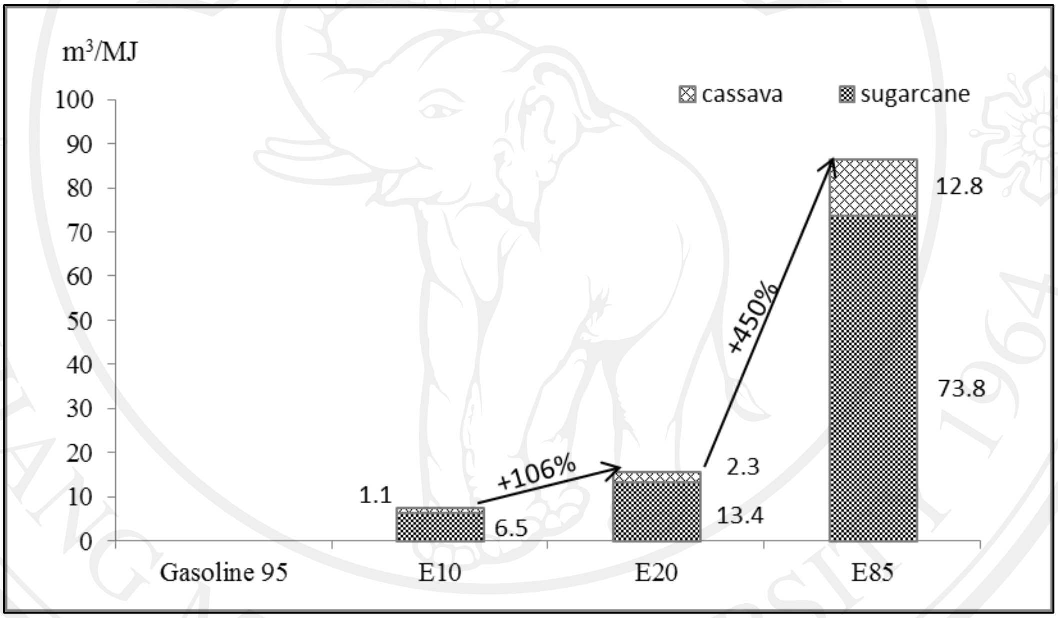


Figure 4.24 Water consumption for different types of fuel production.

4.4.2 Scenario II: Increase of ethanol production to 9 million liters per day by 2021

Scenario II analyzes and compares various proportions of sugarcane-based and cassava-based ethanol production to meet the target of 9 million liters per day by 2021, whereas the total capacity is 1.5 million liters per day at present. As usual, the cycle of ethanol production starts from cultivation, raw material production, ethanol production to transportation. On the one hand, there is the fixed proportion of 70% sugarcane-based and 30% of cassava-based ethanol production. On the other hand, the initial proportion (70%:30%) is varied by lowering sugarcane-based ethanol by 5% while simultaneously increasing cassava-based ethanol by 5% each year. The details for yearly production are as follows:

4.4.2.1 Land use

The impacts on land use of ethanol production for the two cases (i.e., fixed and varying proportions) are shown in Figure 4.25. In the case of fixed proportion, land use is proportional to the production of ethanol. For instance, if the production of ethanol is increased from 1.5 million liters to 9 million liters per day, land use would rise from 2.67 million ha per year to 5.32 million ha per year (or 96.3%). In the case of varying proportion, an increase in the ethanol production would increase land use in the beginning until 2017 when the ethanol production would be 7 million liters per day and the production ratio would be 45% sugar-based and 55% cassava-based ethanol. The land required would be 3.80 million ha per year for cultivation and decrease afterward.

The study also found that production of ethanol from cassava requires less land than production of ethanol from molasses. As seen in Table 4.20, in 2016 when the ethanol production volume is 6 million liters per day or 2.19 billion liters per year and the ratio between sugarcane-based ethanol and cassava-based ethanol is 50%:50%, the land use for sugarcane-based ethanol is 2.10 million ha per year whereas that for cassava-based ethanol is only 1.60 million ha per year.

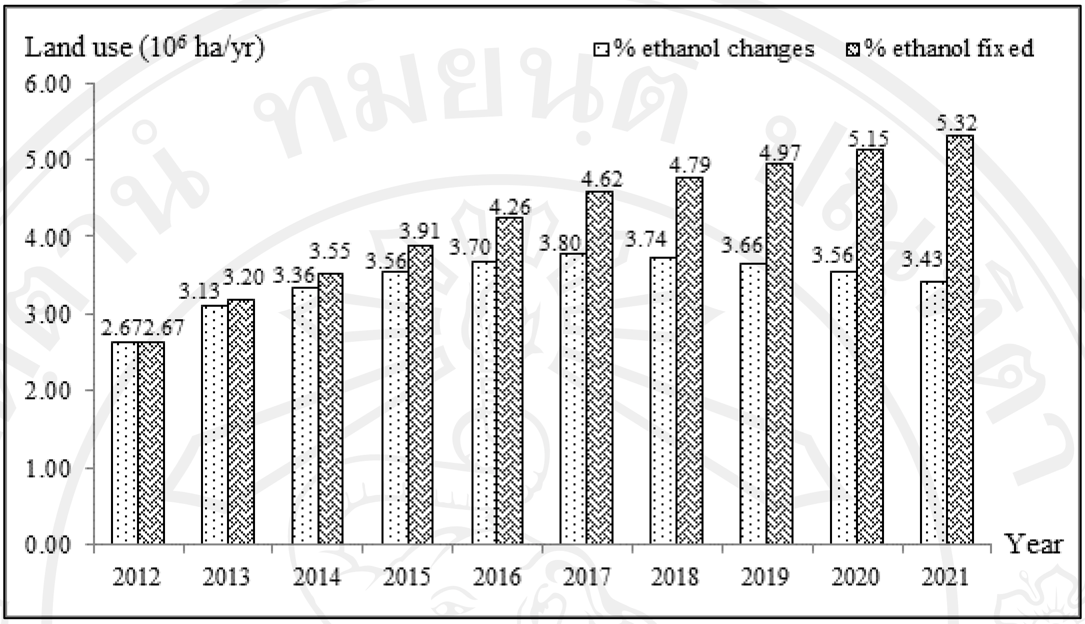


Figure 4.25 Comparison of land use for fixed and varying proportions of sugarcane-based and cassava-based ethanol production

Table 4.20 Annual land use for growing sugarcane and cassava.

Year	Ethanol (10^6 l /day)	% ethanol changes (million ha/yr)				% ethanol fixed (million ha/yr)			
		sugarcane	cassava	Total	% change	sugarcane	cassava	Total	% change
2012	1.5	1.13	1.53	2.67		1.13	1.53	2.67	
2013	3.0	1.58	1.55	3.13	17.32	1.65	1.54	3.20	19.95
2014	4.0	1.80	1.56	3.36	7.60	2.00	1.55	3.55	11.09
2015	5.0	1.97	1.58	3.56	5.67	2.35	1.56	3.91	9.98
2016	6.0	2.10	1.60	3.70	4.05	2.69	1.57	4.26	9.08
2017	7.0	2.17	1.62	3.80	2.62	3.04	1.58	4.62	8.32
2018	7.5	2.10	1.64	3.74	-1.50	3.21	1.58	4.79	3.84
2019	8.0	2.00	1.66	3.66	-2.15	3.39	1.58	4.97	3.70
2020	8.5	1.88	1.68	3.56	-2.83	3.56	1.59	5.15	3.57
2021	9.0	1.73	1.70	3.43	-3.57	3.73	1.59	5.32	3.44

In 2012, Thailand had 1.29 million ha and 1.20 million ha of sugarcane plantations and cassava plantations, respectively. With AEDP's ethanol production target of 9 million liters per day by 2021, this study indicated that the land currently used to cultivate sugarcane and cassava could not produce ethanol to meet the target. For instance, if the ethanol production were 1.5 million liters per day (or 547.5 million liters per year), it would require land use of 2.67 ha per year, 1.13 million ha per year of which is for sugarcane and approximately 1.53 million ha per year for cassava. As such, cultivation areas for both crops need to be expanded. A study report by the Land Development Department suggested the use of deserted areas to expand the cultivation of both crops. In 2008-2009, the report indicated that there was a total of 1.47 million ha per year of deserted and abandoned areas in Thailand, which could be improved and converted to grow both crops to produce ethanol. Doing so would increase the areas for sugarcane and cassava cultivation in Thailand to 3.69 million ha per year and thereby would be enough to grow both sugarcane and cassava to meet the target of 9 million liters per day by 2021 providing that the varying proportion scheme of ethanol production is used. However, under the fixed proportion scheme of 70% sugarcane-based and 30% cassava-based ethanol, the available land would not be sufficient to produce 9 million liters per day of ethanol but merely sufficient to produce 5 million liters per day.

However, converting all abandoned areas to grow sugarcane and cassava is a difficult task. On the contrary, it is much easier and more feasible to ensure sufficient raw materials to produce ethanol according to the AEDP through increasing the average yields per ha of sugarcane and cassava. The goal of the AEDP (2012-2021) is to increase the national average production per ha per year of cassava and sugarcane with their respective yields no less than 31.50 and 93.75 tons per ha per year by 2021.

With the increased average yields per ha of sugarcane and cassava and with the varying proportion of ethanol production, land required to produce ethanol to meet the target is reduced. Figure 4.21 shows that, in the varying proportion scheme of 30% sugarcane-based and 70% cassava-based ethanol, the production of 9 million liters per day would require 1.27 ha and 1.06 million ha per year of land for sugarcane and cassava. However, with this amount of land (i.e., 1.27 & 1.06 million ha per year) and under the fixed proportion scheme of ethanol production, only about 3 million liters per day of ethanol could be produced.

Table 4.21 Land required for sugarcane and cassava cultivation to meet the AEDP target.

Year	Ethanol (10^6 L/day)	% ethanol changes (million ha/yr)				% ethanol fixed (million ha/yr)			
		sugarcane	cassava	Total	% change	sugarcane	cassava	Total	% change
2012	1.5	0.83	0.95	1.79		0.83	0.95	1.79	
2013	3.0	1.16	0.96	2.12	18.87	1.21	0.96	2.18	21.78
2014	4.0	1.32	0.97	2.30	8.13	1.47	0.97	2.44	11.92
2015	5.0	1.45	0.98	2.43	6.01	1.72	0.97	2.69	10.65
2016	6.0	1.54	1.00	2.54	4.25	1.98	0.98	2.95	9.63
2017	7.0	1.60	1.01	2.61	2.71	2.23	0.98	3.21	8.78
2018	7.5	1.54	1.02	2.56	-1.68	2.36	0.98	3.34	4.04
2019	8.0	1.47	1.03	2.50	-2.38	2.49	0.99	3.47	3.88
2020	8.5	1.38	1.05	2.42	-3.13	2.61	0.99	3.60	3.74
2021	9.0	1.27	1.06	2.33	-3.95	2.74	0.99	3.73	3.60

4.4.2.2 Carbon footprint

The carbon footprint (CF) from the production of ethanol from molasses as allocated by mass and economic value in both fixed and varying proportions are respectively presented in Figures 4.26 and 4.27. The study of carbon footprint indicated that in the fixed proportion GHG would be released proportionally to higher ethanol production. The ethanol production of 1.5 million L/day released GHG of 0.8 million tonCO_2eq with allocation of molasses by economic value. However, at 9 million L/day, carbon footprint would respectively increase to 3.8 and 4.7 million tonCO_2eq in case of the varying and fixed proportion schemes. For allocation of molasses by mass, carbon footprint at 1.5 million L/day would be 1.4 million tonCO_2eq and, at 9 million L/day, would increase to 5.1 and 8.4 million tonCO_2eq in case of the varying and fixed proportion schemes. Nevertheless, if there were an increase in average yield per cultivation area, the annual accumulation of carbon footprint would be reduced.

With the fixed proportion of ethanol production, carbon footprint would rise with increase in ethanol production. Likewise, with the varying proportion scheme, carbon footprints tend to increase but at a slow rate compared to the production of ethanol under the fixed proportion. In addition, the greenhouse gas emission from cassava-based ethanol is lower than sugarcane-based ethanol. Therefore, increase in production of ethanol from cassava would result in reduced emission of greenhouse gases.

In short, the study has showed that increasing annual quantity of ethanol produced would result in increased greenhouse gas emissions.

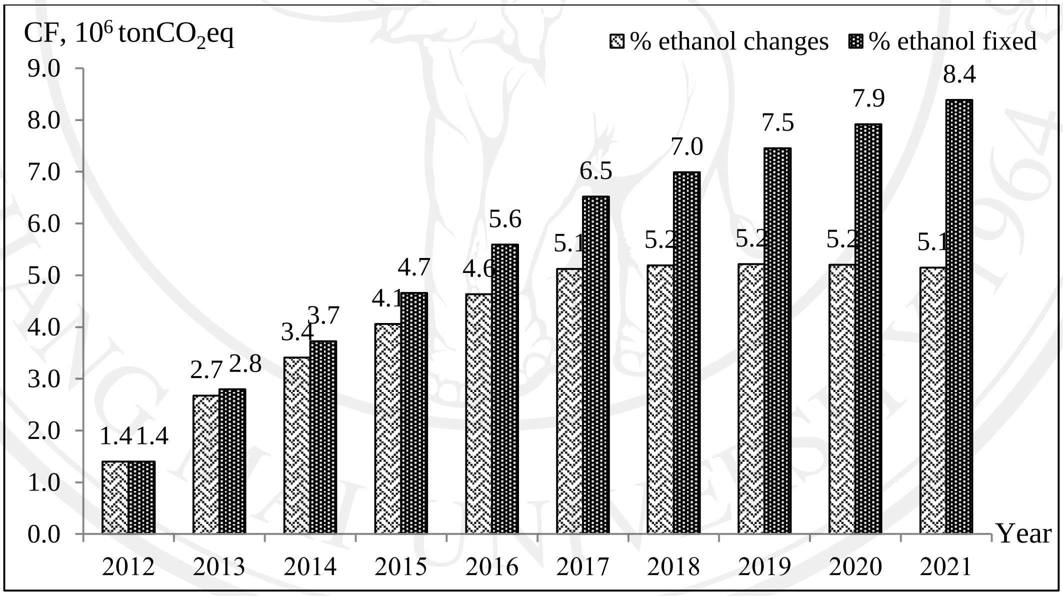


Figure 4.26 Carbon footprints from fixed vs. varying proportions of ethanol production (Allocation of molasses by mass)

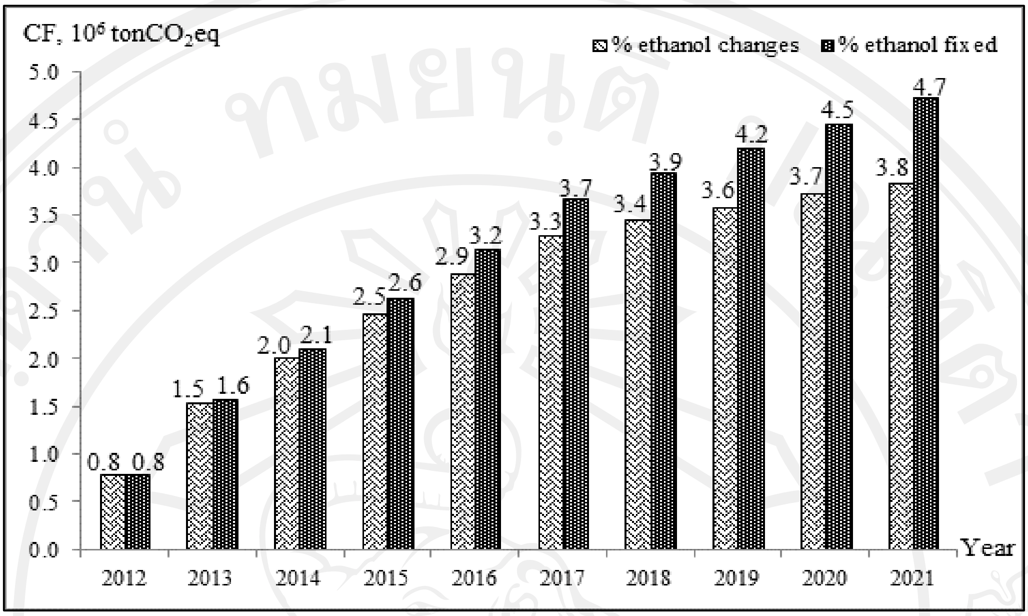


Figure 4.27 Carbon footprints from fixed vs. varying proportions of ethanol production (Allocation of molasses by economics)

4.4.2.2 Water footprint (WF)

This section examines water use in the ethanol production to meet the target of 9 million liters per day. WFs of the fixed and varying proportions are presented in Table 4.22 and Figure 4.28. As seen, in the case of fixed proportion of ethanol production, WFs of irrigation water of both crops increase as the production volume of ethanol increases. Water consumption would continue to increase until the year 2017, when water use peaks at 10.24 km^3 per year, and then decrease.

Even though cassava is more resistant to drought than is sugarcane, all plants require an adequate amount of water to grow and produce crops. The study shows that cassava required (crop water requirement) 8,108 m^3/ha of water during its growth, while sugarcane required 12,049 m^3/ha (crop water requirement). In addition, other key factors in plant growth are climate, plant types and soil properties. The effective rainfall also plays a role in the growth of plants; thus, if plants receive inadequate rainfall, they need irrigation water.

Table 4.22 Water footprints from sugarcane and cassava production

Year	Ethanol (10^6 L /day)	% ethanol changes (km^3/yr)				% ethanol fixed (km^3/yr)			
		sugarcane	cassava	Total	% changes	sugarcane	cassava	Total	% changes
2012	1.5	2.36	5.40	7.76		2.36	5.40	7.76	
2013	3.0	3.28	5.46	8.74	12.67	3.44	5.45	8.88	14.48
2014	4.0	3.75	5.51	9.26	5.89	4.16	5.48	9.63	8.43
2015	5.0	4.11	5.57	9.68	4.56	4.88	5. 50	10.38	7.78
2016	6.0	4.36	5.65	10.01	3.39	5.60	5.53	11.13	7.21
2017	7.0	4.52	5.73	10.24	2.35	6.32	5.56	11.88	6.73
2018	7.5	4.36	5.79	10.15	-0.91	6.68	5.57	12.26	3.15
2019	8.0	4.16	5.85	10.01	-1.38	7.04	5.59	12.63	3.06
2020	8.5	3.90	5.92	9.83	-1.86	7.40	5.60	13.00	2.97
2021	9.0	3.59	6.00	9.59	-2.37	7.76	5.62	13.38	2.88
Average		3.84	5.69	9.53		5.56	5.53	11.09	

The study has also shown that use of water from rainfall of cassava was 4,581 m^3/ha, which is much less than the effective rainfall requirement of sugarcane of 9,968 m^3/ha.

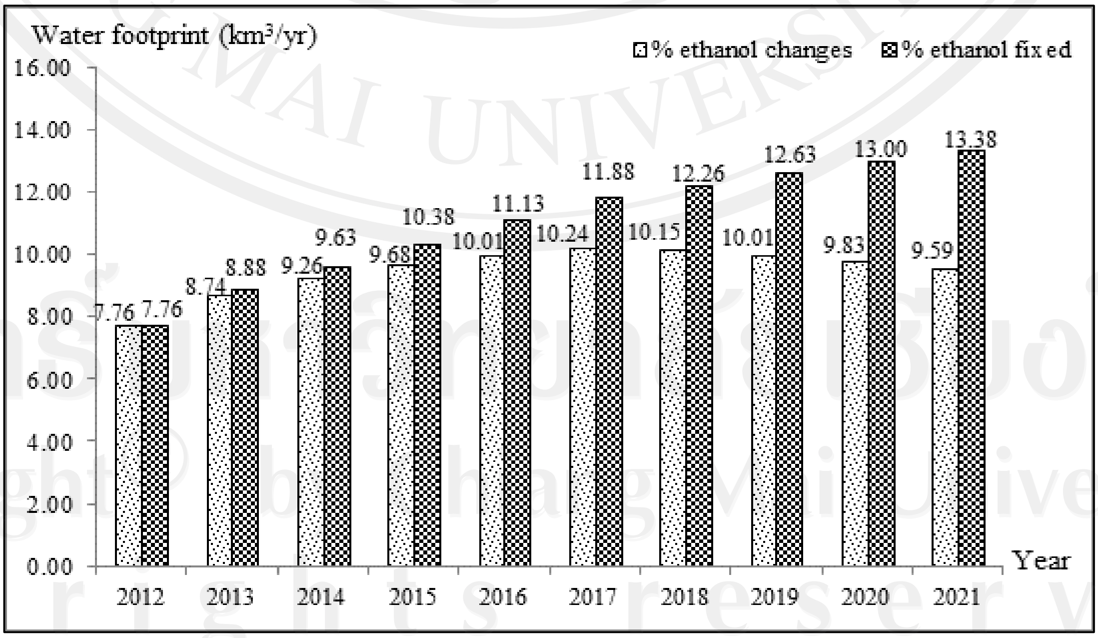


Figure 4.28 WFs from the fixed and varying proportions of ethanol production.

In 2012, the Irrigation Department drew up plans to allocate water of 21,130 million m^3 (or 21.13 k m^3) during the rainy season to the agricultural sector, of which 0.939 k m^3 was set aside for sugarcane plantations of around 146,560 ha. Nevertheless, cassava cultivation areas have not been included in the irrigation water allocation plans of the agency. During the drought season, the irrigation water allocation for agriculture was set at 41,970 million m^3 (or 41.97 k m^3), of which 2.88 k m^3 was for 155,200 ha of sugarcane plantations but none was for cassava cultivation areas. As such since 2012 the Irrigation Department has set aside a total of 63.10 k m^3 of water for the agricultural sector. However, if Thailand is to increase the capacity of ethanol production to meet the target of 9 million liters per day by 2021 as planned, better allocation of water is required so that other crops, especially cassava, receive some share of water allocation. In the case of varying proportion of ethanol production, water allocation to both sugarcane and cassava cultivation needs to increase by 9%, while in the case of fixed proportion of ethanol production, the allocation should increase by 12%; otherwise, the target of the production of ethanol of 9 million liters per day would not be met. With successful increase in average yields per cultivation area of sugarcane and cassava, the rise in the amount of water needed for growing both plants would be slower. That is, in the varying proportion case water use would rise to 6.36 km^3 per year, compared to 9.53 km^3 per year without improvement in crop yields. However, in the fixed proportion case water consumption would soar to 11.09 km^3 per year when compared with 7.53 km^3 per year without yield per cultivation area improvement. The annual requirements of water of sugarcane and cassava in both fixed and varying proportions of ethanol production are presented in Table 4.23.

Table 4.23 WFs from sugarcane and cassava plants with increasing yields.

Year	Ethanol (10^6 L /day)	% ethanol changes (km^3/yr)				% ethanol fixed (km^3/yr)			
		sugarcane	cassava	Total	% changes	sugarcane	cassava	Total	% changes
2012	1.5	1.73	3.37	5.10		1.73	3.37	5.10	
2013	3.0	2.41	3.40	5.81	14.04	2.52	3.39	5.92	16.09
2014	4.0	2.75	3.44	6.19	6.41	3.05	3.41	6.47	9.24
2015	5.0	3.02	3.47	6.49	4.90	3.58	3.43	7.01	8.46
2016	6.0	3.21	3.52	6.72	3.59	4.11	3.45	7.56	7.80
2017	7.0	3.32	3.57	6.89	2.43	4.64	3.46	8.11	7.24
2018	7.5	3.21	3.61	6.81	-1.09	4.91	3.47	8.38	3.37
2019	8.0	3.05	3.65	6.70	-1.61	5.17	3.48	8.65	3.26
2020	8.5	2.86	3.69	6.56	-2.16	5.44	3.49	8.93	3.16
2021	9.0	2.64	3.74	6.38	-2.74	5.70	3.50	9.20	3.06