APPENDICES

APPENDIX A

THE DATA OF SOIL SERIES OF CULTIVATION AREA OF SUGARCANE AND CASSAVA IN NORTHERN THAILAND

Table A.1 Soil series of cultivation areas of sugarcane.

Province	Soil series	Cultivation area (ha)	% cultivation area per total cultivation area
Nakhon Sawan	52	37187.07	39
	28	9134.26	10
	6	8659.25	9
Kamphaeng Phet	33	52085.87	58
	15	7177.03	8
Sukhothai	33	25522.32	46
	7	7014.68	13
	38	6284.06	11
	15	5548.98	10
Uthai Thani	40	14650.27	28
	44	4689.81	9
	55	4607.47	9
Phetchabun	62	21964.20	42
	28	7794.96	15
	52	6736.04	13
	36	4441.87	9
Lampang	48	5886.57	52
	47	1552.17	14
Uttaradit	33	2900.28	31
	47	1250.64	13
	49	1117.22	12
	15	877.60	9
Phichit	33	4154.49	49
	7	2222.06	26
	38	1445.04	17

Table A.2 Soil series of cultivation areas of cassava.

Province	Soil series	Cultivation area (ha)	% cultivation area per total cultivation area
Kamphaeng Phet	35	57088.09	47
	46	19454.84	16
	48	11488.62	9
Nakhon Sawan	35	11516.77	21
	29	9690.282	17
	44	6468.41	12
	46	5939.09	11

Table A.2 (Continued)

Province	Soil series	Cultivation area (ha)	% cultivation area per total cultivation area
Kamphaeng Phet	35	57088.09	47
	46	19454.84	16
	48	11488.62	9
Nakhon Sawan	35	11516.77	21
	29	9690.282	17
	44	6468.41	12
	46	5939.09	11
Uthai Thani	44	6312.21	25
	40	5094.57	20
	35	2440.81	10
	37	2194.68	9
Phetchabun	47	2538.22	31
	25	1669.85	21
	28	1093.52	13
Uttaradit	35	1248.61	40
	40	465.261	15
	49	426.926	14
	48	322.25	10
Sukhothai	48	1766.06	69
	49	348.18	14
Chiang Rai	29	675.79	42
	30	508.61	32

APPENDIX B

THE SUMMARY OF IMPORTANCE SERVEY DATA

Table B.1 Survey data of sugarcane and cassava plantations in northern Thailand.

Activity	Value	Sugarcane	Cassava
Total area (ha)		122,450	73,638
Yield (ton/ha)	Min	43.75	6.25
	Max	187.50	50.00
	Mean	78.91	22.90
	Median	81.25	25.00
	SD	14.53	6.62
Diesel fuel for land preparation (L/ha)	Min	6.25	6.25
	Max	62.50	50.00
	Mean	15.93	18.08
	Median	12.50	12.50
	SD	6.07	7.37
Diesel fuel for plantation (L/ha)	Min	0.00	0.00
	Max	31.25	0.00
	Mean	13.46	0.00
	Median	12.50	0.00
	SD	6.97	0.00
Diesel fuel for harvesting (L/ha)	Min	0.00	6.25
	Max	31.25	31.25
	Mean	12.31	17.41
	Median	12.50	12.50
	SD	5.00	6.60
Diesel fuel for transport to truck (L/ha)	Min	6.25	0.00
	Max	31.25	31.25
	Mean	14.05	9.42
	Median	12.50	6.25
	SD	5.28	6.35
Fertilizers for land preparation			
N (kg N/ha)	Min	14.06	4.69
	Max	287.50	234.38
	Mean	76.68	61.86
	Median	50.00	50.00
	SD	45.27	42.09
P (kg P/ha)	Min	0.00	0.00
	Max	234.38	234.38
	Mean	36.23	31.04
	Median	25.00	25.00
	SD	32.84	29.22
K (kg K/ha)	Min	0.00	0.00
	Max	234.38	234.38
	Mean	39.55	33.71
	Median	46.88	25.00
	SD	38.07	30.80

Table B.1 (Continued).

Activity	Value	Sugarcane	Cassava
Fertilizers for crop maintenance	Min	14.06	0.00
N (kg N/ha)	Max	287.50	234.38
	Mean	69.71	56.26
	Median	50.00	46.88
	SD	47.96	38.17
P (kg P/ha)	Min	0.00	0.00
	Max	234.38	234.38
	Mean	40.20	39.27
	Median	25.00	25.00
	SD	35.65	34.58
K (kg K/ha)	Min	0.00	0.00
	Max	281.25	234.38
	Mean	50.51	41.61
	Median	46.88	46.88
	SD	41.86	36.47
Herbicides (kg/ha)	Min	3.13	0.31
	Max	46.88	106.50
	Mean	8.09	17.42
	Median	4.69	15.63
	SD	5.72	12.18

APPENDIX C

CARBON FOOTPRINT CALCULATIONS OF SUGARCANE-BASED AND CASSAVA-BASED BIOETHANOL

Table C.1 GHG emissions of raw material, energy, and resource acquisition and utilization for sugarcane-based bioethanol. (Allocation by mass)

Activity	Unit	Quantity (per FU)	EF ($kgCO_2eq$/ Unit)	Allocation by mass (%)	GHG emissions ($kgCO_2eq$)
Raw materials acquisition					
Sugar milling					
Input					
Unburned sugarcane	kg	38.4537	0.0193	27	0.2004
Burned sugarcane	kg	59.3630	0.0571	27	0.9152
Calcium hydroxide	kg	0.1578	0.0366	27	0.0016
Biocide	kg	0.0006	1.0400	27	0.0002
Precipitating agents	kg	0.0004	1.4300	27	0.0002
Sanitizer	kg	0.0001	1.3325	27	0.0000
Waterlock	kg	0.0006	2.8008	27	0.0005
Scale inhibitor	kg	0.0018	1.9493	27	0.0009
Enzyme (Amylase)	kg	0.0009	1.1500	27	0.0003
Sodium hydroxide	kg	0.0171	1.1148	27	0.0051
Butanedioic Acid	kg	0.0001	1.3325	27	0.0000
Water	L	9.9744	0.0013	27	0.0035
Steam	kg	26.9409	0.0134	27	0.0975
Electricity	kWh	1.2528	0.1181	27	0.0399
Diesel (Production)	kg	0.0001	0.3282	27	0.0000
Diesel (Combustion)	L	0.0001	2.7080	27	0.0001
Grease	kg	0.0008	1.0547	27	0.0002
Lubricants	kg	0.0008	0.8319	27	0.0002
Output					
Bagasse	kg	29.1931	0.0000	27	0.0000
Filter cake	kg	3.9902	0.0000	27	0.0000
Waste water	L	10.9844	0.0014	27	0.0042
Bioethanol production					
Yeast	L	0.0000	3.2040	100	0.0001
Phosphoric acid	kg	0.0000	1.4067	100	0.0001
Ammonium sulfate	kg	0.0012	2.8300	100	0.0034
Diammonium sulfate	kg	0.0000	2.8300	100	0.0000
Sulfuric acid	kg	0.0132	0.1219	100	0.0016
				Total	**1.2751**
Manufacturing					
Input					
Soft water	L	10.0580	0.00003	100	0.0003
Electricity	kWh	0.3095	0.6093	100	0.1886
Steam	kg	2.8627	0.2340	100	0.6699
Output					
Vinasse	L	11.6054	0.0000	100	0.0000
Fusel oil	kg	0.0004	0.0000	100	0.0000
				Total	**0.8587**

Table C.2 GHG emissions of raw material, energy and resource transportation for sugarcane-based bioethanol. (Allocation by mass)

Activity	To go (tkm)	Come back (km)	EF ($kgCO_2eq$/Unit)		Allocation by mass (%)	GHG emissions ($kgCO_2eq$)
			To go	Come back		
Raw materials acquisition						
Sugar milling						
Input						
Unburned sugarcane S1	0.1945	0.0278	0.1402	0.3111	27	9.70E-03
	0.4052	0.0579	0.0674	0.4246	27	1.40E-02
	0.2269	0.0324	0.0610	0.4892	27	8.00E-03
	0.3566	0.0509	0.0530	0.5863	27	1.32E-02
	1.0698	0.1528	0.0441	0.8629	27	4.83E-02
	0.5673	0.0810	0.0530	0.5863	27	2.09E-02
Unburned sugarcane S2	1.5015	0.2145	0.0530	0.5863	27	5.54E-02
	0.1668	0.0238	0.0409	0.8801	27	7.50E-03
Burned sugarcane S1	1.0601	0.1514	0.1402	0.3111	27	5.28E-02
	2.1960	0.3137	0.0674	0.4246	27	7.59E-02
	1.2494	0.1785	0.0610	0.4892	27	4.42E-02
	1.9688	0.2813	0.0530	0.5863	27	7.27E-02
	5.7928	0.8275	0.0457	1.0142	27	2.98E-01
	3.1425	0.4489	0.0486	0.6015	27	1.14E-01
Burned sugarcane S2	1.4513	0.2073	0.0530	0.5863	27	5.36E-02
	1.4513	0.2073	0.0409	0.8801	27	6.53E-02
	0.3870	0.0553	0.1402	0.3111	27	1.93E-02
	0.5805	0.0829	0.0610	0.4892	27	2.05E-02
Calcium hydroxide	0.0359	0.0051	0.0530	0.5863	27	1.30E-03
Biocide	0.0003	0.00004	0.0530	0.5863	27	1.00E-05
Precipitating agents	0.0002	0.00003	0.0530	0.5863	27	1.00E-05
Sanitizer	0.00002	0.000003	0.1402	0.3111	27	1.00E-06
Waterlock	0.0002	0.00002	0.1402	0.3111	27	1.00E-05
Scale inhibitor S1	0.0004	0.00005	0.1402	0.3111	27	2.00E-05
Scale inhibitor S2	0.0002	0.00003	0.0530	0.5863	27	1.00E-05
Enzyme (Amylase)	0.0002	0.00003	0.1402	0.3111	27	1.00E-05
Sodium hydroxide S1	0.0031	0.0004	0.1402	0.3111	27	2.00E-04
Sodium hydroxide S2	0.0029	0.0004	0.0530	0.5863	27	1.00E-04
Butanedioic Acid	0.00003	0.000004	0.1402	0.3111	27	1.00E-06
Diesel	0.0000004	0.0000001	0.0674	0.4246	27	2.00E-08
Grease	0.00002	0.000002	0.0610	0.4892	27	1.00E-06
Lubricants	0.00002	0.000002	0.0610	0.4892	27	1.00E-06
Yeast	3.00E-06	4.29E-07	0.0457	1.0142	100	5.72E-07
Phosphoric acid	4.00E-06	5.71E-07	0.0457	1.0142	100	7.62E-07
Ammonium sulfate	1.23E-04	1.76E-05	0.0457	1.0142	100	2.34E-05
Diammonium sulfate	1.00E-06	1.43E-07	0.0457	1.0142	100	1.91E-07
Sulfuric acid	0.0013	0.0002	0.0457	1.0142	100	3.00E-04
Molasses	0.4255	0.0608	0.0457	1.0142	100	8.11E-02
					Total	**1.0773**

Table C.3 GHG emissions of raw material, energy, and resource acquisition and utilization for sugarcane-based bioethanol. (Allocation by economics)

Activity	Unit	Quantity (per FU)	EF ($kgCO_2eq$/ Unit)	Allocation by mass (%)	GHG emissions ($kgCO_2eq$)
Raw materials acquisition					
Sugar milling					
Input					
Unburned sugarcane	kg	38.4537	0.0193	8	0.0594
Burned sugarcane	kg	59.3630	0.0571	8	0.2712
Calcium hydroxide	kg	0.1578	0.0366	8	0.0005
Biocide	kg	0.0006	1.0400	8	0.0000
Precipitating agents	kg	0.0004	1.4300	8	0.0000
Sanitizer	kg	0.0001	1.3325	8	0.0000
Waterlock	kg	0.0006	2.8008	8	0.0001
Scale inhibitor	kg	0.0018	1.9493	8	0.0003
Enzyme (Amylase)	kg	0.0009	1.1500	8	0.0001
Sodium hydroxide	kg	0.0171	1.1148	8	0.0015
Butanedioic Acid	kg	0.0001	1.3325	8	0.0000
Water	L	9.9744	0.0013	8	0.0010
Steam	kg	26.9409	0.0134	8	0.0289
Electricity	kWh	1.2528	0.1181	8	0.0118
Diesel (Production)	kg	0.0001	0.3282	8	0.0000
Diesel (Combustion)	L	0.0001	2.7080	8	0.0000
Grease	kg	0.0008	1.0547	8	0.0001
Lubricants	kg	0.0008	0.8319	8	0.0001
Output					
Bagasse	kg	29.1931	0.0000	8	0.0000
Filter cake	kg	3.9902	0.0000	8	0.0000
Waste water	L	10.9844	0.0014	8	0.0012
Bioethanol production					
Yeast	L	0.0000	3.2040	100	0.0000
Phosphoric acid	kg	0.0000	1.4067	100	0.0000
Ammonium sulfate	kg	0.0012	2.8300	100	0.0034
Diammonium sulfate	kg	0.0000	2.8300	100	0.0000
Sulfuric acid	kg	0.0132	0.1219	100	0.0016
				Total	**0.3813**
Manufacturing					
Input					
Soft water	L	10.0580	0.00003	100	0.0003
Electricity	kWh	0.3095	0.6093	100	0.1886
Steam	kg	2.8627	0.2340	100	0.6699
Output					
Vinasse	L	11.6054	0.0000	100	0.0000
Fusel oil	kg	0.0004	0.0000	100	0.0000
				Total	**0.8587**

Table C.4 GHG emissions of raw material, energy and resource transportation for sugarcane-based bioethanol. (Allocation by economics)

Activity	To go (tkm)	Come back (km)	EF ($kgCO_2eq$/Unit)		Allocation by mass (%)	GHG emissions ($kgCO_2eq$)
			To go	Come back		
Raw materials acquisition						
Sugar milling						
Input						
Unburned sugarcane S1	0.1945	0.0278	0.1402	0.3111	8	2.87E-03
	0.4052	0.0579	0.0674	0.4246	8	4.15E-03
	0.2269	0.0324	0.0610	0.4892	8	2.38E-03
	0.3566	0.0509	0.0530	0.5863	8	3.90E-03
	1.0698	0.1528	0.0441	0.8629	8	1.43E-02
	0.5673	0.0810	0.0530	0.5863	8	6.20E-03
Unburned sugarcane S2	1.5015	0.2145	0.0530	0.5863	8	1.64E-02
	0.1668	0.0238	0.0409	0.8801	8	2.22E-03
Burned sugarcane S1	1.0601	0.1514	0.1402	0.3111	8	1.57E-02
	2.1960	0.3137	0.0674	0.4246	8	2.25E-02
	1.2494	0.1785	0.0610	0.4892	8	1.31E-02
	1.9688	0.2813	0.0530	0.5863	8	2.15E-02
	5.7928	0.8275	0.0457	1.0142	8	8.83E-02
	3.1425	0.4489	0.0486	0.6015	8	3.38E-02
Burned sugarcane S2	1.4513	0.2073	0.0530	0.5863	8	1.59E-02
	1.4513	0.2073	0.0409	0.8801	8	1.93E-02
	0.3870	0.0553	0.1402	0.3111	8	5.72E-03
	0.5805	0.0829	0.0610	0.4892	8	6.08E-03
Calcium hydroxide	0.0359	0.0051	0.0530	0.5863	8	3.91E-04
Biocide	0.0003	0.00004	0.0530	0.5863	8	3.15E-06
Precipitating agents	0.0002	0.00003	0.0530	0.5863	8	2.26E-06
Sanitizer	0.00002	0.000003	0.1402	0.3111	8	2.99E-07
Waterlock	0.0002	0.00002	0.1402	0.3111	8	2.74E-06
Scale inhibitor S1	0.0004	0.00005	0.1402	0.3111	8	5.73E-06
Scale inhibitor S2	0.0002	0.00003	0.0530	0.5863	8	2.26E-06
Enzyme (Amylase)	0.0002	0.00003	0.1402	0.3111	8	2.99E-06
Sodium hydroxide S1	0.0031	0.0004	0.1402	0.3111	8	4.47E-05
Sodium hydroxide S2	0.0029	0.0004	0.0530	0.5863	8	3.11E-05
Butanedioic Acid	0.00003	0.000004	0.1402	0.3111	8	4.36E-07
Diesel	0.0000004	0.0000001	0.0674	0.4246	8	5.55E-09
Grease	0.00002	0.000002	0.0610	0.4892	8	1.76E-07
Lubricants	0.00002	0.000002	0.0610	0.4892	8	1.76E-07
Yeast	3.00E-06	4.29E-07	0.0457	1.0142	100	5.72E-07
Phosphoric acid	4.00E-06	5.71E-07	0.0457	1.0142	100	7.62E-07
Ammonium sulfate	1.23E-04	1.76E-05	0.0457	1.0142	100	2.35E-05
Diammonium sulfate	1.00E-06	1.43E-07	0.0457	1.0142	100	1.91E-07
Sulfuric acid	0.0013	0.0002	0.0457	1.0142	100	2.62E-04
Molasses	0.4255	0.0608	0.0457	1.0142	100	8.11E-02
					Total	**0.3763**

Table C.5 GHG emissions of raw material, energy, and resource acquisition and utilization for cassava-based bioethanol. (Allocation by economics)

Activity	Unit	Quantity (per FU)	Emission factor ($kgCO_2eq$/Unit)	Allocation (%)	GHG emissions ($kgCO_2eq$)
Raw materials acquisition					
Cassava processing					
Input					
Fresh cassava	kg	7.6091	0.0651	100	0.4954
Diesel (Production)	kg	0.0102	0.3282	100	0.0033
Diesel (Combustion)	L	0.0121	2.7080	100	0.0328
Electricity	kWh	0.0011	0.6093	100	0.0007
Bioethanol production					
Input					
Enzyme (Amylase)	kg	0.0004	1.1500	100	0.0005
Sodium hydroxide	kg	0.0085	1.1148	100	0.0095
Yeast	kg	0.0008	3.2040	100	0.0026
Diesel (Production)	kg	0.0010	0.3282	100	0.0003
				Total	**0.5451**
Manufacturing					
Input					
Diesel (Combustion)	L	0.0012	2.7080	100	0.0032
Steam	ton	0.0034	1.9189	100	0.0065
Soft water	m3	0.0101	3.1399	100	0.0317
Electricity	kWh	0.4430	0.6093	100	0.2699
Output				100	
Vinasse	m3	0.0100	0.0000	100	0.0000
Fusel Oil	kg	0.0040	0.0000	100	0.0000
				Total	**0.3113**

Table C.6 GHG emissions of raw material, energy and resource transportation for cassava-based bioethanol. (Allocation by economics)

Activity	To go (tkm)	Come back (km)	EF ($kgCO_2eq$/Unit)		Allocation by mass (%)	GHG emissions ($kgCO_2eq$)
			To go	Come back		
Raw materials acquisition						
Cassava processing						
Input						
Fresh cassava	0.7609	0.0238	0.0457	1.0142	100	5.89E-02
Diesel	0.0004	0.0000	0.0649	0.4043	100	4.57E-05
Bioethanol production						
Input						
Cassava root F1	0.7000	0.0438	0.0530	0.5863	100	6.28E-02
Cassava root F2	0.0913	0.0130	0.1402	0.3111	100	1.69E-02
Cassava root F3	0.3652	0.0114	0.0441	0.8629	100	2.60E-02
Enzyme (Amylase) S1	0.0015	-	0.0107	-	100	1.57E-05
Enzyme (Amylase) S2	0.0059	-	0.0107	-	100	6.28E-05
Enzyme (Amylase) S3	0.0001	0.00001	0.0530	0.5863	100	1.32E-05
Enzyme (Amylase) S4	0.0001	0.00002	0.0649	0.4043	100	1.65E-05
Sodium hydroxide	0.0034	0.0002	0.0530	0.5863	100	3.03E-04
Yeast	0.0003	0.00002	0.0530	0.5863	100	3.03E-05
Diesel	0.00004	0.000005	0.0649	0.4043	100	4.56E-06
					Total	**0.1650**

APPENDIX D

WATER FOOTPRINT OF SUGARCANE-BASED AND CASSAVA-BASED BIOETHANOL CALCULATION

D.1 Water footprint of sugarcane-based bioethanol under rain-fed condition

Basis: $WF_{green,sugarcane}$ = 154 m^3/ton
$WF_{blue,sugarcane}$ = 0 m^3/ton
$WF_{grey,sugarcane}$ = 51 m^3/ton

➢ **Green water footprint**

SOLUTION:

- **Juice Extraction**

$WF_{prod[bioethanol]}$ = {0 + (154/1.00)} × 0.90
= 138.600 m^3/ton of sugarcane

- **Juice Purification**

$WF_{prod[bioethanol]}$ = {0 + (138.600/0.93)} × 1.00
= 149.032 m^3/ton of sugarcane

- **Evaporation**

$WF_{prod[bioethanol]}$ = {0 + (149.032/0.30)} × 1.00
= 496.773 m^3/ton of sugarcane

- **Crystallization**

$WF_{prod[bioethanol]}$ = {0 + (496.773/0.55)} × 1.00
= 903.224 m^3/ton of sugarcane

- **Centrifugation**

$WF_{prod[bioethanol]}$ = {0 + (903.224/0.27)} × 0.06
= 200.716 m^3/ton of sugarcane

- **Mixing**

$WF_{prod[bioethanol]}$ = {0 + (200.716/1.00)} × 1.00
= 200.716 m^3/ton of sugarcane

- **Fermentation**

$WF_{prod[bioethanol]}$ = {0 + (200.716/0.93)} × 1.00
= 215.824 m^3/ton of sugarcane

- **Distillation**

$WF_{prod[bioethanol]}$ = {0 + (215.824/0.08)} × 0.89
= 2,401.042 m^3/ton of sugarcane

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0 + (2{,}401.042/0.95)\} \times 1.00$$
$$= 2{,}527.421 \quad m^3/\text{ton of sugarcane}$$

➢ **Blue water footprint**

SOLUTION:

- **Juice Extraction**

$$WF_{prod[bioethanol]} = \{0.275 + (0/1.00)\} \times 0.90$$
$$= 0.248 \quad m^3/\text{ton of sugarcane}$$

- **Juice Purification**

$$WF_{prod[bioethanol]} = \{0.107 + (0.248/0.93)\} \times 1.00$$
$$= 0.374 \quad m^3/\text{ton of sugarcane}$$

- **Evaporation**

$$WF_{prod[bioethanol]} = \{0.046 + (0.374/0.30)\} \times 1.00$$
$$= 1.293 \quad m^3/\text{ton of sugarcane}$$

- **Crystallization**

$$WF_{prod[bioethanol]} = \{0.046 + (1.293/0.55)\} \times 1.00$$
$$= 2.397 \quad m^3/\text{ton of sugarcane}$$

- **Centrifugation**

$$WF_{prod[bioethanol]} = \{0 + (2.397/0.27)\} \times 0.06$$
$$= 0.533 \quad m^3/\text{ton of sugarcane}$$

- **Mixing**

$$WF_{prod[bioethanol]} = \{0\ .081 + (0.533/1.00)\} \times 1.00$$
$$= 0.614 \quad m^3/\text{ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0.056 + (0.614/0.93)\} \times 1.00$$
$$= 0.716 \quad m^3/\text{ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0.039 + (0.716/0.08)\} \times 0.89$$
$$= 8.000 \quad m^3/\text{ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0.008 + (8.000/0.95)\} \times 1.00$$
$$= 8.429 \quad m^3/\text{ton of sugarcane}$$

➢ **Grey water footprint**

SOLUTION:

- **Juice Extraction**

$$WF_{prod[bioethanol]} = \{0 + (51/1.00)\} \times 0.90$$
$$= 45.900 \quad m^3/\text{ton of sugarcane}$$

- **Juice Purification**

$$WF_{prod[bioethanol]} = \{0 + (45.900/0.93)\} \times 1.00$$
$$= 49.355 \quad m^3/\text{ton of sugarcane}$$

- **Evaporation**

$$WF_{prod[bioethanol]} = \{0 + (49.355/0.30)\} \times 1.00$$
$$= 164.517 \quad m^3/\text{ton of sugarcane}$$

- **Crystallization**

$$WF_{prod[bioethanol]} = \{0 + (164.517/0.55)\} \times 1.00$$
$$= 299.122 \quad m^3/\text{ton of sugarcane}$$

- **Centrifugation**

$$WF_{prod[bioethanol]} = \{0 + (299.122/0.27)\} \times 0.06$$
$$= 66.472 \quad m^3/\text{ton of sugarcane}$$

- **Mixing**

$$WF_{prod[bioethanol]} = \{0 + (66.472/1.00)\} \times 1.00$$
$$= 66.472 \quad m^3/\text{ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0 + (66.472/0.93)\} \times 1.00$$
$$= 71.475 \quad m^3/\text{ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0 + (71.475/0.08)\} \times 0.89$$
$$= 795.159 \quad m^3/\text{ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0 + (795.159/0.95)\} \times 1.00$$
$$= 837.009 \quad m^3/\text{ton of sugarcane}$$

➢ **Water footprint of sugarcane-based bioethanol under rain-fed condition**

$$WF_{prod[bioethanol]} = WF_{green} + WF_{blue} + WF_{grey}$$
$$= 2,527.421 + 8.429 + 837.009$$
$$= 3,372.859 \quad m^3/\text{ton of sugarcane}$$

D.2 Water footprint of sugarcane-based bioethanol under optimal condition

<u>Basis:</u> $WF_{green,sugarcane} = 123 \quad m^3/ton$
$WF_{blue,sugarcane} = 26 \quad m^3/ton$
$WF_{grey,sugarcane} = 42 \quad m^3/ton$

➢ **Green water footprint**

SOLUTION:

- **Juice Extraction**

$$WF_{prod[bioethanol]} = \{0 + (123/1.00)\} \times 0.90$$
$$= 110.700 \quad m^3/\text{ton of sugarcane}$$

- **Juice Purification**

$$WF_{prod[bioethanol]} = \{0 + (110.700/0.93)\} \times 1.00$$
$$= 119.032 \quad m^3/\text{ton of sugarcane}$$

- **Evaporation**

$$WF_{prod[bioethanol]} = \{0 + (119.032/0.30)\} \times 1.00$$
$$= 396.773 \quad m^3/\text{ton of sugarcane}$$

- **Crystallization**

$$WF_{prod[bioethanol]} = \{0 + (396.773/0.55)\} \times 1.00$$
$$= 721.405 \quad m^3/\text{ton of sugarcane}$$

- **Centrifugation**

$$WF_{prod[bioethanol]} = \{0 + (721.405/0.27)\} \times 0.06$$
$$= 160.312 \quad m^3/\text{ton of sugarcane}$$

- **Mixing**

$$WF_{prod[bioethanol]} = \{0 + (160.312/1.00)\} \times 1.00$$
$$= 160.312 \quad m^3\text{/ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0 + (160.312/0.93)\} \times 1.00$$
$$= 172.378 \quad m^3\text{/ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0 + (172.378/0.08)\} \times 0.89$$
$$= 1{,}917.705 \quad m^3\text{/ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0 + (1{,}917.705/0.95)\} \times 1.00$$
$$= 2{,}018.637 \quad m^3\text{/ton of sugarcane}$$

➢ **Blue water footprint**

SOLUTION:

- **Juice Extraction**

$$WF_{prod[bioethanol]} = \{0.275 + (26/1.00)\} \times 0.90$$
$$= 23.648 \quad m^3\text{/ton of sugarcane}$$

- **Juice Purification**

$$WF_{prod[bioethanol]} = \{0.107 + (23.648/0.93)\} \times 1.00$$
$$= 25.535 \quad m^3\text{/ton of sugarcane}$$

- **Evaporation**

$$WF_{prod[bioethanol]} = \{0.046 + (25.535/0.30)\} \times 1.00$$
$$= 85.163 \quad m^3\text{/ton of sugarcane}$$

- **Crystallization**

$$WF_{prod[bioethanol]} = \{0.046 + (85.163/0.55)\} \times 1.00$$
$$= 154.888 \quad m^3\text{/ton of sugarcane}$$

- **Centrifugation**

$$WF_{prod[bioethanol]} = \{0 + (154.888/0.27)\} \times 0.06$$
$$= 34.420 \quad m^3\text{/ton of sugarcane}$$

- **Mixing**

$$WF_{prod[bioethanol]} = \{0.081 + (34.420/1.00)\} \times 1.00$$
$$= 34.501 \quad m^3\text{/ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0.056 + (34.501/0.93)\} \times 1.00$$
$$= 37.154 \quad m^3\text{/ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0.039 + (37.154/0.08)\} \times 0.89$$
$$= 413.373 \quad m^3\text{/ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0.008 + (413.373/0.95)\} \times 1.00$$
$$= 435.137 \quad m^3\text{/ton of sugarcane}$$

➢ **Grey water footprint**

SOLUTION:

- **Juice Extraction**

$$WF_{prod[bioethanol]} = \{0 + (42/1.00)\} \times 0.90$$
$$= 37.800 \quad m^3\text{/ton of sugarcane}$$

- **Juice Purification**

$$WF_{prod[bioethanol]} = \{0 + (37.800/0.93)\} \times 1.00$$
$$= 40.645 \quad m^3\text{/ton of sugarcane}$$

- **Evaporation**

$$WF_{prod[bioethanol]} = \{0 + (40.645/0.30)\} \times 1.00$$
$$= 135.483 \quad m^3\text{/ton of sugarcane}$$

- **Crystallization**

$$WF_{prod[bioethanol]} = \{0 + (135.483/0.55)\} \times 1.00$$
$$= 246.333 \quad m^3\text{/ton of sugarcane}$$

- **Centrifugation**

$$WF_{prod[bioethanol]} = \{0 + (246.333/0.27)\} \times 0.06$$
$$= 54.741 \quad m^3\text{/ton of sugarcane}$$

- **Mixing**

$$WF_{prod[bioethanol]} = \{0 + (54.741/1.00)\} \times 1.00$$
$$= 54.741 \quad m^3/\text{ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0 + (54.741/0.93)\} \times 1.00$$
$$= 58.861 \quad m^3/\text{ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0 + (58.861/0.08)\} \times 0.89$$
$$= 654.829 \quad m^3/\text{ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0 + (654.828/0.95)\} \times 1.00$$
$$= 689.294 \quad m^3/\text{ton of sugarcane}$$

➢ **Water footprint of sugarcane-based bioethanol under optimal condition**

$$WF_{prod[bioethanol]} = WF_{green} + WF_{blue} + WF_{grey}$$
$$= 2{,}018.637 + 435.137 + 689.294$$
$$= 3{,}143.068 \quad m^3/\text{ton of sugarcane}$$

D.3 Water footprint of cassava-based bioethanol under rain-fed condition

<u>**Basis:**</u>

$$WF_{green,sugarcane} = 284 \quad m^3/\text{ton}$$
$$WF_{blue,sugarcane} = 0 \quad m^3/\text{ton}$$
$$WF_{grey,sugarcane} = 165 \quad m^3/\text{ton}$$

➢ **Green water footprint**

SOLUTION:

- **Cassava chips processing**

$$WF_{prod[bioethanol]} = \{0 + (284/0.40)\} \times 1.00$$
$$= 710.000 \quad m^3/\text{ton of sugarcane}$$

- **Milling and Mixing**

$$WF_{prod[bioethanol]} = \{0 + (710.000/0.98)\} \times 1.00$$
$$= 724.490 \quad m^3/\text{ton of sugarcane}$$

- **Liquefaction**

$$WF_{prod[bioethanol]} = \{0 + (724.490/1.00)\} \times 1.00$$
$$= 724.490 \quad m^3/\text{ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0 + (724.490/0.97)\} \times 1.00$$
$$= 746.897 \quad m^3/\text{ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0 + (746.897/0.10)\} \times 0.89$$
$$= 6{,}647.383 \quad m^3/\text{ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0 + (6{,}647.383/0.95)\} \times 1.00$$
$$= 6{,}997.245 \quad m^3/\text{ton of sugarcane}$$

➢ **Blue water footprint**

SOLUTION:

- **Cassava chips processing**

$$WF_{prod[bioethanol]} = \{0 + (0/0.40)\} \times 1.00$$
$$= 0 \quad m^3/\text{ton of sugarcane}$$

- **Milling and Mixing**

$$WF_{prod[bioethanol]} = \{1.049 + (0/0.98)\} \times 1.00$$
$$= 1.049 \quad m^3/\text{ton of sugarcane}$$

- **Liquefaction**

$$WF_{prod[bioethanol]} = \{0.003 + (1.049/1.00)\} \times 1.00$$
$$= 1.052 \quad m^3/\text{ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0 + (1.052/0.97)\} \times 1.00$$
$$= 1.085 \quad m^3/\text{ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0.197 + (1.085/0.10)\} \times 0.89$$
$$= 9.832 \quad m^3/\text{ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0.085 + (9.832/0.95)\} \times 1.00$$
$$= 10.434 \quad m^3\text{/ton of sugarcane}$$

➢ **Grey water footprint**

SOLUTION:

- **Cassava chips processing**

$$WF_{prod[bioethanol]} = \{0 + (165/0.40)\} \times 1.00$$
$$= 412.500 \quad m^3\text{/ton of sugarcane}$$

- **Milling and Mixing**

$$WF_{prod[bioethanol]} = \{0 + (412.500/0.98)\} \times 1.00$$
$$= 420.918 \quad m^3\text{/ton of sugarcane}$$

- **Liquefaction**

$$WF_{prod[bioethanol]} = \{0 + (420.918/1.00)\} \times 1.00$$
$$= 420.918 \quad m^3\text{/ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0 + (420.918/0.97)\} \times 1.00$$
$$= 433.936 \quad m^3\text{/ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0 + (433.936/0.10)\} \times 0.89$$
$$= 3{,}862.030 \quad m^3\text{/ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0 + (3{,}862.030/0.95)\} \times 1.00$$
$$= 4{,}065.295 \quad m^3\text{/ton of sugarcane}$$

➢ **Water footprint of cassava-based bioethanol**

$$WF_{prod[bioethanol]} = WF_{green} + WF_{blue} + WF_{grey}$$
$$= 6{,}997.245 + 10.434 + 4{,}065.295$$
$$= 11{,}072.974 \quad m^3\text{/ton of sugarcane}$$

D.4 Water footprint of cassava-based bioethanol under optimal condition

Basis:

$WF_{green,sugarcane}$ = 162 m^3/ton

$WF_{blue,sugarcane}$ = 125 m^3/ton

$WF_{grey,sugarcane}$ = 113 m^3/ton

➢ **Green water footprint**

SOLUTION:

- **Cassava chips processing**

$$WF_{prod[bioethanol]} = \{0 + (162/0.40)\} \times 1.00$$
$$= 405.000 \ m^3\text{/ton of sugarcane}$$

- **Milling and Mixing**

$$WF_{prod[bioethanol]} = \{0 + (405.000/0.98)\} \times 1.00$$
$$= 413.265 \ m^3\text{/ton of sugarcane}$$

- **Liquefaction**

$$WF_{prod[bioethanol]} = \{0 + (413.265/1.00)\} \times 1.00$$
$$= 413.265 \ m^3\text{/ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0 + (413.265/0.97)\} \times 1.00$$
$$= 426.046 \ m^3\text{/ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0 + (426.046/0.10)\} \times 0.89$$
$$= 3{,}791.809 \ m^3\text{/ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0 + (3{,}791.809/0.95)\} \times 1.00$$
$$= 3{,}991.378 \ m^3\text{/ton of sugarcane}$$

➢ **Blue water footprint**

SOLUTION:

- **Cassava chips processing**

$$WF_{prod[bioethanol]} = \{0 + (125/0.40)\} \times 1.00$$
$$= 312.500 \ m^3\text{/ton of sugarcane}$$

- **Milling and Mixing**

$$WF_{prod[bioethanol]} = \{1.049 + (312.500/0.98)\} \times 1.00$$
$$= 319.927 \quad m^3\text{/ton of sugarcane}$$

- **Liquefaction**

$$WF_{prod[bioethanol]} = \{0.003 + (319.927/1.00)\} \times 1.00$$
$$= 319.930 \quad m^3\text{/ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0 + (319.930/0.97)\} \times 1.00$$
$$= 329.825 \quad m^3\text{/ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0.197 + (329.825/0.10)\} \times 0.89$$
$$= 2{,}935.618 \quad m^3\text{/ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0.085 + (2{,}935.618/0.95)\} \times 1.00$$
$$= 3{,}090.209 \quad m^3\text{/ton of sugarcane}$$

➢ **Grey water footprint**

SOLUTION:

- **Cassava chips processing**

$$WF_{prod[bioethanol]} = \{0 + (113/0.40)\} \times 1.00$$
$$= 282.500 \quad m^3\text{/ton of sugarcane}$$

- **Milling and Mixing**

$$WF_{prod[bioethanol]} = \{0 + (282.500/0.98)\} \times 1.00$$
$$= 288.265 \quad m^3\text{/ton of sugarcane}$$

- **Liquefaction**

$$WF_{prod[bioethanol]} = \{0 + (288.265/1.00)\} \times 1.00$$
$$= 288.265 \quad m^3\text{/ton of sugarcane}$$

- **Fermentation**

$$WF_{prod[bioethanol]} = \{0 + (288.265/0.97)\} \times 1.00$$
$$= 297.180 \quad m^3\text{/ton of sugarcane}$$

- **Distillation**

$$WF_{prod[bioethanol]} = \{0 + (297.180/0.10)\} \times 0.89$$
$$= 2,644.902 \ \ m^3\text{/ton of sugarcane}$$

- **Dehydration**

$$WF_{prod[bioethanol]} = \{0 + (2,644.902/0.95)\} \times 1.00$$
$$= 2,784.107 \ \ m^3\text{/ton of sugarcane}$$

➢ **Water footprint of cassava-based bioethanol**

$$WF_{prod[bioethanol]} = WF_{green} + WF_{blue} + WF_{grey}$$
$$= 3,991.378 + 3,090.209 + 2,784.107$$
$$= 9,865.694 \ \ m^3\text{/ton of sugarcane}$$

APPENDIX E

LIST OF PUBLICATION

This thesis results in the following paper:

1. Rattikarn Kongboon and Sate Sampattagul., The water footprint of sugarcane and cassava in northern Thailand, 2012 (Spring) International APBITM Conference on 13th – 15th of January, 2012 in JomTien Plam Beach Resort Hotel, Pattaya, Thailand.
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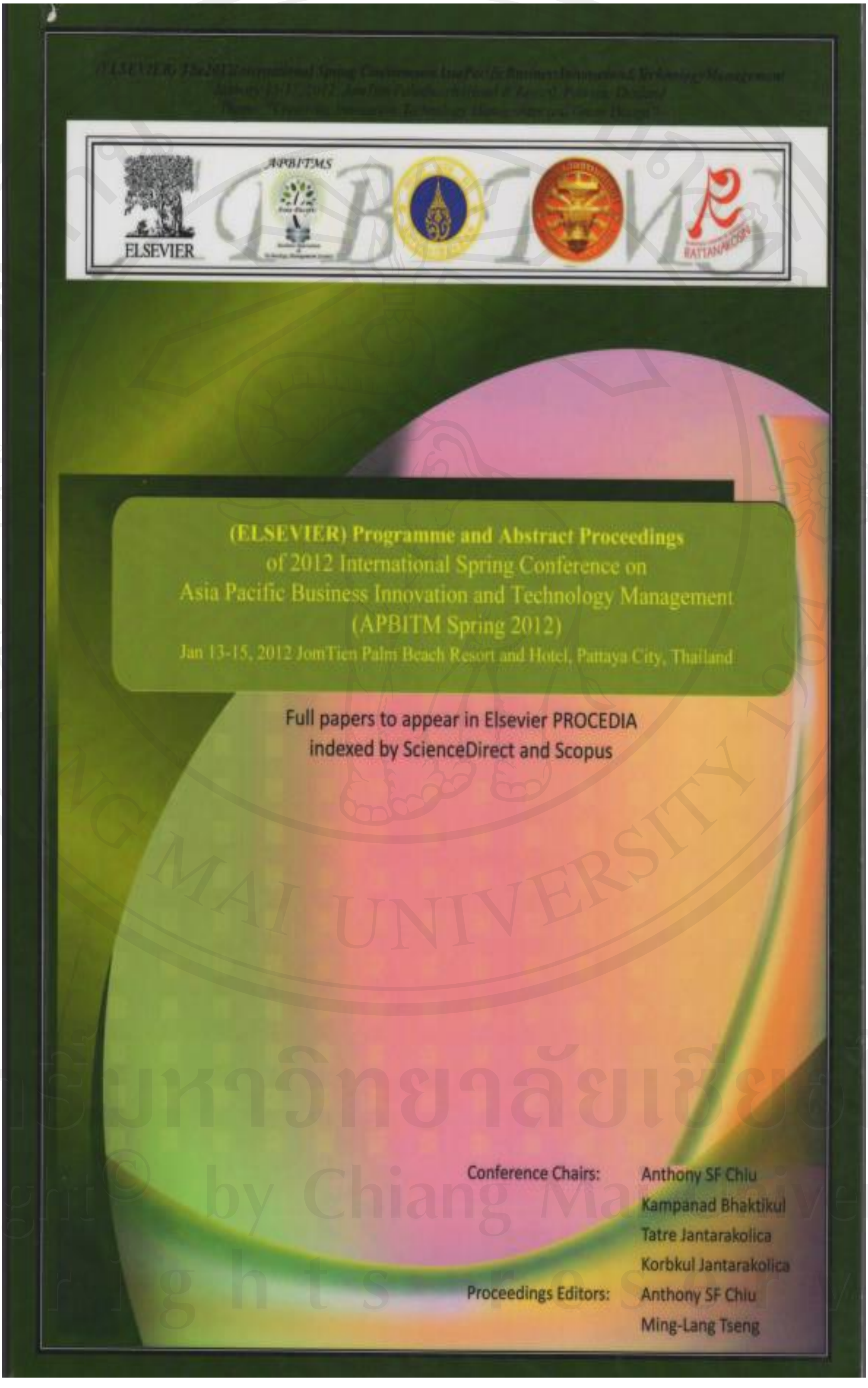
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The water footprint of sugarcane and cassava in northern Thailand

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Abstract

This study assesses the water footprint (WF) of sugarcane and cassava in northern Thailand. The WF is an indicator that expresses the amount of freshwater embodied in each ton of crop produce. It varies considerably for each region, which is characterized by different climate and agricultural production systems. On average the WF of sugarcane (202 m^3/ton) is less than that of cassava (509 m^3/ton). At the provincial level, the WF of sugarcane is most intensive in Lampang (252 m^3/ton) and less intensive in Kamphaeng Phet (167 m^3/ton). Uthai Thani is the province where the WF of cassava is the highest (547 m^3/ton), while Kamphaeng Phet has the lowest WF. If Thailand were to move toworads a low carbon society by switching from fossil fuel to bioenergy the effect on the volume of water usage in agricultural production is likely to increase. Therefore, the main problem facing Thailand will be water scarcity if water resource is not managed properly, this study showed the importance of water management for sustainable – bioenergy production and the competition for water resource between “water for food” or “water for energy”

Keywords:Water footprint, sugarcane, cassava

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1. Introduction

High economic growth and increased industrial production in Thailand has resulted in higher energy requirement, particularly for fossil Fuel. Low fossil fuel prices have been a major factor that helped promote its economic development. Over the last 5 year, however, world oil prices have been rising steadily. This is one of the main reason that the Thai government has recently increased it's a support to promote energy efficiency and alternative energy. In particular, ethanol (or ethyl alcohol) is an alternative type of energy that can be produced from agricultural raw materials such as sugarcane and cassava [12, 13,14, 15]. The Thai government has set the target to produce and use ethanol at least 9 million litres per day by 2065 to reduce the cost of importing fuel, with the expectation to increase income for farmers and to reduce green house gas emissions from fossil fuel combustion.

Global warming is affecting climate change, which is mainly due to increase of greenhouse gas emissions. The report of the Intergovernmental Panel on Climate Change indicates that the Earth's surface temperature has risen rapidly averaging 0.2 degrees per decade over the past 40 year. Water scarcity is expected to occur more quickly and severely than anticipated.

In recent years, Thailand experienced a severe drought in the agricultural sector causing a decline in yields. As a result the government promoted the cultivation of sugar cane and cassava for energy. Given that these crops require a large amount of water to grow and water is also a scarce resource, the information water usage for bioenergy production is essential for an effective energy policy [16]. A tool that has been used to assess water needs for production is the water footprint (WF) which was introduced by Hoekstra (2002). The WF can assess water need for crop production.

The objective of this study is to assess WF of sugarcane and cassava in northern Thailand. The result can be used to prepare guideline for the management of water resource for bioethanol production.

2. Methodology

2.1 The concept of water footprint (WF)

The water footprint (WF) has been introduced by Hoekstra (2002). It is tool that assesses the total volume of fresh water by considering both direct and indirect uses to produce the goods and services, measured over the full supply chain. It shows water consumption and pollution for a specified geographical region over a particular time horizon. The WF is expressed in water volume per unit of mass (m^3/ton or litre/kg), unit of time (m^3/month, m^3/year), or unit of energy (m^3/MJ, m^3/GJ) [6].

The WF consists of three components: blue, green and grey water footprint. The blue water footprint refers to surface and groundwater in a catchment area that evaporates during crop growth. The green water footprint refers to the rainwater that evaporated during crop growth. And the grey water footprint is the volume of freshwater for assimilating waste water base on ambient water quality standards [6]. The aim of this paper is to calculate WF of sugarcane and cassava for bio-ethanol production in the cultivated area of northern Thailand.

2.2 Calculating the WF of sugarcane and cassava

The WF of crop production is calculated following the WF assessment manual of Hoekstra et al. (2011). In the beginning, evapotranspiration (Et_c in mm/day) is calculated over the growing period of the crop using CROPWAT 8.0 model which was developed by the Food and Agriculture Organization of the United Nation. Crop water requirement (CWR) and irrigation requirement are then evaluated based on soil, climate and crop data [3]. Finally, the WF of crop is calculated by using the following steps [6]:

Step 1: Calculation of green and blue components of crop water usage (CWU, m^3/ha). These are calculated by accumulation of daily evapotranspiration (ET, mm/day) using the CROPWAT model:

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green} \quad (1)$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue} \quad (2)$$

where the factor 10 is applied to convert the unit from mm into m^3/ha. lgp denotes the length of growing period in days.

Step 2: Calculation of the green and blue water footprint of growing a crop (WF, m^3/ton). This is calculated as the crop water use (CWU, m^3/ha) divided by the crop yield (Y, ton/ha):

$$WF_{geen} = \frac{CWU_{green}}{Y} \quad (3)$$

$$WF_{blue} = \frac{CWU_{blue}}{Y} \quad (4)$$

Step 3: The grey water footprint (WF_{grey}, m^3/ton) is calculated for a growing crop by multiplying the chemical application rate per hectare (Appl, kg/ha) with the leaching-run-off fraction (α) divided by the maximum acceptable concentration (c_{max}, kg/m^3) minus the natural concentration for the pollutant considered (c_{nat}, kg/m^3) and then divided by the crop yield (Y, ton/ha).

$$WF_{grey} = \frac{(\alpha \times Appl)/(c_{max} - c_{nat})}{Y} \quad (5)$$

Step 4: The total water footprint of the process of growing crops (WF_{proc}) is the sum of green, blue and grey water footprints.

$$WF_{Proc} = WF_{green} + WF_{blue} + WF_{grey} \quad (6)$$

This paper expressed the process water footprint in water volume per mass (m^3/ton).

3. Data Sources

The main source of data which is used in the CROPWAT model available thought the website of FAO (www.fao.org) [5]. In this study, the CWR is calculated on the basis of optimal assumption that is irrigated at critical depletion and the soil refill to field capacity.

3.1 Sugarcane and Cassava

Sugarcane and Cassava is generally grown in northern, northeastern and central plain. In the northern cultivated area there is a minimum and a maximum average yield (see, Table 1). The planting time of sugarcane is either between July and September or between October and December [10]. For cassava the planting time is May through to July. This paper calculated crop water requirement of crops on optimal assumption.

3.2 Climate Data

The climate data needed as input to CROPWAT model has been taken from Thai Meteorological Department [14]. The climate data for each province contains temperature (°C), humidity (%), wind (km/day) and sunshine (hours).

3.3 Crop parameters

The crop parameters is required for input to CROPWAT model are the crop coefficients (K_c) different crop development stage, the length of growth stage, the root depth, the planting date. The K_c was evaluated by the Penman-Monteith equation used data from Royal Irrigation Department [8] (Table 2).

Table 1 Area, production and yield by province of sugarcane and cassava. Period: 2008 – 2010

Province	Sugarcane			Cassava		
	Average Harvested area (ha)	Average production (ton/year)	Average Yield (ton/ha)	Average Harvested area (ha)	Average production (ton/year)	Average Yield (ton/ha)
Whole Kingdom	1,009,112	69,708,619	69.08	1,226,178	25,728,215	20.98
Northern	289,433	21,055,085	72.75	203,794	4,437,445	21.77
Northeastern	368,357	24,879,543	67.54	656,362	13,576,188	20.68
Central Plain	351,322	23,773,991	67.67	366,021	7,714,582	21.08
Chiang Rai*	81	4,056	49.80	1,626	32,638	20.08
Phayao	0	0	0	760	15,324	20.17
Lampang	4,972	244,804	49.23	157	2,917	18.52
Chiang Mai	372	21,010	56.42	0	0	0
Tak	1,405	85,614	60.91	2,527	55,314	21.89
Kamphaeng Phet	65,021	4,894,977	75.28	79,045	1,792,598	22.68
Sukhothai	24,337	1,597,524	65.64	1,397	29,100	20.83
Phrae	316	20,894	66.19	215	4,270	19.83
Uttaradit	14,293	949,094	66.40	2,312	46,126	19.95
Phitsanulok	19,932	1,370,927	68.78	28,068	599,334	21.35
Phichit	6,727	450,508	66.97	624	12,634	20.25
Nakhon Sawan	86,130	6,543,702	75.98	42,833	915,179	21.37
Uthai Thani	30,750	2,170,396	70.58	33,945	720,818	21.24
Phetchabun	35,149	2,704,294	76.94	10,285	211,192	20.53

*Data only 2008 (Source: Office of Agricultural Economics, 2009)

Table 2 The K_c of sugarcane and cassava

Crop	K_c,int	K_c,mid	K_c,end
Sugarcane	0.65	1.27	0.57
Cassava	0.35	1.04	0.50

(Source: Royal Irrigation Department, 2010)

3.4 The grey water footprint

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Sugar cane and cassava production use fertilizer (Table 3), herbicide and pesticide in stage of growing to get high yield. This study considered the effect of nitrogen fertilizer and it is calculated based on the average areas of crops harvesting (Table 4, 5). The environmental impact on the use of other nutrients, herbicide and pesticide has not been analyzed. Nitrogen can leach from the field to water which will have a direct impact on water quality. The leaching run off fraction is assumed to be 10% [1]. The maximum acceptable concentration for nitrate in drinking water quality standard is 10 mg/l and calculated volume water for dilution [1].

Table 3 Average fertilizer application rate

Crop	N	P_2O_5	K_2O
	(kg/ha)		
Sugarcane	125	206	156
Cassava	175	113	169

(Source: Department of Agriculture, 2010)

Table 4 Total fertilizer application and Nitrogen leaching to water body of sugarcane (ton/year)

Province	Total fertilizer application			Nitrogen leaching
	N	P_2O_5	K_2O	
Chiang Rai	10	17	13	1
Lampang	622	1025	777	62
Chiang Mai	47	77	58	5
Tak	176	290	220	18
Kamphaeng Phet	8128	13411	10160	813
Sukhothai	3042	5020	3803	304
Phrae	40	65	49	4
Uttaradit	1787	2948	2233	179
Phitsanulok	2492	4111	3114	249
Phichit	841	1387	1051	84
Nakhon Sawan	10766	17764	13458	1077
Uthai Thani	3844	6342	4805	384
Phetchabun	4394	7249	5492	439
Average	2784	4593	3479	278

Table 5 Total fertilizer application and Nitrogen leaching to water body of cassava (ton/year)

Province	Total fertilizer application			Nitrogen leaching
	N	P_2O_5	K_2O	

Chiang Rai	285	183	274	28
Phayao	133	86	128	13
Lampang	27	18	26	3
Tak	442	284	426	44
Kamphaeng Phet	13833	8893	13339	1383
Sukhothai	244	157	236	24
Phrae	38	24	36	4
Uttaradit	405	260	390	40
Phitsanulok	4912	3158	4736	491
Phichit	109	70	105	11
Nakhon Sawan	7496	4819	7228	750
Uthai Thani	5940	3819	5728	594
Phetchabun	1800	1157	1736	180
Average	2743	1764	2645	274

4. Results and Discussion

Table 6 shows the result for the WF of sugarcane and cassava for 14 provinces in northern Thailand, expressed in cubic meters per unit of mass (m^3/ton). Fig 1 shows that sugarcane consist of green, blue and grey WF. The WF increases in the following order: Lamphang (252 m^3/ton), Chiang Mai (244 m^3/ton), Chiang Rai (240 m^3/ton), Tak (216 m^3/ton), Sukhothai (206 m^3/ton), Uttaradit and Uthai Thani (192 m^3/ton), Nakhon Sawan and Phitsanulok (188 m^3/ton), Phrae (186 m^3/ton) and Phichit (185 m^3/ton).

Fig 2 shows the WF of cassava. Uthai Thani (547 m^3/ton) has substantially larger WF than Nakhon Sawan (545 m^3/ton), Lampang (547 m^3/ton), Phetchabun (525 m^3/ton), Sukhothai (522 m^3/ton), Uttaradit (518 m^3/ton), Phrae (505 m^3/ton), Phichit (499 m^3/ton), Phitsanulok (495 m^3/ton), Tak (490 m^3/ton), Phayao (486 m^3/ton), Chiang Rai (482 m^3/ton) and Kamphaeng Phet (451 m^3/ton).

The WF of crops varies across region. This is difference in crop yields and WF. The WF of cassava is larger than sugarcane by 2.5 times. The result showed that different region, crop, agricultural production systems and yields have an effect on WF. In each region, sugarcane is better than cassava. For these crops, the study applied average yield data taken from production system. The low average of cassava was caused by inefficient water use.

The WF in northern Thailand for both crops is lowers than the global average (Table 7). The green WF, which is the rainwater that evaporated during crop growth for Thailand is substantially lesser than the global average. This is mainly due to the differences in crop yield.

Table 6 The WF of sugarcane and cassava in northern Thailand

Province	Sugarcane (m^3/ton)				Cassava (m^3/ton)			
	Green	Blue	Grey	Total	Green	Blue	Grey	Total
Chiang Rai	142	65	33	240	207	188	87	482
Phayao	-	-	-	-	203	196	87	486
Lampang	99	120	33	252	217	236	94	547
Chiang Mai	120	95	29	244	-	-	-	-
Tak	97	92	27	216	179	231	80	490
Kamphaeng Phet	71	74	22	167	176	198	77	451

Sukhothai	95	86	25	206	198	240	84	522
Phrae	71	90	25	186	198	219	88	505
Uttaradit	84	84	24	192	182	248	88	518
Phitsanulok	73	91	24	188	182	231	82	495
Phichit	77	84	24	185	190	223	86	499
Nakhon Sawan	92	75	21	188	182	281	82	545
Uthai Thani	70	99	23	192	196	269	82	547
Phetchabun	82	70	21	173	188	252	85	525
Average	90	87	25	202	192	232	85	509

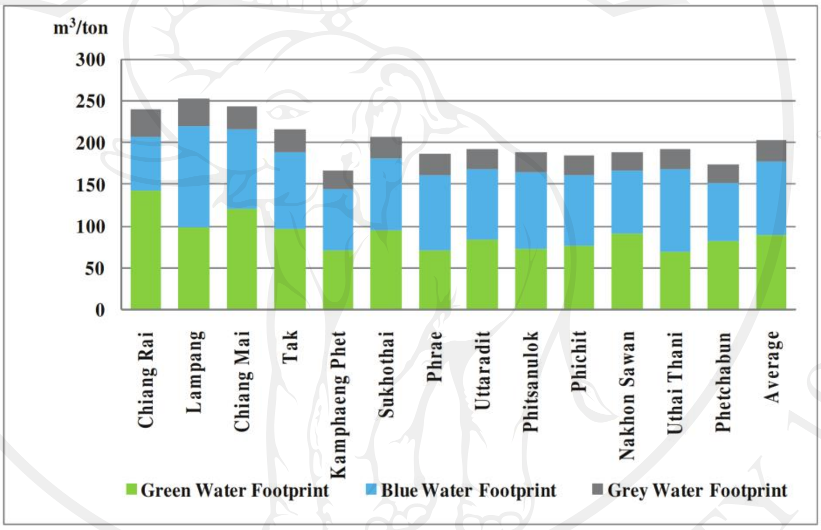

Figure 1 Water footprint of sugarcane in northern Thailand

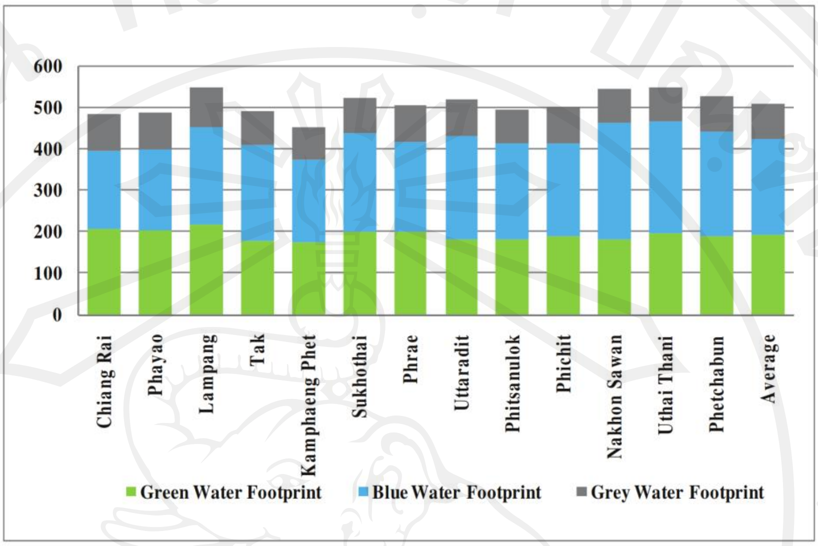

Figure2 Water footprint of cassava in northern Thailand

Table 7 Global and Thailand average water footprint

Province	Sugarcane (m^3/ton)				Cassava (m^3/ton)			
	Green	Blue	Grey	Total	Green	Blue	Grey	Total
Global average*	139	57	13	210	550	0	13	564
Thailand	90	87	25	202	192	232	85	509

(* Source: Mekonnen and Hoekstra, 2011)

5. Uncertainties

The data presented in this study based on period 2008-2010 and rough estimate of fresh water requirement in crop production that optimal assumption. For assessment of the WF of crops, the study integrated information from several sources which adds a degree of uncertainty. For example, the CROPWAT model required input of planting date that was base on an assumption of data from Department of Agriculture which is not the same as the actual planting date. In fact, farmers are cultivating the crop in the rainy season which may differ from the reference in the calculation. Although the study cited data from the literature, it shows that water use efficiency of crops. The result from this study provides suitable guidelines for the management of water resource in northern Thailand.

6. Conclusions

The study shows the water footprint of sugarcane and cassava production in northern Thailand for the period 2008-2010. It has shown volume of freshwater use per average yield. The result showed that the average WF of cassava is 2.5 times more than that of sugarcane. The differences in the value of WF are caused by various factors, including climate, crop characteristics, agricultural production system which differs for each region. For example, Kamphaeng Phet has the smallest WF for both sugarcane and cassava where yield of sugarcane is lower than in Nakhon Sawan and the largest of cassava in northern Thailand. The result shows the WF are somewhat similar for each province. For example, the WF of sugarcane from Kamphaeng Phet is 1.5 times larger than that form Lampang. The WF of cassava from Uthai Thani is 1.2 times larger than from Kamphaeng Phet. At the present, the northern region has witnessed an increasing trend for cultivation area and production yield. The demand for bioenergy in Thailand has increased too. The bioenegy derived from biomass uses freshwater for agricultural production system. If the demand of biomass increases the volume of water usage also increases. The results from this paper can be used to prepare suitable guidelines for the management of water resource and increase crop yield. As bioenergy is promoted to decrease the impact of fossil fuel on climate change, it will also bring non-sustainable water resource and raise confliction between "water for food" and "water for energy" [4].

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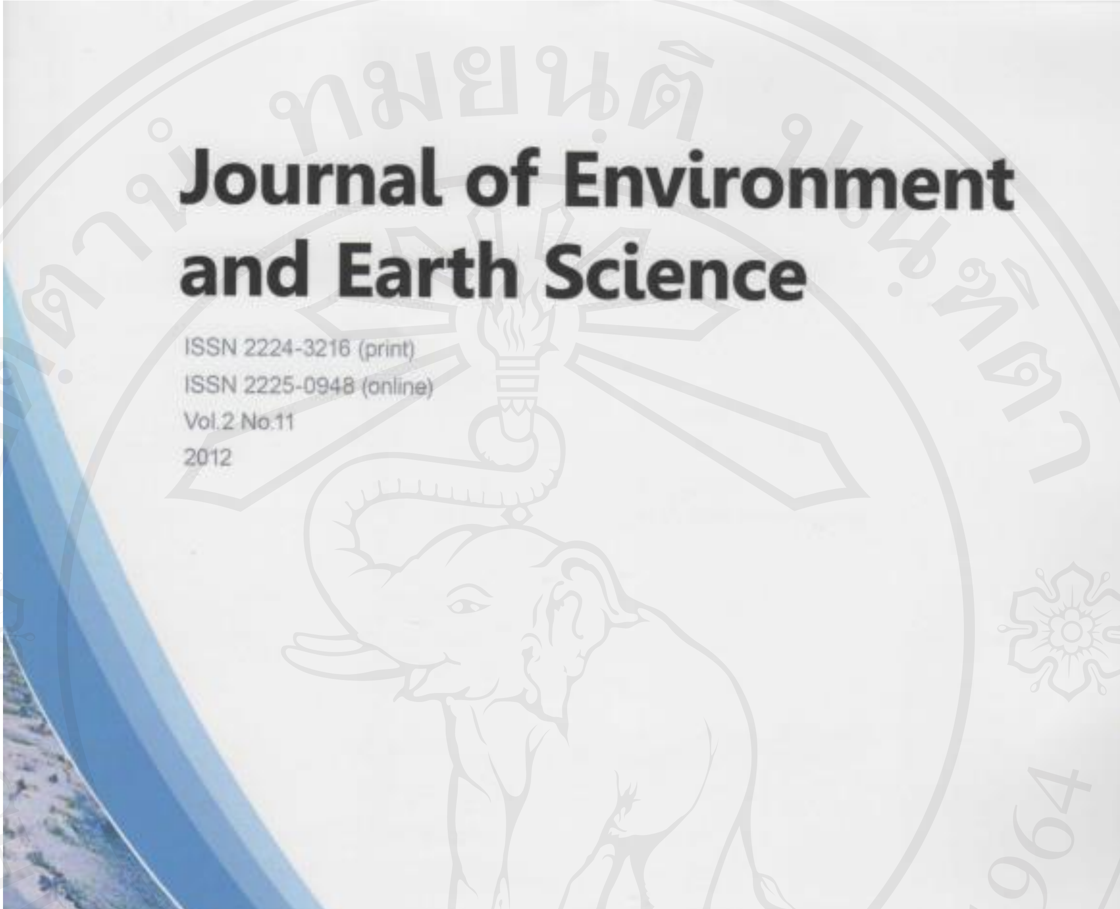
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Water Footprint of Bioethanol Production from Sugarcane in Thailand

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Abstract

Following Thailand's policy framework on bioenergy as stipulated in the Alternative Energy Development Plan (AEDP), ethanol use is encouraged and thereby results in increasing cultivation of sugarcane and other ethanol plants. Inadvertently, the use of scarce water resources has increased in tandem. This research aims to assess water footprint (WF) of sugarcane-based bioethanol production in Thailand. The study consists of into two parts, i.e., cultivation and ethanol production processes.

The study result shows WF of sugarcane of 226 m^3/ton, which consists of green WF of 146 m^3/ton, blue WF of 31 m^3/ton, and grey WF of 49 m^3/ton. Based on the AEDP ethanol production targets of 3, 6.2 and 9 million m^3/day by 2011, 2016, and 2022, demand of water is thus anticipated at 18,041; 37,787 and 54,853 million m^3/year, respectively. The promotion of ethanol use in such an agricultural country as Thailand is definitely poised to cause the competition for water resources in plant growing for human consumption and energy production. The results of this study can be applied to drawing up the future policy on water and to producing bioethanol in the manner that is the most efficient use of water resources.

Keywords: Water footprint, sugarcane, Bioethanol, water resource, Thailand

1. Introduction

The rapid economic growth in Thailand has led to the inevitable exponential growth in energy demand, and fossil fuel is of great importance in the economic prosperity of the Kingdom; the global oil prices however have been on the rise. As such, the administration has launched a number of energy saving policies and promoted the alternative use of different types of renewable energy, especially ethanol from agricultural products such as sugarcane and cassava. The government has also financially supported the ethanol production so as to reduce dependence on oil imports while increasing the incomes of Thai farmers.

Increased sugarcane cultivation for ethanol production can significantly have an adverse impact on the use of land, fertilizer, and water. The scarcity of water resources is an international problem which is anticipated to become graver in the 21st century when the need of water for production and consumption continues to rise while the water resources are limited. Even though the world is covered with 1,400 billion m^3 of water, only 35 billion m^3 or 2.5 percent of the total amount is fresh water. Moreover, 70 percent of the fresh water is ice and snow covering mountains in the north and south poles and almost 30 percent is groundwater, thus leaving only 0.3 percent as water in rivers and lakes. Of all, groundwater is most used and accounts for 97 percent of fresh water being used (UN-Water Statistics, 2011).

Of fresh water, approximately 70 percent is being used in agriculture, 22 percent in industries, and 8 percent for household consumption (UN-Water Statistics, 2011). The promotion of ethanol use will unavoidably affect the water use in agriculture and industries, especially in such an agricultural country as Thailand. Therefore, there should be serious research studies and subsequently plans for suitable use of water.

Water footprint (WF) is an indicator of water use taking into consideration the direct and indirect water use throughout the life cycle of a product or service. The concept of WF introduced by Hoekstra (2003) and subsequently elaborated by Hoekstra and Chapagain (2008) provides a framework to analyze the link between human consumption and the appropriation of the global freshwater. The WF of product expressed in water volume per unit of product (m^3/ton) is the sum of the WF of the steps taken to produce the product. The WF within a geographically delineated area (e.g., a province, nation or catchment area) is equal to the sum of the WF of all process taking place in that area. The blue WF refers to the volume of surface and groundwater consumed (evaporated) as a result of the production of a product, the green WF refers to the rain water consumed, and the

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grey WF refers to the amount of clean water for the dilution of pollutants to meet the standard of the existing ambient water (Mekonnen and Hoekstra., 2011). WF shows not merely the amount of rainwater and irrigation water used but also that of fresh water needed for diluting wastewater to standard water (Chapagain et.al, 2011). It indicates whether the amount of rainwater is sufficient for the need of plants, how to allocate irrigation water for agriculture in order to avoid water war between food and energy. As a result, the objective of this research is to study the water footprint of sugarcane–based ethanol production taking into account the whole life cycle starting from sugarcane cultivation, sugar milling and ethanol production with the findings to be used as guidelines for future water management in Thailand.

2. Materials and Methods

2.1 Goal and Scope Definition

This paper aims to assess WF of sugarcane–based ethanol production and the functional unit in this study is defined as one ton of sugarcane.

2.2 System boundary

The system boundaries of the life cycle of sugarcane–based ethanol production are shown in Figure 1, which encompass sugarcane cultivation, sugar milling (molasses generation) and bioethanol production. Since every step in the process consumes water, calculation of the total water use throughout the life cycle of bioethanol is thus performed. Water footprint consists of green, blue and grey components, each of which looks at the use of water from different sources. The green component refers to the use of rainwater excluding run-off water, the blue component to the use of surface water and groundwater, and the grey component is indicative of the amount of clean water for the dilution of waste water to meet the standard of surface water.

2.3 WF of sugarcane

2.3.1 Site description, planting design and crop management

The data from the Office of Agricultural Economics of 2008 – 2012 show that the cultivation areas of sugarcane in northern Thailand cover 12 provinces. Geographic Information System (GIS) was employed in the selection of areas to collect the field data to determine density of the sugarcane cultivation area and soil series. The field data were collected from 3 provinces in the north of Thailand, i.e., Nakorn Sawan, Kampaengpetch, and Utai Thani. The growers were interviewed individually with a close-ended questionnaire whereby 200 respondents from each of the three provinces were asked, bringing the total of participants to 600. The averages of the collected data were then computed and then used as the representative of residents of northern Thailand.

It has been found that most of the growers in northern Thailand plant sugarcane during January and February. As shown in Table 1, the same group of growers in the northern part of Thailand would apply fertilizers during the periods land preparation and crop maintenance. For one hectare of sugarcane cultivation, the quantities of N-fertilizer, P-fertilizer, and K-fertilizer used are respectively 166.9 kg, 101.3 kg, and 125 kg. Most of the sugarcane growers are found to rely mainly on rainwater without the use of irrigation water.

2.3.2 Evapotranspiration

The volume of water required to grow sugarcane in the field is typically equal to that of crop evapotranspiration. Evapotranspiration is defined as the combination of two separate processes whereby water is lost on one hand from the soil surface by evaporation and on the other hand from the crop by transpiration [Eva Sevigne et al., 2010]. Crop evapotranspiration is equal to crop water requirement (CWR). The evapotranspiration, according to Chapagian et al. (2011), contains two components: green water for the use of effective rainfall and blue water for the use of irrigation water. The calculation has been performed over the growing period of the crops using CROPWAT 8.0 model, which was developed by the Food and Agriculture Organization of the United Nations (FAO).

In this study, the crops were grown under optimal conditions and the calculation option selected was the irrigation schedule option. The model would calculate the crop evapotranspiration using soil water balance approach. The climate data as inputs of the CROPWAT model were obtained from the Thai Meteorological Department, which consisted of minimum and maximum temperatures, humidity, wind and amounts of sunshine. The crop coefficients (K_c) of sugarcane by Penman-Monteith as depicted in Table 2 were obtained from the Royal Irrigation Department (2010). The K_c values vary by crop, stage of growth of the crop, and certain cultural practices. The soil data were derived from the Land develop department while those concerning area, production, and yield were from the Office of Agricultural Economics (2009), averaged over the period of

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2008-2012. The calculation of evapotranspiration can be performed with the following equation (Hoekstra et al., 2011).

$$ET_a \text{ (mm/growing period)} = K_s \times K_c \times ET_0 \quad [1]$$

where K_c is the crop coefficient, K_s a water stress coefficient, and ET_0 the reference evapotranspiration (mm/day). In calculating the green and blue water evapotranspiration, the irrigation timing and application of irrigation are different. In this study, the default value is 'irrigate at critical depletion' and 'refill soil to field capacity,' which are regarded as optimal irrigation (Hoekstra et al., 2011).

The water footprint of sugarcane was calculated according to the methodologies described in the "Water Footprint Assessment Manual" (Hoekstra et.al, 2011). The green water footprint (WF_{green}) was estimated as the ratio of effective rainfall (R_{eff}) to the crop yield (Y, ton/year) (Eq.[2]) while the blue water footprint (WF_{blue}) as the ratio of irrigation water requirement (Irr) to the crop yield (Y, ton/year) (Eq.[3]). In both equations, the factor 10 was used to convert from mm to m^3 per hectare.

$$WF_{green} = 10\frac{Reff}{Y} \quad [2]$$

$$WF_{blue} = 10\frac{Irr}{Y} \quad [3]$$

The grey water footprint (WF_{grey}) was defined as the ratio of the chemical application rate per year (A_{ppl}, ton/year) times the leaching-run-off-fraction (α) to the maximum acceptable concentration (C_{max}, kg/m^3) minus the natural concentration for the pollutant considered (C_{nat}, kg/m^3) and then divided by the crop yield (Y, ton/ha) (Eq. [4]).

$$WF_{grey} = \frac{(\alpha \times Appl)/(c_{max} - c_{nat})}{Y} \quad [4]$$

The field data on sugarcane cultivation show that the growers applied fertilizers and insecticides. In this study, only the effects of application of Nitrogen fertilizer were investigated since nitrogen can leach from the field into water, the incident of which would have an adverse impact on water quality. The leaching run off fraction was assumed to equal 10 percent of the total fertilizer use (Chapagian et al., 2006). The maximum acceptable concentration for nitrate in the surface water is 5 mg/l (Pollution Control Department, 2011). The water footprint of sugarcane in the unit of volume per mass (m^3/ton) is calculated by summing the three components as shown in [Eq.5].

$$WF_{sugarcane} = WF_{green} + WF_{blue} + WF_{grey} \quad [5]$$

2.4 WF of bioethanol production

The data on water use of the entire process in this study are primary data from factory, which were collected according to the life cycle assessment (LCA). Bioethanol production begins with cane stalks being cut and then transported to a sugar milling factory where juice extraction, juice clarification, evaporation, and crystallization and centrifuging take place and molasses is derived. Molasses is subsequently used as the raw material of bioethanol production which involves pre-treatment, fermentation, distillation, and dehydration. In this research, the water footprint of bioethanol is calculated following the stepwise accumulative approach proposed by

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Hoekstra (2011).

The production of sugar and bioethanol also generates by-products with economic value. To calculate the WF of these products and their by-products, the allocation methodology as proposed in Hoekstra et.al.'s work (2011) is used. The WF of the crop over to crop products is determined by dividing the crop WF (WF_{prod}) by the production fraction *fp*[p,i]. The production fraction is defined as the ratio of the product mass (kg) to the aggregated mass of the crop (kg). Next, the WF of all the products with economic value is represented by their value fraction *fv*[p,i]. The value fraction is defined as the ratio of the product with economic value to the aggregated market value of all products obtained from the crop. Finally, to calculate the WF of a product (WF_{prod}[p]), one needs to add the process water footprint WF_{proc}[p] (Gerbens-Leenes W, Hoekstra AY, 2011). The product WF is calculated by:

$$WF_{prod}[p] = \left(WF_{proc}[p] + \sum_{i=1}^{y} \frac{WFprod[i]}{f_p[p,i]}\right) \times f_v[p,i] \qquad [6]$$

Figure 2 shows the flowchart of bioethanol production from one ton of sugarcane. It was found that the sugar milling process and ethanol production respectively used 0.19 m^3 and 0.14 m^3 of water. The production fractions of molasses and ethanol were 0.05 and 0.19, both of which were derived from the data garnered from the factory. According to the Thailand Environment Institute Foundation (2009), the value fraction of molasses is 0.09 while that of ethanol is 0.89 in reference to W.Scholten's work (2009).

3. Results and Discussion

3.1 WF of sugarcane

The calculation of WF of sugarcane as shown in Table 3 is the average value of sugarcane cultivation area in northern Thailand. It was found that the crop water requirement of sugarcane equaled 1,204.85 mm/growing period, comprising 996.81 mm/growing period of effective rainfall and 208.04 mm/growing period of irrigation water requirement. From the calculation, WF of sugarcane was 226 m^3/ton, which consisted of green WF of 146 m^3/ton, blue WF of 31 m^3/ton, and grey WF of 49 m^3/ton.

3.2 WF of bioethanol

As shown in Table 4, WF of bioethanol is 1,906 m^3/ton, consisting of green WF of 1,232 m^3/ton, blue WF of 262 m^3/ton, and grey WF of 412 m^3/ton. The WF of molasses production is 407 m^3/ton, which consists of green WF of 263 m^3/ton, blue WF of 56 m^3/ton, and grey of WF 88 m^3/ton.

4. Conclusions

Even though Thailand is estimated to have around 444 billion m^3 of total renewable water resource (TRWR) (Beau, 2010), increase in biofuel production to meet the AEDP targets will negatively impact the water resource. As seen in Figure 3, to meet the AEDP's annual ethanol production targets of 3, 6.2 and 9 million m^3 by 2011, 2016, and 2022, it is anticipated that demand for water would be 18,041; 37,787 and 54,853 million m^3/year, respectively. Therefore, the water demand in the respective years for the ethanol production will account for 4.1, 8.5 and 12.4 percent of Thailand's TRWR. Based on this analysis, the impact of the AEDP's promotion of ethanol use on Thailand's water resources is inevitable. The total water consumption associated with sugarcane-based bioethanol production is expected to grow rapidly, particularly consumption of water from effective rainfall. Therefore, as Thailand is one of the world's major producers of agricultural products and at the same time is ranked among the top countries that use a large amount of water, water crisis in Thailand has become more serious each year. If Thailand is to promote the use of bioethanol as alternative energy, Thai citizens need be made aware of the problem of competition for water resources between food and energy production which is expected to happen in the near future not only in Thailand but all over the globe.

The reduction of WF in the agricultural sector of Thailand is of greater importance than in the industrial sector, and WF would reduce if yield could increase. An improper way to improve yield is to expand the area of cultivation; a suitable means is instead to expand the area of irrigated land. In sugarcane cultivation it is possible to reduce the use of N-fertilizer, which subsequently decreases grey WF. While this contributes to higher agricultural output, it will nevertheless require more use of water resources. The Thai government should draw up a concrete water plan in which WF is taken into consideration. In addition, greater research funds should be allocated to the study on WF in agriculture and industry with a belief that the findings could be applied to water management through a water policy that enables us to achieve the most efficient use of scarce water resources.

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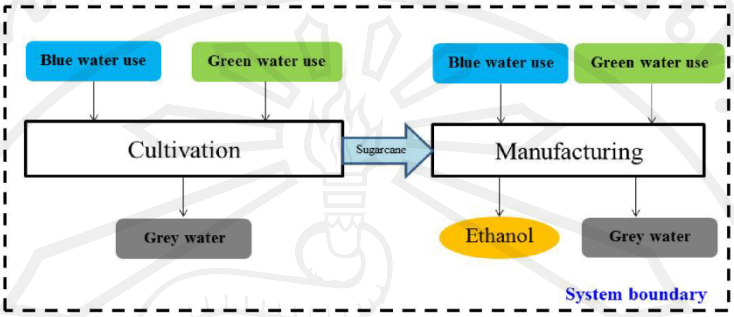

Figure 1. Schematic of water use in the sugarcane-based bioethanol production.

Table 1. Fertilizers and planting date of sugarcane.

Step	Fertilizer (kg/ha)			Planting date
	N	P	K	
Land preparation	62.5	37.5	37.5	1 February (January – February)
Crop maintenance	104.4	63.8	87.5	
Total	166.9	101.3	125.0	

Table 2. The crop coefficients (K_c) of sugarcane.

Month	1	2	3	4	5	6	7	8	9	10	11	12
K_c	0.65	0.86	1.13	1.35	1.56	1.29	1.20	0.93	0.63	0.52	-	-

Source: RID (2009)

Table 3. Water footprint of sugarcane in northern Thailand.

Region	Average crop water requirement	Effective rainfall	Irrigation water requirement	Yield	WF_{green}	WF_{blue}	WF_{grey}	WF_{Total}
	mm/growing period			(ton/ha)	m^3/ton			
Northern	1,204.85	996.81	208.04	69.3	146	31	49	226

Table 4. The water use in each stage of sugarcane-based bioethanol production (m^3/ton)

Stage	Green	Blue	Grey	Total
Sugarcane	146	31	49	226
Molasses	263	56	88	407
Ethanol	1,232	262	412	1,906

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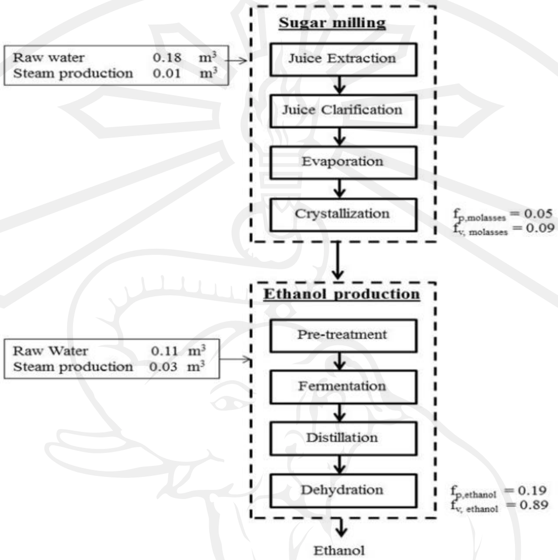

Figure 2. The flowchart of sugarcane-based ethanol production.

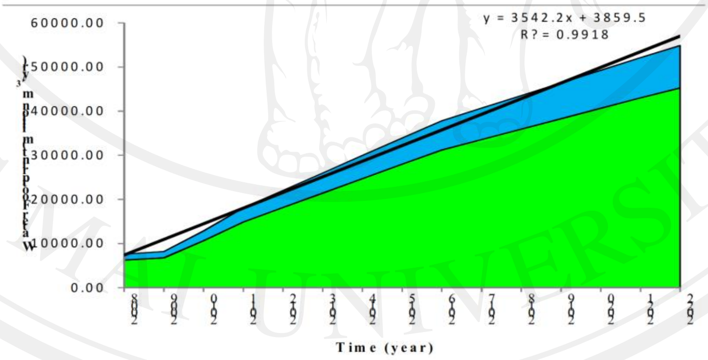

Fig 3. The water footprint of bioethanol production followed by a 15-year renewable energy plan.

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