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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 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

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

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:

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

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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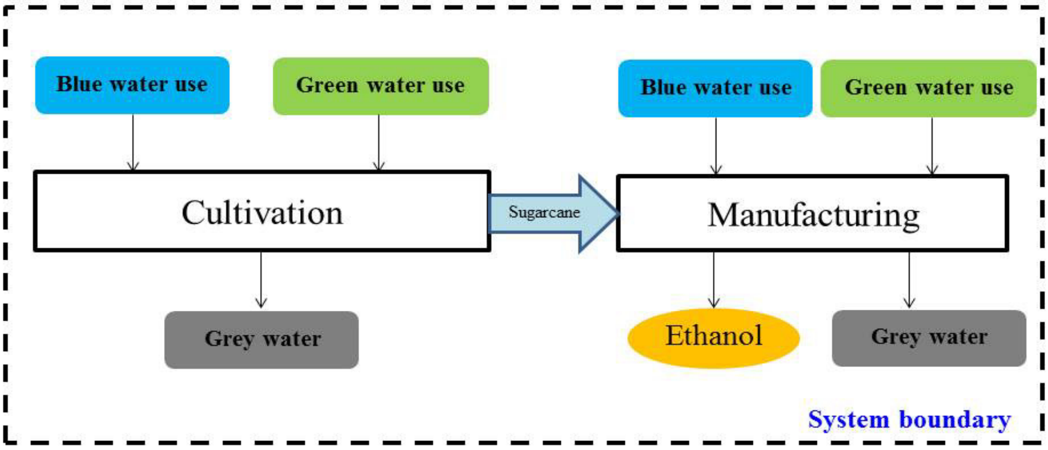

Figure 1. Schematic of water use in the sugarcane-based bioethanol production.

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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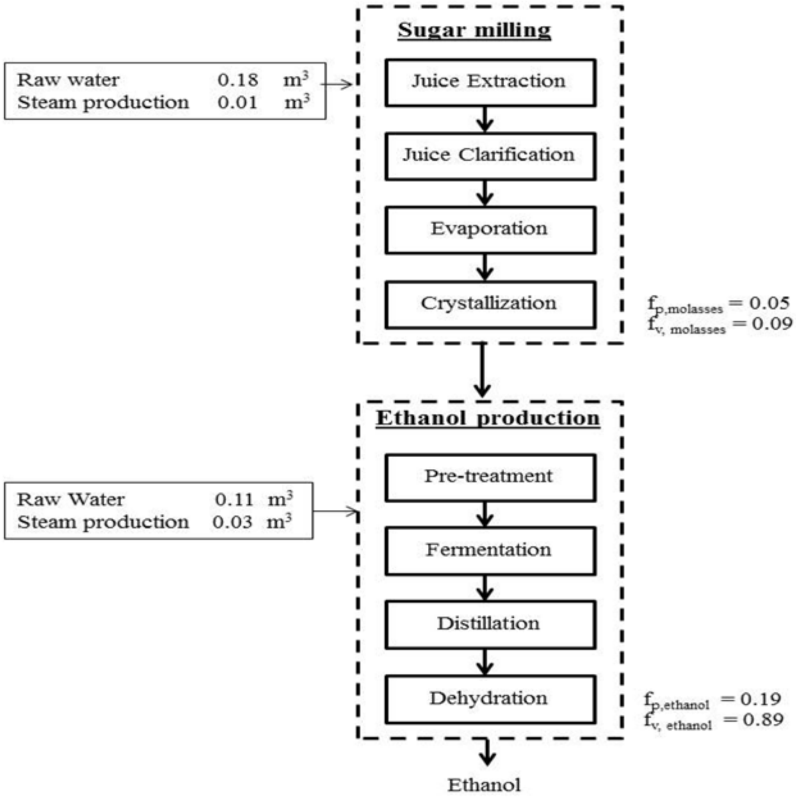

Figure 2. The flowchart of sugarcane-based ethanol production.

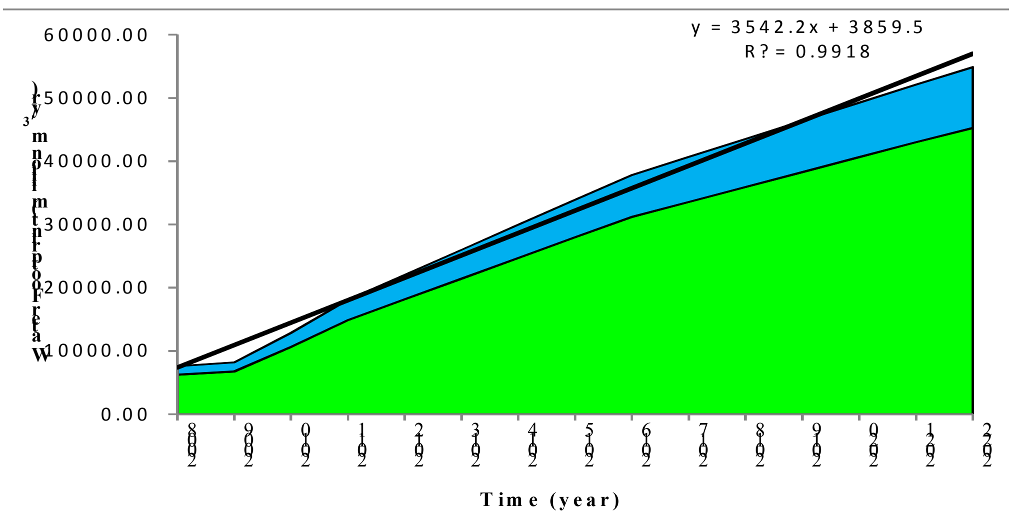

Fig 3. The water footprint of bioethanol production followed by a 15-year renewable energy plan.

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