

**WATER FOOTPRINT OF BIO-DIESEL PRODUCTION:
A CASE STUDY OF THE CHAIPATTANA-MAE FAH LUANG
REFORESTATION PROJECT, HUAY SAI,
PHETCHABURI, THAILAND**

LUKKANAPORN SEEWISENG

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ABSTRACT

Recently, there has been a growing interest in assessing the water footprint (WF) of bio-diesel production from oil palms in Chaipattana-Mae Fah Luang Reforestation Project, Phetchaburi Province, Thailand. The area is located in a rain-shadow and a major cultivar used for commercial pineapple plantations causes soil infertility.

The objectives of this study were to quantify the WF of bio-diesel products and total water use during the production process during the period from 2006 to 2010. Process calculations started from cultivation, harvesting, and transportation of energy crops, and production of bio-diesel. The framework of the WF assessment was developed, following the method provided by Hoekstra et al. (2011), which was applied in the WF assessment of oil palms and bio-diesel. Crop water use (CWU) was calculated using the CROPWAT model version 8.0, on the irrigation schedule option. The result of CWU in this study was theoretical CWU only.

The results showed that the WF of bio-diesel production from oil palms in the period 2006-2010 was 15,249 L of water per L of bio-diesel (2,003 green, 6,992 blue and 6,254 grey WFs) for total WF and was 8,995 L of water per L of bio-diesel, excluding grey WF. The WFs of oil palms and palm oil were 3,989 m³ per ton and 13,249 L of water per L of palm oil, respectively. The largest water consumption was found in blue WF (blue > grey > green). The irrigation water (blue water) was the main water source during the dry season. The largest use of freshwater on the oil palm plantation was approximately 1.3×10⁻⁵ km³ per ha per year. The estimated demand for irrigation water will likely increase by the year 2015. Finally, the oil palms had a relatively lower yield than the harvesting standard, resulting in high WF value of bio-diesel in this study. Therefore, efficiency in water management and technology should be improved in this area in order to reduce water consumption and increase oil palm productivity.

KEY WORDS: WATER FOOTPRINT/ OIL PALM/ BIO-DIESEL/ RAIN SHADOW AREA

92 pages.

วอเตอร์ฟุตพริ้นท์ของไบโอดีเซล ณ โครงการปลูกป่ามูลนิธิชัยพัฒนา-แม่ฟ้าหลวง ห้วยทราย เพชรบุรี ประเทศไทย

WATER FOOTPRINT OF BIO-DIESEL PRODUCTION: A CASE STUDY OF THE CHAIPATTANA-MAE FAH LUANG REFORESTATION PROJECT, HUAY SAI, PHETCHABURI, THAILAND

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บทคัดย่อ

การศึกษาวอเตอร์ฟุตพริ้นท์ (WF) ของผลิตภัณฑ์ไบโอดีเซลจากปาล์มน้ำมัน ณ โครงการปลูกป่ามูลนิธิชัยพัฒนา-แม่ฟ้าหลวง จังหวัดเพชรบุรีนั้นมีความน่าสนใจ เนื่องจากตั้งอยู่ในเขตพื้นที่เกษตรและดินยังขาดความอุดมสมบูรณ์เนื่องจากการทำไร่สับปะรดเป็นเวลานาน

วัตถุประสงค์ของการศึกษานี้เพื่อแสดงถึงวอเตอร์ฟุตพริ้นท์และปริมาณน้ำทั้งหมดที่ใช้ในกระบวนการผลิตไบโอดีเซลในช่วงปี 2549-2553 เริ่มตั้งแต่กระบวนการเพาะปลูก การเก็บเกี่ยว การขนส่งและการผลิตไบโอดีเซล โดยนำหลักการของ Hoekstra และคณะมาช่วยประเมินหาค่าวอเตอร์ฟุตพริ้นท์ของดินปาล์ม น้ำมันและกระบวนการผลิตไบโอดีเซล ปริมาณน้ำที่พืชต้องการจะประมาณค่าโดยใช้โมเดล CROPWAT เวอร์ชัน 8.0; ประเมินผลบนพื้นฐาน โมเดล Irrigation schedule option และการคำนวณปริมาณน้ำที่พืชต้องการ หมายถึงน้ำทางทฤษฎีเท่านั้น

ผลจากการศึกษาพบว่า วอเตอร์ฟุตพริ้นท์ของไบโอดีเซลจากปาล์มน้ำมันที่ผลิตในช่วงปี 2549-2553 เท่ากับ 15,249 ลิตร น้ำ/ลิตร ไบโอดีเซล; 2,003 green, 6,992 blue และ 6,254 grey WF (หรือ 8,995 น้ำ/ลิตร ไบโอดีเซลถ้าไม่รวม grey WF) ส่วนวอเตอร์ฟุตพริ้นท์ของปาล์มน้ำมันและน้ำมันปาล์มที่สกัดเท่ากับ 3,989 m^3 /ตันและ 13,249 ลิตร น้ำ/ลิตร น้ำมันตามลำดับ Blue WF ของทุกช่วงผลิตกันจะมีค่าสูงที่สุด (Blue > grey > green WFs) ในฤดูแล้งระบบน้ำชลประทาน (Blue water) เป็นแหล่งน้ำหลักที่ใช้ในกระบวนการ ซึ่งจะถูกใช้สูงสุดในช่วงการเพาะปลูกปาล์มน้ำมันถึง 1.3×10^{-5} km^3 /เฮกตาร์/ปี และการใช้น้ำชลประทานในปี 2558 มีแนวโน้มเพิ่มขึ้น วอเตอร์ฟุตพริ้นท์ของไบโอดีเซลในพื้นที่ศึกษามีปริมาณสูง เนื่องจากผลผลิตที่เก็บเกี่ยวได้มีปริมาณต่ำกว่าเกณฑ์มาตรฐาน และการใช้น้ำในปริมาณสูงในช่วงการเพาะปลูกปาล์มคือจุดอ่อนของระบบผลิตภัณฑ์ ดังนั้นแนวทางการลดค่าวอเตอร์ฟุตพริ้นท์ของผลิตภัณฑ์คือ เพิ่มประสิทธิภาพการบริหารจัดการน้ำรูปแบบของเทคโนโลยีกรรมวิธีในการผลิตไบโอดีเซลและเพิ่มผลผลิตปาล์มต่อพื้นที่ให้มากที่สุด

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LIST OF ABBREVIATIONS

WF	water footprint
LCA	life cycle assessment
WF _{proc}	water footprint of a process
CWU	crop water use
CWR	crop water requirement
Y	yield
ET _{green or blue}	green or blue evapotranspiration
ET _a	adjusted crop evapotranspiration
K _c	crop coefficient
K _s	water stress coefficient
P _{eff}	effective precipitation
Irr	irrigation
CROPWAT	CROPWATER requirement
AR	chemical application rate
HI	harvest index
HHV	higher heating value
FFB	fresh fruit bunch
CPO	crude palm oil
GJ	gigajoule
Cap/yr	capita per year
MOAC	Ministry of Agriculture and Cooperative
NBB	National Biodiesel Board

CHAPTER I

INTRODUCTION

1.1 Background and statement of problems

All kinds of products or services were relevant to use of the water resources. Therefore, it has adapted by finding ways to manage water resources to make have sustainable on global warming that is happening. African and Asian region show high sensitive to agricultural water scarcity (Motoshita et al., 2009). Like the energy crisis that is increasing so the alternative energy as 'bio-diesel' is good choice to produce renewable energy from crop bio-energy. Thus, the oil resources will be able to continue in the world. (Lienden et al., 2010) Consumption trend of bio-diesel from oil palm is increasing in Thailand; the plant has the potential to grow in Thailand. The crop energy in Thailand has been expanded to grow for support the future demand. (Khamthep, 2010) As same at the Chaipattana-Mae Fah Luang Reforestation Project is demonstrated to grow energy crop and transform it to bio-diesel by themselves. And which is located on low-fertilizer and rain-shadow area.

The water is a key factor in the existence of all things on the earth. Although the amount of water on land has only 1 percent of all water its can be used to consumption. The pressure from climate change results in nature, human activities, the increase of population and the advancement of technology that the water resources are affected by temperature and rainwater changes. This factor is dependent on individual of specific area and more tend to scarce in the future of water. (Bhaktikul, 2010) As agricultural water use dominates the large part of withdrawal water demand that agricultural water scarcity will result in the loss of agricultural production. It will cause the increase of undernourishment damage due to the shortage of food supply and the decline in agricultural commodity production. (Motoshita et al., 2009) Of all that the water footprint concept that has introduced on various sectors.

The water footprint (WF) instituted in 2002 by Hoekstra (2003) and was developed in 2009 by Hoekstra et al. (2009). The WFs is a good tool for cost analysis of water consumption of the product or service. In this study, the CROPWAT model 8.0 was used to analyze the volume of crop water use in growth until harvest period. These WFs make it see overview the water volume of the product and indicate weak spots and create awareness for producers and consumers to produce and purchase of themselves to be used water resources for highest efficiency. So the WFs is considered as an alternative tool for plan and management the water use for energy properly under the existence of a limited resource on global warming. Therefore, the WF of product in drought area is interested.

1.2 Education Conceptual Framework

This study use an CROPWAT model 8.0 for simulate the crop water requirement of plant, under the principle of daily soil-water balance and use water footprint concept for analysis to water used of products and process. For study the water consumption of the product at drought area of oil palm plots, where located in the Chaipattana- Mae Fah Luang Reforestation Project, Tampon Raimai Pattana, Amphoe Cha Am, Phetchaburi provinces and Tambon Nongplub, Amphoe Hua Hin, Prachuap Khiri Khan provinces.

So the volume of water use calculated is only a theory in planting stage of oil palm (by CROPWAT model estimation). Bio-diesel production stage is actual water use in study area.

1.3 Research Objective

1.3.1 To study the water footprint of oil palm (m^3 / ton), palm oil (L of water/ L of palm oil) and bio-diesel products (L of water/ L of bio-diesel) on study area.

1.3.2 To study the trend of blue water use in the production of energy crops on the current and future situations in 2015.

1.4 Scope of Study

1.4.1 To analyze about water footprint of oil palm crop palm oil and bio-diesel product that classified into the green, blue and grey components

1.4.2 To compare and analyze the volume of water use of oil palm (m^3 /ton) at the experimental field in drought areas and bio-diesel production (L of water/ L of bio-diesel) at small-scale mill model of palm oil and biodiesel community level at the Chaipattana- Mae Fah Luang Reforestation Project.

1.5 Expecting Results

1.5.1 To obtain the water footprint of oil palm crop and bio-diesel product, and can be used as a water footprint label of the product.

1.5.2 To analyze exploited water used for all stage of production process.

1.5.3 To show the weak spot of fresh water used in product system for strategy improving and saving water used of oil palm cultivation and manufacturing processes.

1.6 Conceptual framework

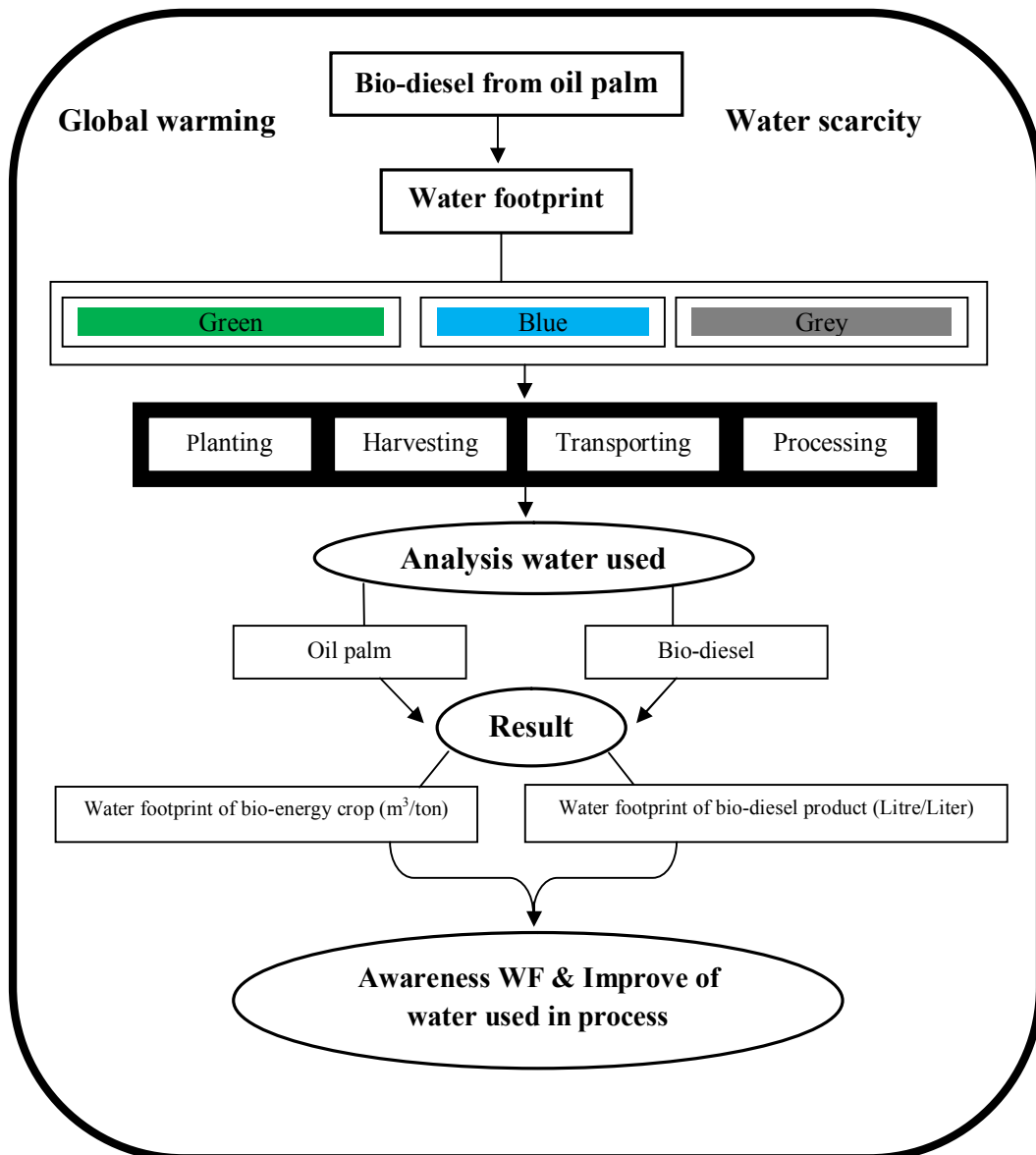


Figure 1-1 Conceptual framework of researches

CHAPTER II

LITERATURE REVIEW

This study had reviewed literature as the basis for application of water footprint assessment tool to study of the water footprint of bio-diesel productions from oil palm at the Chaipattana- Mae Fah Luang Reforestation Project as follows:

- 2.1 The concept of the water footprint
- 2.2 Water footprint calculating
- 2.3 Bio-energy crop
- 2.4 Bio-diesel
- 2.5 General characteristic of study area
- 2.6 Relevant researches

2.1 The concept of the water footprint

In the future, all country or particular not can be produce energy from all natural resources for ever. So, it needs improved more than that in process of production for has been sustainable. After that the ‘water footprint (WF)’ concept was born on 2002 by Hoekstra (2003) and was developed in 2009 by Hoekstra et al. (2009). From the best utility of the WF concept which help us to use fresh water in the efficiency way. The networks of WF was set up by the organization which online at www.waterfootprint.org (Hoekstra et al., 2009 and 2011).

The WF concept was introduced in Europe by Netherlands. And this principle has been widely used in worldwide (Netherlands, Denmark, Italy, Japan, China, Thailand, Malaysia, Indonesia and Philippines countries ect.) and various companies (Nestles, Coca Cola, PepsiCo, Unilever and SABMiller ect.).

2.1.1 What is water footprint?

The use of freshwater in the way of consumption, production or service can use the WF as indicator which indicates the association of fixed pattern at anywhere and anytime. Moreover, WF shows the direct and indirect of water use and has extensive use to indicate the freshwater resources appropriation instead of the traditional limited measure of water withdrawal. The WF has 3 components as green, blue and grey WF as Figure 2-1 (Hoekstra et al., 2011).

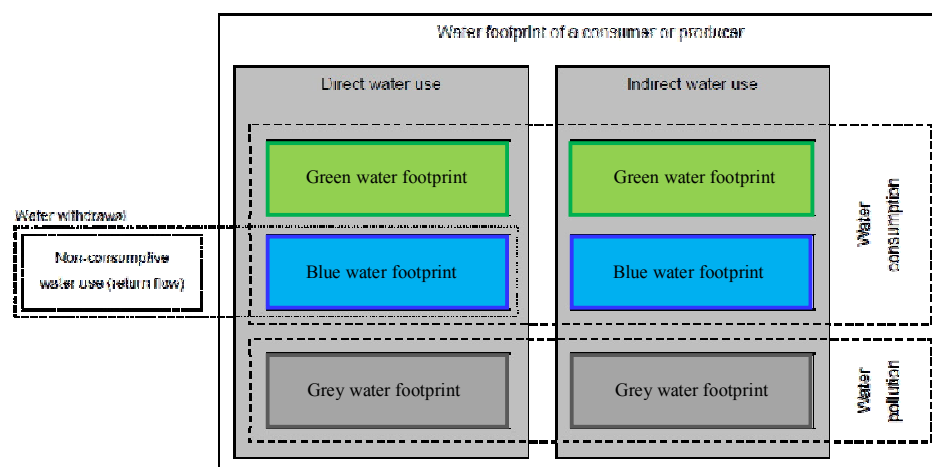


Figure 2-1 Components of a water footprint; the return flow is not part to the WFs
Source: Modified from Hoekstra et al. (2009 and 2011)

The reference of the direct and indirect used of the freshwater to produce the product or service is '*Water footprint of product*' or virtual-water content. These estimate water consumption and pollution in all steps of production chain. The calculation of procedure use all sort of product which derive from agricultural, industrial or service sector. The virtual-water content consider to volume only. The volume value of WF is usually higher than the amount of water embedded in goods. And most water is used in the life cycle of crop as Figure 2-1 (Hoekstra et al., 2011).

2.1.2 The components of water footprint

➤ *Green water footprint* or 'green water' refers to volume of rainwater on land (green water resources) and consumption by crop growth. That is top on crop and evaporated, and does not runoff or recharges the groundwater. Green water is a total

rainwater evapotranspiration (from fields and plantations) plus water related in harvest crop (Hoekstra et al., 2011; Mekonnen and Hoekstra, 2011).

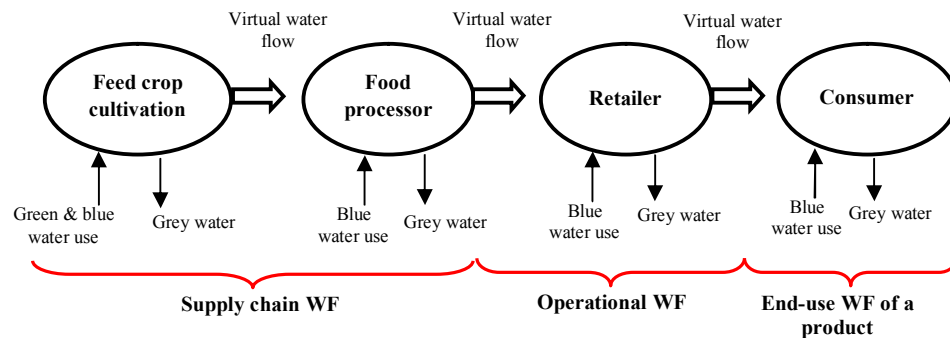


Figure 2-2 WF of supply chain in the production process

Source: Hoekstra et al. (2011)

➤ *Blue water footprint* or ‘blue water’ is the volume of surface and ground water used (blue water resources) along the supply chain plus water related with harvest product. The blue WF assesses the consumption of available volume in certain period. The surface and ground water flows not consumed for people purposes but is run to the ecosystems (Hoekstra et al., 2011; Mekonnen and Hoekstra, 2011).

‘Consumption’ alludes to loss of water from the available ground-surface water body in catchment area and water evaporated. The water is not returned to another catchment area or the sea or was incorporated into a product. Blue water in agriculture is usually used the model for the irrigation water requirement estimated with climatic data or can be direct determined (Hoekstra et al., 2011; Mekonnen and Hoekstra, 2011).

➤ *Grey water footprint* or ‘grey water’ is the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. Pollutant from surface water body as herbicide, fertilizer or pesticide can be direct determined. The grey WF is an indicator of pollution and the less pollution the better. Some recent researches that include volume of grey WF. If the grey WF is included in research, it is usually analyzed to nitrogen use only because of nutrients leaching from agricultural fields are main causes of non-point source pollution of

surface and subsurface water bodies (Hoekstra et al., 2011; Mekonnen and Hoekstra, 2011).

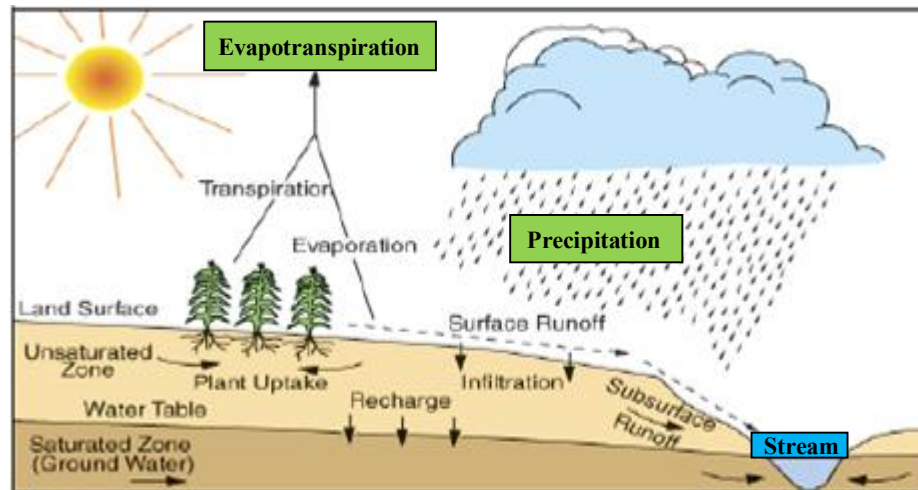


Figure 2-3 Water systems

Source: Modified from RIVM (2008)

The WF is a multi-dimensional indicator, showing water consumption of volumes by source and polluted volumes by type of pollutant (all components of a total WF are specified geographically and temporally). A unit of WF is shown in terms of a water volume per unit of product or time. And the WF of a process is shown as water volume per unit of time when divided over the quantity of product that results from the process. Unit of product WF is in terms of m^3/ton or L/kg . However, the factors that make a difference in the WF of the product as crop type, agricultural product system, climatic condition and location. Water consumption and pollution are volumetrically determined. Violence of the regional environmental impact of water consumption is not purpose of determinant (Hoekstra et al., 2009 and 2011; Leenes et al., 2009).

2.1.2 What is difference of water footprint, carbon footprint and life cycle assessment? That shows in Tables 2-1 and 2-2.

Table 2-1 Water footprint and carbon footprint; they is complementary tools

Water footprint	Carbon footprint
<ul style="list-style-type: none"> • Actual, locally specific values • Spatial and temporal dimension • Focus on reducing own water footprint (water use units are not interchangeable) • Always referring to full supply-chain 	<ul style="list-style-type: none"> • Global average values • No spatial and temporal dimension • Many efforts focused on offsetting (carbon emission units are interchangeable) • Supply-chain included only in scope 3 carbon accounting

Source: Hoekstra (2009)

Table 2-2 Water footprint and life cycle assessment (LCA); WF and LCA are the part of each other

Water footprint	LCA
<ul style="list-style-type: none"> • Measuring freshwater appropriation • Multi-dimensional (type of water use, location, timing) • Actual water volumes, no weighing • WF accounts offer basis for impact assessment and formulation of sustainable water use strategy 	<ul style="list-style-type: none"> • Measuring overall environmental impact • Three dimension (impact on the environmental, economic and social) • Weighing water volumes based on impacts • LCA offers basis for comparing products with respect to overall environmental impact

Source: Hoekstra (2009)

2.1.3 The water footprint in Thailand

The concept of water footprint was born on 2002 (Hoekstra, 2003) in European while Thailand is just beginning and tries to change the direction of WF’s Thailand as same as the international standards in further. Because of Thailand is an agricultural country and export of agricultural products in world markets. And Water

footprint label of product, the process is consistent with the principles of the ISO-14046; PWI and can be done in 2 ways; WFs and LCA concepts. The results from assessing from both that will have lead to environmental labels. For promote the growth of eco-product. (Inaba, 2011)

Rewtakulpaiboon (2008) applied that the virtual water concept to collect the tax of water supply in Thailand on the 21st century. Then the world will have affected by water scarcity. So, this study is supported the 'virtual water fund' for enhance efficiency of water use.

Boonyachotima (2009) studied that global warming and water management for sustainable business. This study is supported the water footprint label on products; especially agricultural products. For gives information and reports of CSR or sustainability of the business environment to consumer and social. By improved in the breeding and manufacturing of process, for save the water use.

Chumpathong et al. (2011) studied that the water management for rice production in Thailand based on the concept of WF. And offer to idea for can save their WF of rice by improved manufacturing and technological process.

Gianan et al. (2011) studied that the water footprint from sugar cane and cassava for the production of ethanol in Thailand. Results of studies showed as sugar cane-based ethanol consumes larger amount of water than cassava based ethanol (827.24 and 703.09 liters of water to produce ethanol per liter of ethanol from those in Suphan Buri and Lop Buri provinces, respectively). The cassava uses only green water while sugar cane uses both blue and green water.

Pongpinyopap and Mungcharoen (2011) studied that the water footprint of bio-ethanol production from Cassava in Thailand (2008) was 0.267 km³/ year followed the Alternative Energy Development Plan 2008-2022. So in 2022, the water requirement will be as 2.605 km³/ year or 10 times of 2008. Then the water use should have reduced and increase crop yield per rai as possible.

2.2 Water footprint calculating the WF calculating is followed as Hoekstra et al. (2009 and 2011):

2.2.1 WF of planting a crop or tree

This methods can apply to assessment both annual and perennial crops. The ‘crop’ is used for food or medicine. The ‘tree’ planted for the wood or the carbon credit. The total WF calculating of the planting crops or trees (WF_{proc}) as equation [1]:

$$WF_{proc} = WF_{proc,green} + WF_{proc,blue} + WF_{proc,grey} \quad [1]$$

The water volume per mass is the unit of WFs. WF unit in agriculture or forestry is L/kg (Hoekstra et al., 2009 and 2011).

-Green and blue WF of planting process (WF_{proc} , m^3/ton) is calculated as the green and blue of crop water use (CWU , m^3/ha) divided by the crop yield (Y , ton/ha) as equation [2]:

$$\begin{aligned} WF_{proc,green} &= CWU_{green} / Y \\ WF_{proc,blue} &= CWU_{blue} / Y \end{aligned} \quad [2]$$

Accumulating of daily evapotranspiration (ET , mm/day) over the complete planting period is the CWU of green and blue calculated. The total rainwater evaporated from the land during the planting period is the green crop water use. The blue crop water use is the total irrigation water evaporated from the land as equation [3]:

$$CWU_{green\ or\ blue} = 10 * \sum_{d=1}^{l_{gp}} ET_{green\ or\ blue} \quad [3]$$

The green water evapotranspiration is definition of ET_{green} . The blue water evapotranspiration is definition of ET_{blue} . For water depth converting from mm into water volumes per land surface in m^3/ha is used the factor 10. The l_{gp} is length of planting period in days (Hoekstra et al., 2009 and 2011). Evapotranspiration from a field can be direct kept or estimated by CROPWAT model of FAO (2007) (Hoekstra et al., 2009 and 2011).

-Grey WF (WF_{grey} , $volume/time$) can assess by the used chemical application rate per hectare (AR , kg/ha) as equation [4]:

$$WF_{proc, grey} = \frac{(\alpha * AR) / (C_{max} - C_{nat})}{Y} \quad [4]$$

The α is times the leaching fraction. 10% of nitrogen fertilizers assuming can be used if on databases available. The AR is chemical application rate per hectare (kg/ha). Y is crop yield (ton/ha). The c_{max} is maximum allowable concentration and c_{nat} is natural concentration (Hoekstra et al., 2009 and 2011).

2.2.2 Water footprint of product

The WF of production system can calculate in 2 alternative ways but both options give the same result at the end.

- *Chain-summation approach* can be calculated in only one output product of production system. This way is simpler than the step-wise accumulative approach as Figure 2-4 as equation [5]:

$$WF_{prod} [p] = \frac{\sum_{s=1}^k WF_{proc} [s]}{P [p]} \quad [5]$$

$WF_{proc} [s]$ is the process WF of process step s (volume/mass). $P [p]$ is the production quantity of product p (mass/time) (Hoekstra et al., 2009 and 2011).

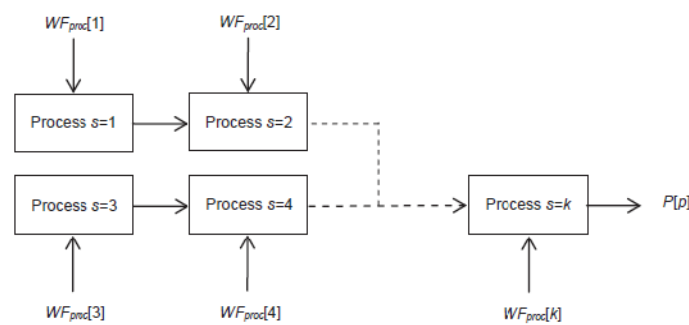


Figure 2-4 Production system of chain-summation approach

Source: Hoekstra et al. (2009 and 2011)

- *The step-wise accumulative approach* can be calculated when we have a number of input products for making one output product. The WF of input product is added to WF of output product. Other case, the WF of input product is separated if one input product and a number of output products. The WF process is added to the WFs

of the input products before the total is distributed over the various output products as Figure 2-5 as equation [6]:

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

$WF_{prod} [p]$ is the WF of output product p (volume/mass). $WF_{prod} [i]$ is the WF of input product i (volume/mass). $WF_{proc} [p]$ is the process WF of the process step that changes the y input products into the z output product (volume/mass). The $f_p [p,i]$ is product fraction (mass/mass), $f_v [p]$ is value fraction (mass/mass):

$$f_p [p,i] = \frac{w [p]}{w [i]}$$

The $f_p [p,i]$ is the product fraction is quantity of an output product p (obtained per quantity of primary input product i , mass/mass). The $w [p]$ is quantity of the output product obtained (mass). The $w [i]$ is quantity of the input product (mass).

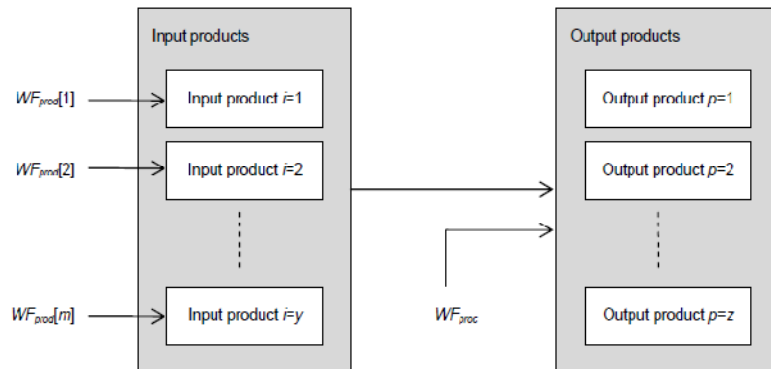


Figure 2-5 Production system of step-wise accumulative approach

Source: Hoekstra et al. (2009 and 2011)

$$f_v [p] = \frac{price [p] * weight [p]}{\sum_{p=1}^z (price [p]) * weight [p]}$$

The $f_v [p]$ is the value fraction that is ratio of the market value of the product to the aggregated market value of the entire product obtained from input product (monetary unit/monetary unit). $Price [p]$ is price of product p (monetary unit/mass). The denominator is summed over the z output products ($p=1$ to z) that originate from the input products (Hoekstra et al., 2009 and 2011; Mekonnen and Hoekstra., 2011).

For WFs of energy plant to produce a energy product that has been done by combining data on higher heating values of plant components with information on the composition of H-crop as equation [7]:

$$E(c)=HI(c)*DM_Y(c)*\sum_{i=1}^5 C_i*A_{y,i}+(1-HI(c))*DM_R(c)*\sum_{i=1}^5 C_i*A_{r,i} \quad [7]$$

HI(c) is harvest index of crop c . $DM_Y(c)$ is the fraction of dry mass in the crop yield. $DM_R(c)$ is the fraction of dry mass in the rest fraction. C is the heat of combustion of composition i (HHV in kJ/g). A is the amount of component i in the DM of the crop yield or rest fraction (g/g) (Leenes et al., 2008 and 2009).

2.2.3 Models for the water footprint

The CROPWAT models was developed by the Food and Agriculture Organization of the United Nations (FAO) which estimate evapotranspiration. This model is good one because its wide application, online availability, good documentation and embedding in FAO practice (Hoekstra et al., 2009 and 2011). So, in nation researcher has use this model for estimated evapotranspiration of WF such as Leenes et al. (2008 and 2009), Hoekstra et al. (2009 and 2011), Mekonnen et al. (2011) and Lienden et al. (2010) etc.

CROPWAT 8.0 Model

CROP WATER requirement for Windows is a tool to estimate evapotranspiration and demand of crop water consumption. CROPWAT assessed the crop under rain-fed area and irrigation conditions under various irrigation patterns (Hoekstra et al., 2009 and 2011).

Crop water requirement option (CWR option) calculate from crop water requirement based on FAO Penman Montieth equation of Allen et al. (1998) as equation [8] with optimal assumptions (well-fertilized plants, disease-free, under optimum soil water conditions and perfect full production) (Hoekstra et al., 2009 and 2011).

$$ET_c = K_c \times ET_0 \quad [8]$$

ET_c is crop evapotranspiration. K_c is crop coefficients. ET_0 is reference of crop evapotranspiration and effective precipitation (P_{eff}). Green and blue

evapotranspiration under rain-fed condition are calculated as equation [9] (Hoekstra et al., 2009 and 2011):

$$\begin{aligned}
 ET_{green} &= \min (ET_c , P_{eff}) \\
 ET_{blue} &= \max (0, ET_c - P_{eff}) , \text{unit mm/period}
 \end{aligned}
 \tag{9}$$

The example of the CWR option calculated:

ET_c (mm/day)	ET_c (mm/day)	Eff_{rain} (mm/day)	ET_{blue} (mm/day)	ET_{green} (mm/day)
4.19	20.9	17.4	3.5	17.4

Irrigation schedule option The crop evapotranspiration is calculated base on optimal and non-optimal conditions in all period of growth by the daily soil water balance approach as equation [10]:

$$ET_a = K_s \times ET_c = K_s \times K_c \times ET_0 \tag{10}$$

ET_a is the adjusted crop evapotranspiration. K_s is the stress coefficient. The result of the irrigation schedule option needs more details of input data than CWR option. So, it is better representative of site such as the irrigation timing, irrigation efficiency, irrigation application timing ect as equation [11] (Hoekstra et al., 2009 and 2011):

<p>In rain-fed scenario:</p> $ ET_{green}(\text{rain-fed}) = ET_a(\text{rain-fed}) $ $ ET_{blue}(\text{rain-fed}) = 0 $ <p>In irrigation scenario:</p> $ ET_{green}(\text{irrigation supply}) = ET_a(\text{rain-fed}) - ET_{blue}(\text{irrigation supply}) $ $ ET_{blue}(\text{irrigation supply}) = \min (\text{total net irrigation, actual irrigation requirement}) $	<p>[11]</p>
---	-------------

The example of the Irrigation schedule option calculated:

Rain (mm)	ET_a (mm/day)	Depl (%)	Net Irr (mm)	Deficit (mm)	Loss (mm)	Gr. Irr (mm)	Flow (l/s/ha)
0	4.2	1	0	4.2	0	0	0

In rain-fed scenario: $ET_{green} = 4.2$ mm/day

$ET_{blue} = 0$ mm/day

Rain	ET_a	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
(mm)	(mm/day)	(%)	(mm)	(mm)	(mm)	(mm)	(l/s/ha)
0	4.2	1	0	4.2	0	0	0

In irrigation scenario: $ET_{green} = 4.2 - 4.2 = 0$ mm/day

$$ET_{blue} = 0 \text{ mm}$$

The data has used in 2 types:

1) Crop Characteristics such as crop pattern, Kc value, crop height, rooting depth, critical depletion, soil type, schedule and yield respond ect.

2) Climate data such as rainfall, temperature, humidity, wind and sun duration ect. If there has no data of climate, we can use the database of 144 countries of CLIMWAT (FAO web site). The program need average climate data of period average more than specific year. The system can display resulted data in graphical. The result can be displayed in various period of time such as daily, ten days, weekly or monthly (FAO, 2007a).

2.3 Bio-energy crop

2.3.1 General characteristic of crop energy

'Crop-energy' refer to the crop which use its wood or any part of it to produc fuel we call "clean renewable energy" that replace the scarce of energy. This energy derive from biomass from crop. 'Biomass' is all material come from organic origin, excluding things that turn to fossils. The resources of biomass are land, water, nutrients and sunlight which help to grow into the desired size then harvest for stock of bio-energy. The 'total biomass' show inform of the harvest index (HI) which explains the difference of crop that show the primary energy carrier from energy renewable. This will be decided to made biofuel or or the second renewable energy, in the form of solid, liquid or gas, such as charcoal, ethanol, biodiesel, biogas etc as Figure 2-7 (Leenes et al., 2008 and 2009 and Lienden et al., 2010).

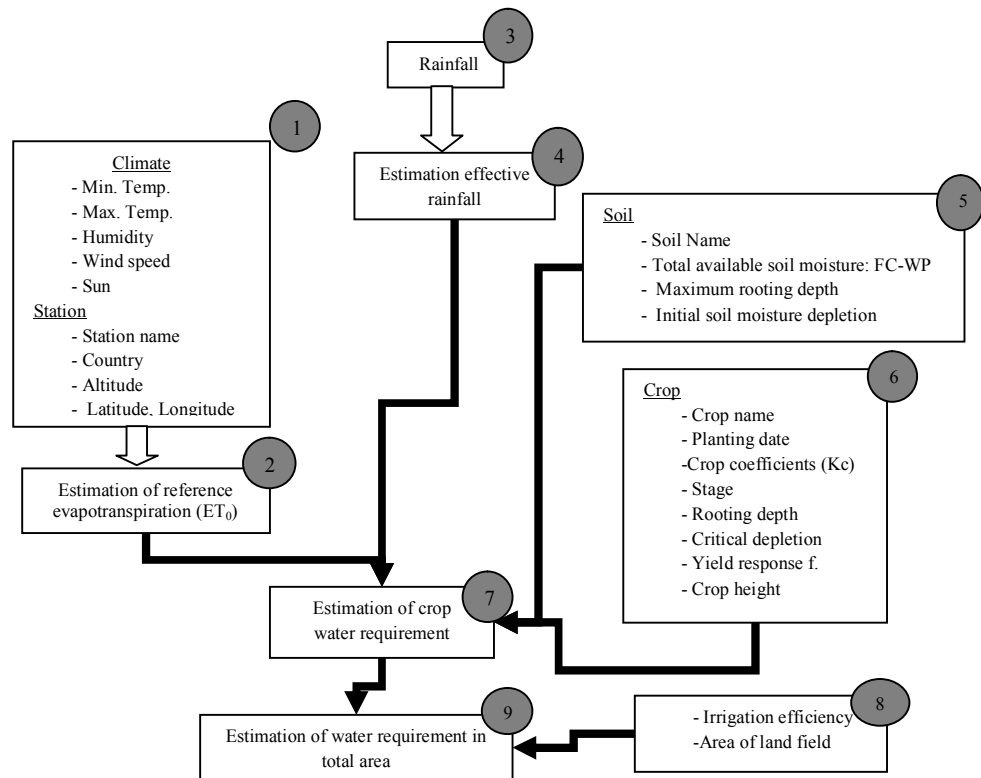


Figure 2-6 A functions of CROPWAT model

Source: Phoesuwan (2011)

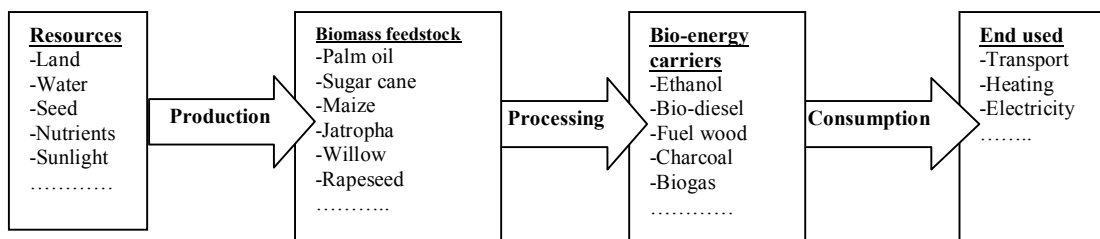


Figure 2-7 Bio-energy from resource to end use

Source: Lienden et al. (2010)

The components of specific energy obtained from the organic matter (carbohydrates, proteins, lipids, lignin, and organic acid) are used to determine the energy from biomass. Some part will be selected to produce fuel can deride into three categories:

- Tree: poplar, horse tamarind and eucalyptus etc.
- Bio-energy crop: miscanthus, jatropha and cotton etc.

-Food crop: oil palm, cassava, coconut, groundnut, maize, potato, wheat, rapeseed, sugar cane, sunflower and soybean etc. WF of bio-energy is larger than WF of energy from fossil fuels (nearly 70-700 times). Because of water needed of feedstock planting or call crop energy (Leenes et al., 2008 and 2009 and Lienden et al., 2010).

The large part of withdrawal water is in the agricultural water used which shows the result of water scarcity in the loss of agricultural production. It will cause the increase of undernourishment damage due to the shortage of food supply and the decline in agricultural commodity production. While an African and Asian region show high sensitive to agricultural water scarcity. (Motoshita et al., 2009)

2.3.2 Oil palm

An oil palm has the single cotyledon plants in the genus *Elaeis*, diploid plant (2n) that can be divided into three types ; i) *E. guineensis* (African oil palm) ,ii) *E. oleifera* (American oil palm) and iii) *E. ordora* The *E. guineensis* is a most kind to produced biodiesel in Malaysia, Indonesia, Thailand and the Philippines countries. Because, this species is appropriate and has high oil content than other kinds. The Thailand is fourth-largest of oil palm plantation in the world after Malaysia, Indonesia and Nigeria country. In 2010, the area planted about 4.07 million rais, the annual FFB yield 1.45 million ton (MOAC, 2011). The oil palm is most grown at Khabi, Surat Thani and Chumphon province in Thailand. In commercial plantations the Ternera variety of the oil palm is most commonly used, because of its superior oil yield and good drought tolerance as Figure 2-8. As in Petchaburi province, must use Tenera hybrids has to grown i.e. *Suratthani I-VI* type etc. (Chorawis, 2005 and Jantaraniyoom, 2007)

The oil palm has 12-15 months for nursery period then prepares area 2 weeks in dry season and some lowland of palm plantation has trenches to drain (2×1 meter) for prevented flood water detention (Figure 2-9). After that, start plantation of young plant in early wet season. And a yield can be harvested throughout over the year; on a monthly (every 15 days) when 30 months after planting (Table 2-3). Ripe fruit has 2 types; virescens and nigrescens. High, medium and low season of yield that is in June to August, April to May and January to March, November to December.

Yield average of FFB was 3617, maximum yield 5020, minimum yield 2681 kg/rai/year when 5-10 oil palm years. The *Tenera* variety gives the constant yield at age of 10 years (Chorawis, 2005; Jantaraniyoom, 2007). Oil palm fruit has moisture as 3.8 %. (Lienden et al., 2010)

Scientific name: *Elaeis guineensis* Jacq.

Common name: oil palm

Family: Palmae or Recaceae

Genus: *Elaeis*

Species: *guineensis*

Origin: Africa



Figure 2-8 Oil palms, *Tenera* variety (a) and ripe fruit (b)

For growth stages of oil palm as 1 to 3 years (initial stage), 4 to 10 years (development stage), 10 to 20 years (mid season) and 20 to 25 years (late season). The properties suitable for oil palm plantation are i) rainfall should be more than 1800-2000 mm/year, ii) average temperature as 25 to 29 degree Celsius, iii) relative humidity over 85%, iv) soil depth is over 0.75 to 1.50 meter and v) loam soil and good drainage and planted an equilateral triangle (9×9×9 m.). The average life spans about 25 years and water requirement as 200-250 L/plant/day. For percent of oil extraction which has dependent on species, continent and climatic condition. (Chorawis, 2005)

and Jantaraniyoom, 2007). The WF of oil palm in Thailand on 2007 was 1586 m³/ton (Lienden et al., 2010).



Figure 2-9 Trenches to drain for prevented flood water detention in some lowland

Table 2-3 Oil palm calendars

Stage	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Land prepare	■											
Grow							■	■	■			
Harvest					▨	▨						

Note : ■ prepare land (Jan-Mar, Apr-Jun) ,Grow (wet season), Harvest (over year, every 15 days/time , every 7 days/time in high season)

Source: Jantaraniyoom (2007)

2.4 Bio-diesel

The bio-diesel can be classify in 3 types; i) straight vegetable oil (oil from plants and animals can use directly), ii) Veggie / Kero Mix (a mixture of vegetable or animal oils with kerosene or diesel oils) and iii) ester-biodiesel (That is a true of bio-diesel, accepted and widely used in the international). The bio-diesel is obtained from first-generation conversion of oil crops. Typically, the extracted vegetable oil (triglyceride) reacts with an alcohol in an esterification reaction to produce alkyl esters (methyl ester) of long chain fatty acids and glycerol as a by-product as Figure 2-10. In warmer countries, the vegetable oil (oil palm, coconut, jatropha and algae ect.) is less

gum and can be used directly as fuel. Bio-diesel produced from crop is similar to fuel from petroleum. So the bio-diesel is a renewable energy as alternative for farmers as well (Poku, 2002; Leenes et al., 2008; Lienden et al., 2010).

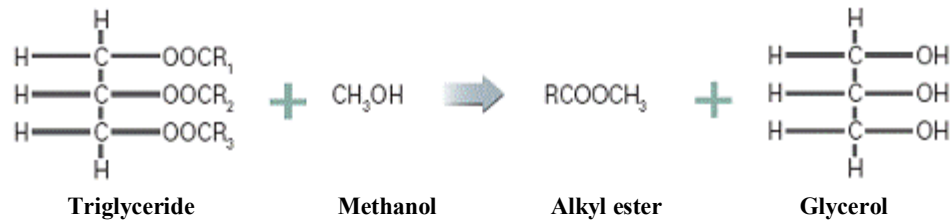


Figure 2-10 The bio-diesel reaction (Transesterification)

Source: National Biodiesel Board (2001)

In the EU, 60% of the bio-diesel production is mainly situated and rapeseed is dominant feedstock. Other bio-diesel producers were the United States of America (from soybean), China, India, Indonesia, Malaysia and Thailand (mostly from palm, coconut and castor oils). The bio-diesel production was born on 2002 in Thailand (Poku, 2002; Leenes et al., 2008; Lienden et al., 2010).

-Advantages; the bio-diesel (ester type) as same as diesel mostly when which using an engine that no problems. Black smoke can be reduced by more than 39%, CO 20%, dusts 39%, CO₂ 78%. This makes the impact of the fuel to reduce global warming (Ngamkanokwan, 2006).

-Disadvantage; the bio-diesel has NO_x emissions more than diesel and may result in parts of oil pump, rubber deterioration (Ngamkanokwan, 2006).

2.4.1 The production of palm oil

The palm oil extraction process has 2 ways as seal of separation and mixture oil which the factory has a high and low capacity, respectively. After harvested fresh fruit from the field (bunch reception) then removal of fruit from bunches (threshing) by cutting the fruit-laden spikelet from the bunch stem. Next, sterilization of bunches by high-temperature wet-heat water to break down gums and resins. Then digestion of the fruit for reduces the viscosity of oil and extracting the palm oil (pressing) by dry and wet method (FAO, 2006).

A dry method uses mechanical presses but wet method uses hot water to leach out the oil. After that turn to clarification and drying of oil by separate the oil palm from its entrained impurities, a hot water is therefore added to press output mixture to thinly it (with ratio of 2:1). The coarse fiber is removed in this step. The screened mixture is boiled from 1 or 2 hours then settle it by gravity in the tank. The palm oil rise to the top while a water is at bottom. To prevent free fatty acid (FFA) of oil with 4-7 % and entered to degumming process. Finally, re-heating oil for remove residual moisture then storage a crude palm oil (CPO) in tanks which for use to bio-diesel production for next time. Some residual of oil palm makes fertilizer or animal feed as Figure 2-11 (FAO, 2006).

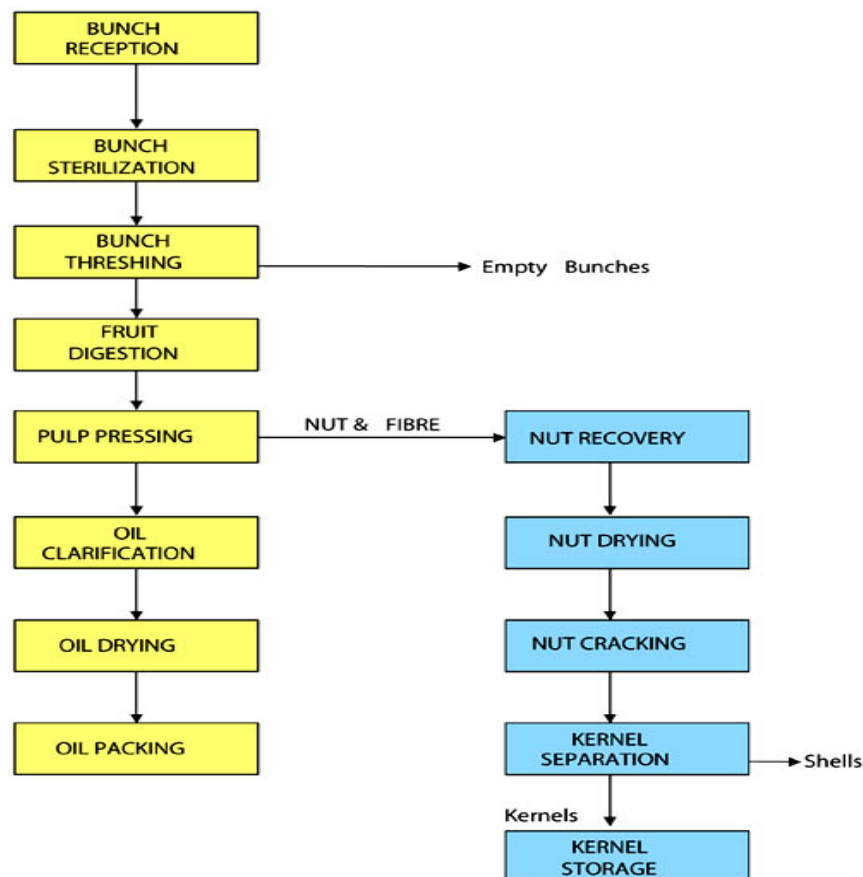


Figure 2-11 The production of palm oil

Source: FAO (2006)

2.4.2 The production of bio-diesel

The productions of bio-diesel process has 3 types as i) base catalyzed transesterification of the oil, ii) direct acid catalyzed transesterification of the oil and iii) conversion of the oil to its fatty acids and then to bio-diesel. Then mostly in bio-diesel productions was produced on base catalyzed transesterification of the oil. Because, the results of process has a yields high conversion (98%) with minimal side reactions and reaction time and its used low temperature and pressure.

A crude palm oil (after passed de-gumming process) was mixed with catalyst-mixing and entered to esterification and transesterification process steps for reduced FFA is less than 1.5% of crude palm oil. This reaction time was varies from 1 to 8 hr. Then neutralized and was separation by settle, the by-products as crude bio-diesel and crude glycerin. Next, evaporated an alcohol as ethanol recovery was return to system. To wash the crude bio-diesel by warm water for removes residual catalyst or soap. After that was purification of them by removed water with filtration of salt, the remaining of water was less than 0.005%. Finally, settler and filter again of bio-diesel (B100) for sent to storage and distribute as Figure 2-12 (FAO, 2006 and NBB, 2001).

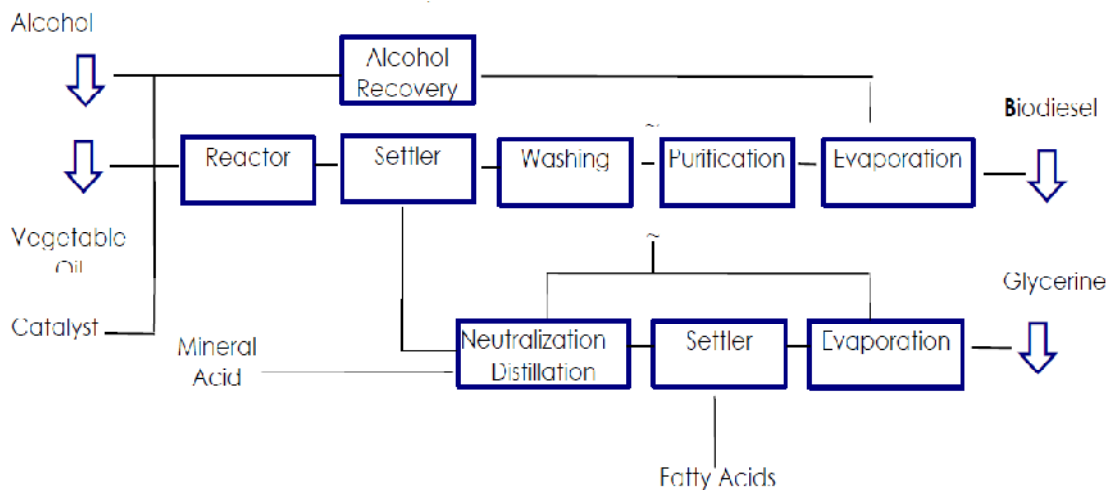


Figure 2-12 The bio-diesel production

Source: National Biodiesel Board (2001)

2.5 General characteristic of study area

The Chaipattana-Mae Fah Luang Reforestation Project established on 2004 by His Majesty King Bhumibol Adulyadeg. Originally, this project was Nongplub-Klad Luang Royal that has been degraded from plantation of pineapple and set in rain shadow area. His Majesty King Bhumibol Adulyadeg wants to restoration of soil fertility cover the area of Raimai Patthana Subdistrict, Cha um District, Pethchaburi Province and Nhong Plub Subdistrict, Hua Hin District, Prachuap Khiri Khan Province. Then Her Royal Highness Princess Maha Chakri Sirinthorn was experimented plantation of oil palm (250 rais) on total area's project about 10,300 rais but oil palm recently can harvested just 104 rai. The yields is used to the processing of renewable energy for future energy crisis and provided a small mill model to be produced bio-diesel. The mill has capacity of produced the bio-diesel about 400 L/day by drying process as Figures 2-13 and 2-14 (Chaipattana Foundation, 2007).

The *Suratthani II* and *Compact Nigeria* (Figure 2-15) are hybrid of *Tenera* varieties those are breeding between *Dura* and *Pisifera*. Good features of those are low height, drought tolerance and high yield (average yield ~3,617 kg/rai, Chorawis, 2005). But *Compact Nigeria* is sensitively than *Suratthani II* in drought condition. And them was grown when August (2005) and September (2006), respectively. When yield was ripped, *Suratthani II* and *Compact Nigeria* were nigrescens (changed from black to red-orange color) and virescens (changed from green to orange), respectively.

Most of the area is lowland between the valley and central area. And area is undulating wave followed down in south, east and northwest of cordillera. The climate is a tropical monsoon in the rain-shadow, so the area was drought conditions. Total annual average rainfall is 1,059 mm. (Tables 2-4, 5). And coordinates UTM X = 581500–582700, Y = 1394800-1395700. Land use of project showed in Table 2-4 and that boundary as followed (Office of Soil Survey and Land Use Planning, 2010):

<i>North:</i>	Tung Kham reservoir
<i>South:</i>	Hui Mai Tai reservoir
<i>East:</i>	Public areas and bio-diesel mill
<i>West:</i>	forests, vetiver grass and jatropa area.

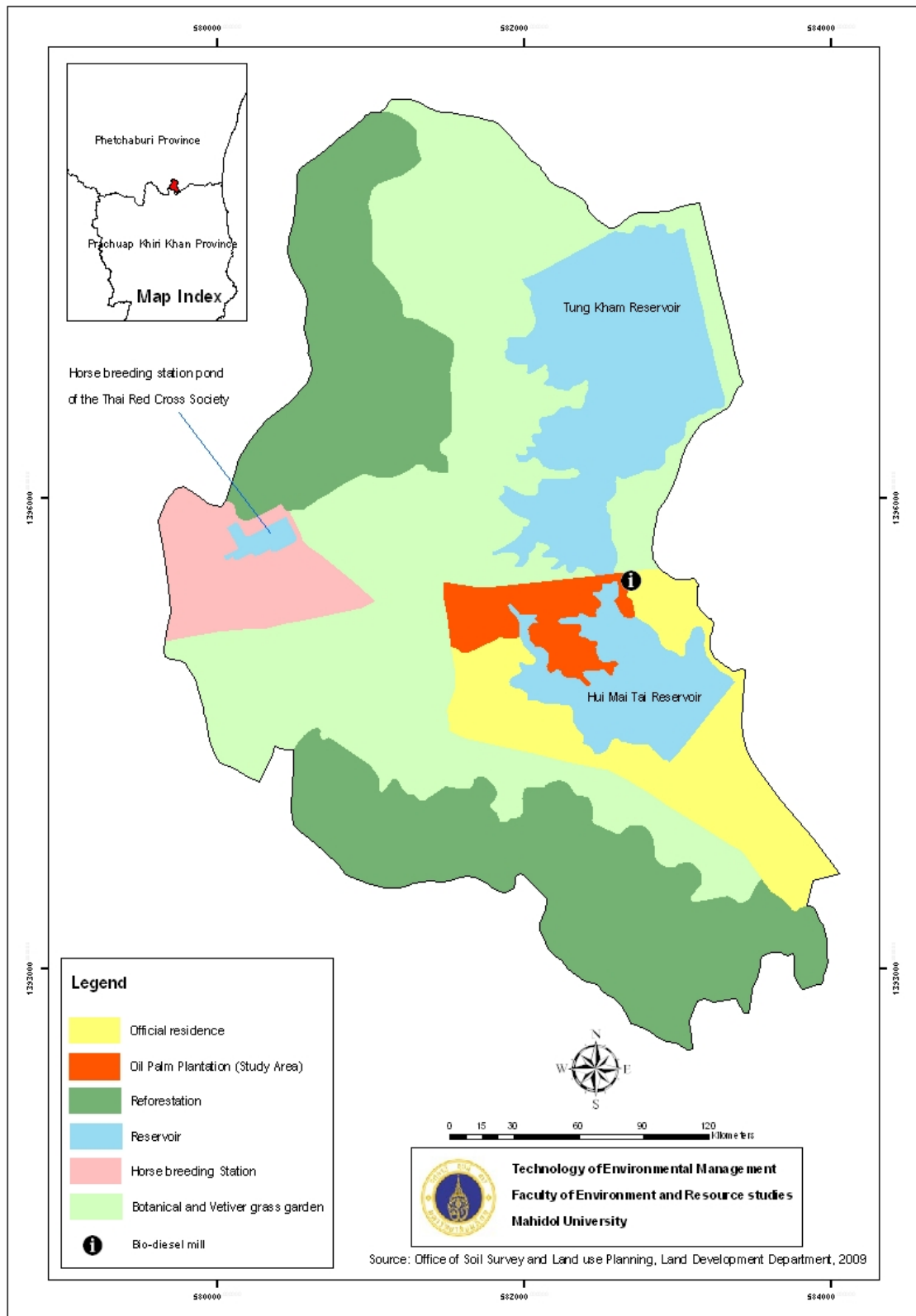


Figure 2-13 Bio-diesel mill and Chaipattana-Mae Fah Luang Reforestation Project

Source: Office of Soil Survey and Land Use Planning (2010)

Table 2-4 The Chaipattana- Mae Fah Luang Reforestation climatic average 30 years, 1981-2010 period, Nong Plub weather station

Climatic factor	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Rainfall (mm)	9.9	8.3	54.5	55.6	136.9	89.4	109.4	96.7	163.5	239.3	89.5	6.1	1059.0
Average Temp.(°c)	22.6	24.3	26.9	28.4	28.7	28.9	28.5	28.6	28.3	27.1	25.2	23.5	27.0
Maximum temp.(°c)	32.2	34.3	36.9	37.4	36.2	36.2	35.8	35.7	35.2	33.9	33.4	33.2	35.0
Minimum temp.(°c)	12.9	14.4	17.0	19.5	21.2	21.6	21.3	21.6	21.3	20.2	17.0	13.8	18.9
Sunshine(hr)	7.3	7.9	7.6	7.2	5.3	4.0	3.9	3.2	3.9	4.5	6.1	7.3	5.7
Relative humidity (%)	66.5	65.2	67.6	68.7	70.4	71.1	76.8	77.5	73.5	78.9	75.2	70.5	71.8
Wind speed (km/day)	100.8	129.6	141.6	124.8	103.2	105.6	96.0	100.8	76.8	81.6	124.8	129.6	109.6

Source: Thai Metrological Department (2010)

Table 2-5 The land use of Chaipattana- Mae Fah Luang Reforestation

Location	Area (rai)	%
Forest area	5737.9	56.2
Water resource area	1907.0	18.5
Agricultural area	994.2	9.6
-palm	445.4	4.2
-jatropha	90	0.8
Other areas	844.7	8.2
Public spaces and buildings area	772.9	7.0
-Horse breeding station	646	5.8
Uses a variety of areas	42.5	0.4
Total	10,300	100

Source: Office of Soil Survey and Land Use Planning (2010)



Figure 2-14 Study area in filed, the Chaipattana- Mae Fah Luang Reforestation (a), Mill model of bio-diesel (b)



Figure 2-15 Tenera hybrid varieties, *Surathani II* (a), *Compact Nigeria* (b)

2.6 Relevant researches

Leens et al. (2008) studies that the water footprint (WF) of bio-energy and other primary energy carriers. This has been done on higher heating values of plant components of H-crop. The result showed that the WF of average biomass grown in the Netherlands, US, Brazil and Zimbabwe were 24, 58, 61 and 143 m³/GJ, respectively. The WF of other primary energy carriers (excluding hydropower) was 70-400 times less than the WF of biomass. Because the WF of biomass was depends on crop type, agricultural production system and climate.

Leens et al. (2009) studies that the water footprint (WF) of energy from biomass: a quantitative assessment and consequences of an increasing share of bio-energy in energy supply. The result showed the largest difference between maize grown in the Netherlands and cotton grown in Zimbabwe; the WF of the cotton was 40 times the WF of Dutch maize. And the total WF of oil palm and kernels was 1,502 m³/ton, in Brazil. Then the trend towards use larger energy use in combination with an increasing contribution of energy from biomass will enlarge the need for fresh water. This causes competition with other claims, such as water for food.

Bhardwaj et al. (2010) studies that the water and energy footprints of bio-energy (soybean) crop production on marginal lands by eddy-covariance flux techniques. The result showed that the WFs for grain, energy production and biomass

were higher on lands converted from agricultural land use compared with those converted from the Conservation Reserve Program (CRP) land. Land management affects WF through soil quality effect. Then crops and management systems similar to CRP grasslands may provide a potential strategy to grow biofuels that would minimize environmental degradation while improving the productivity of marginal lands.

Bulsink et al. (2010) studies the WF of Indonesian provinces related to the consumption of crop products. The result showed that the average WF of crop products in 2000-2004 is 1,131 m³/capita/yr and 853 (green 802, blue 0, grey 51) m³/ton of oil palm. The differences in WF are caused by climate, agricultural practice consumption volume, although same provinces.

Lienden et al. (2010) studies that the biofuels scenarios in a water perspective; the global blue and green WF of road transport in 2030 by uses the WF methodology. The result as in 2030 the bio-diesel and bio-ethanol consumption increase manifold as 84 and 25 times respectively and its will face very large water problem which caused by the agricultural sector in Developing Asia. Then the WF of palm fruit in Honduras, Indonesia, Malaysia, Philippines and Thailand was 1,566, 1,474, 1,110, 2,031, 1,586 (green 867, blue 719) m³/ton and bio-diesel from palm fruit as 96, 90, 68, 124 and 97 (green 53, blue 44) m³/GJ respectively. Trend of blue and green water of bio-diesel were 0.4 and 0.2 km³/year in 2030.

Romaguera et al. (2010) studies that the potential of using remote sensing techniques for global assessment of water footprint of crops. For evapotranspiration, precipitation, water storage, runoff and land use are identified as key variables to potentially be estimated by remote sensing for WF assessment. This key work provides new tools for global WF assessment and represents an innovative approach to global irrigation mapping, estimating the green and blue water use but the use of remote sensing data has not yet been exploited in this field.

Amarasinghe (2011) studies that biofuels and consumptive water use in Thailand and Malaysia. WF of bio-diesel from oil palm was 3,222 L water/ L bio-diesel in Malaysia. The result had not included grey WF. Major problem of biofuel production is not the irrigation water use in Thailand and Malaysia but effluent generated (water quality) by biofuel plant had major environmental bottleneck.

Mekonnen and Hoekstra (2011) studies that the green blue and grey WF of crops and derived crop product in 1996-2005 by high-resolution approach. The result showed that the global average WF of oil palm as 1,098 (green 1,057, blue 0, grey 40) m³/ton and bio-diesel as 5,166 (green 4,975, blue 1, grey 190) L water / L biodiesel. WF of palm oil was 5,000 m³/ton.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Educational attributes

This study is the adaptation of CROPWAT model to estimate event of crop water evaporating what application of soil water balance. That related to the study of the water footprint of bio-diesel production from oil palm at the Chaipattana-Mae Fah Luang Reforestation Project. As well as analysis to crop water requirement and behavior of water use included restrictions of water resource for produced the products at present and future.

3.2 Educational tools and equipments

3.2.1 Equipment and material consisted of the followings:

1. CROPWAT for WINDOWS version 8.0
2. Microsoft Office Excel version 2007
3. Computer, Processor: AMD memory 1.5G of Ram

3.2.2 Educational data consisted of the followings:

1. Geographic Information Systems of Chaipattana-Mae Fah Luang Reforestation Project and soil type from the Office of Soil Survey and Land Use Planning (2010).
2. Meteorological data consisted as temperatures (°c), rainfall (mm), sunshine duration (hr), humidity (%) and wind speed (km/day) from Thai Meteorological Department Monitoring Stations at (2010) Nong Plub station, Hua Hin District, Prachuap Khiri Khan Province from 1981 to 2010. (Figure 3-1)

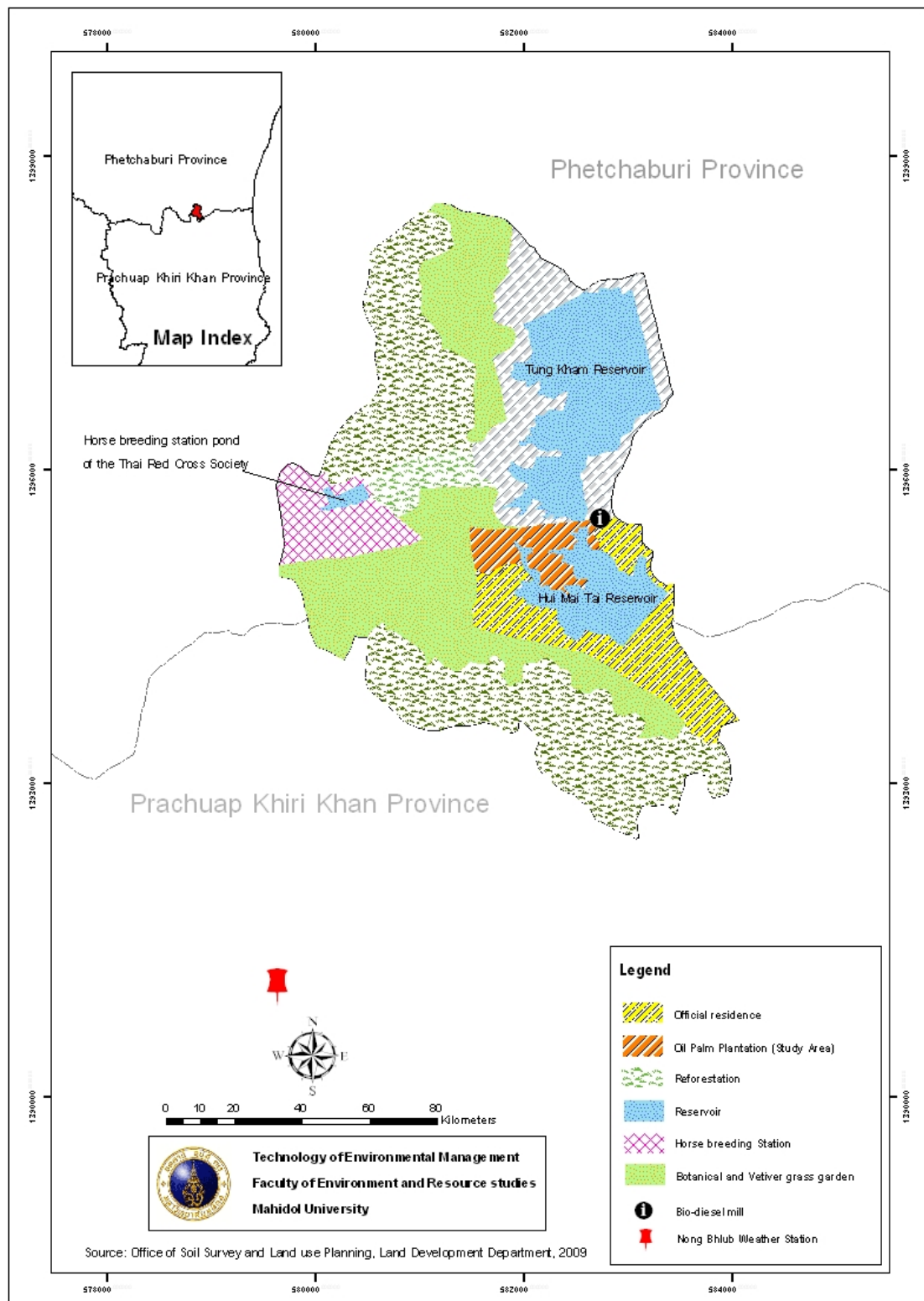


Figure 3-1 Study area and meteorological data at Nong Plub station, Hua Hin District, Prachuap Khiri Khan Province.

Source: Office of Soil Survey and Land Use Planning (2010)

3. Crop data consisted as information of oil palm as crop coefficient (K_c) followed Lienden et al (2010) and Chapagain & Hoekstra (2004), growth stage (days) and rooting depth (m) (cultivation plans, crop harvest, crop yield, cultivation practices and soil type; these data get by observation from site). The effective rainfall used ways followed FAO (2007a) and irrigation efficiency as 70% From RID (2010).

4. Bio-diesel data consisted as mass flow of process, product system, output product, price of product and processing until to bio-diesel product, value fraction of palm oil and bio-diesel were obtained from Chapagain & Hoekstra (2004).

5. Grey water data consisted as water quality (Natural concentration of nitrate-N) and water quality standard (Maximum concentration of nitrate-N as 5 mg/L) at Hua Mai Tai reservoir (the water resource for agriculture) from the Regional Irrigation Office 14 (2010) and Nitrogen leaching or running off to water bodies was 10% from Hoekstra et al. (2010 and 2011) and Fertilizer use statistics data from field and the FAO (2007b).

3.3 Educational steps

3.3.1 Data collection

Data sampling were collected from sources that showed in Table 3-1.

3.3.2 Data analysis

The data analysis was divided into 3 parts: calculate the water footprint of oil palm, palm oil and bio-diesel production from oil palm as product system at the Chaipattana-Mae Fah Luang Reforestation Project and bio-diesel mill model in 2006-2010.

1) Water footprint of oil palm assessment

First, to selected climatic station nearest was study area for input data to model. In this study, the green, blue and grey WFs of oil palm (*Suratthani II* and

Table 3-1: Data and source sampling

	Type of data	Sources	Objectives
1.	Geographic Information Systems of Chaipattana- Mae Fah Luang Reforestation Project	Office of Soil Survey and Land Use Planning	Boundary of study area
2.	Meteorology	Thai Meteorological Department	Calculation of crop water use (green and blue WF)
3.	Crop information	Chapagain & Hoekstra (2004) and Lidence et al.(2010)	Calculation of crop water use
4.	Soil features	Office of Soil Survey and Land Use Planning	Calculation of crop water use
5.	Water quality -study area -standard	Regional Irrigation Office 14	Calculation of grey WF
6.	Crop and bio-diesel system	Chaipattana- Mae Fah Luang Reforestation Project	Calculation of WFs of bio-diesel production

Compact Nigeria, Figure 2-14) were calculated since grown until harvested which following the framework of Hoekstra et al. (2011) method, issue 2.2.1 as equation [1] and exclude nursery period. The palm yield of WF calculated was 70% of FFB followed Lienden et al. (2010) and the palm yield average of full life span was Y (yield) factor in the WF calculation.

$$WF_{proc} = WF_{proc,green} + WF_{proc,blue} + WF_{proc,grey} \quad [1]$$

Green and blue WFs in water requirement termed were estimated by CROPWAT 8.0 model (both CWR and irrigation schedule option) and use method of USDA SCS to estimated effective rainfall, medium soil (sandy loam), refill soil to field capacity of application timing, irrigated at fix interval per 3 day for irrigation timing, 70% irrigation efficiency. Green and blue WFs were analyzed as equations [9] and [11] for the CWR and irrigation-option respectively; the WF output from the irrigation option of the irrigation condition was a representative of study area in 2006-2010 periods.

$$\text{In rain-fed scenario: } ET_{green} = \min (ET_c , P_{eff}) \quad [9]$$

$$ET_{blue} = \max (0, ET_c - P_{eff}) , \text{unit mm/period}$$

$$\text{In Irrigation scenario: } ET_{green}(\text{rain-fed}) = ET_a(\text{rain-fed}) \quad [11]$$

$$ET_{blue}(\text{rain-fed}) = 0$$

$$ET_{green}(\text{irrigation supply}) = ET_a(\text{rain-fed}) - ET_{blue}(\text{irrigation supply})$$

$$ET_{blue}(\text{irrigation supply}) = \min (\text{total net irrigation, actual irrigation requirement})$$

Additionally, above refer to the evapotranspiration from the field, the blue WF was not including water of percolation and runoff and the green and blue water incorporated into harvested crop. The WF results of product as showed in 2006-2010 which compare with 2001-2010 and 1986-2010 periods as Figure 3-2. Then predicted trend of blue water used of oil palm cultivation in 2015. A result of 2006-2010 by the irrigation schedule option model, base on Kc value of Lienden et al. (2010) was representative of this study.

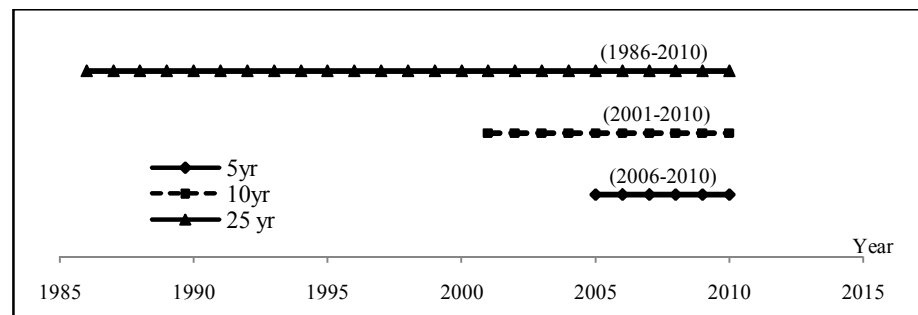


Figure 3-2 Timeline period analysis

For the grey WF was calculated by application rate (AR) as equation [4] and that had not analyzed effect of other nutrients, herbicides and pesticide. This study was analyzed to nitrogen use only; nitrate-N ($NO_3\text{-N}$) was the non point source followed Mekonnen and Hoekstra (2011). The maximum concentration of nitrate allowed as 5.0 mg/L which following the Regional Irrigation Office 14.

$$WF_{proc, grey} = \frac{(\alpha * AR) / (C_{max} - C_{nat})}{Y} \quad [4]$$

2) Water footprint of bio-diesel assessment

In this section the green, blue and grey WFs in process was analyzed by using a step-wise accumulative approach which following the framework of Hoekstra et al. (2011) method, as equation [6]. For residues was only a product fraction while value fraction was assumed to be zero followed Mekonnen and Hoekstra (2011). For product and value fraction of oil palm and palm oil value were followed Chapagian and Hoekstra (2004)

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

3) Efficient of use water assessment

For water use efficiency (WUE) of oil palm cultivation step that calculated following Bhardwaj et al. (2011). A high resulted of WUE means the better yield as equation [12]:

$$WUE = \frac{\text{Grain yield (kg)}}{\text{Crop water use (m}^3\text{)}} \quad [12]$$

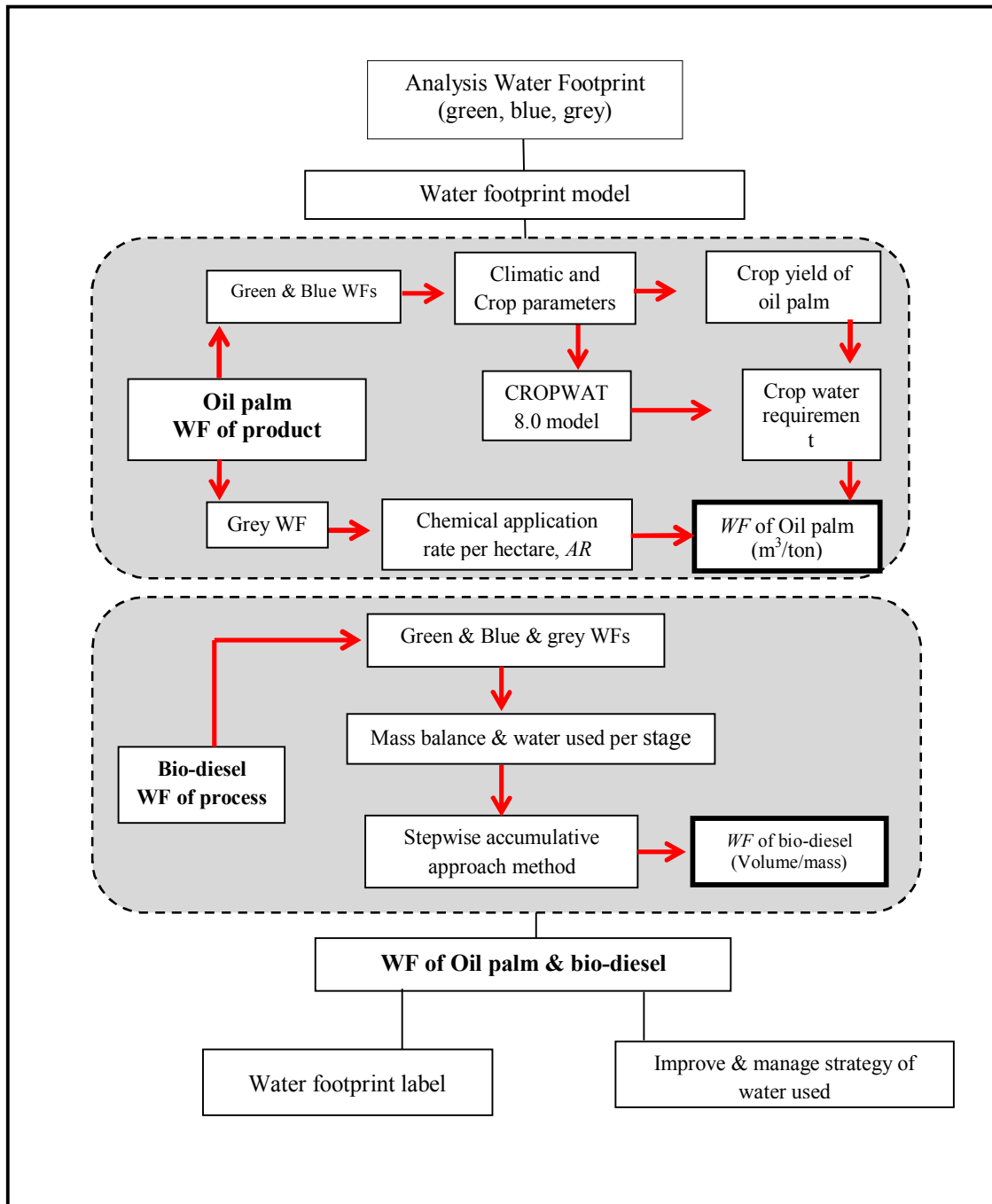


Figure 3-3 Educational flowchart

CHAPTER IV

RESULTS AND DISCUSSIONS

The water footprint concept and CROPWAT 8.0 model were selected to study the WF of bio-diesel and estimated crop water requirement (green and blue WFs) in oil palm plots at the Chaipattana-Mae Fah Luang Reforestation Project, Raimai Patthana Subdistrict, Cha um District, Petchaburi Province and Nhong Plub Subdistrict, Hua Hin District, Prachuap Khiri Khan Province. The results of this study was presented and discussed as follows:

- 1) Life cycle of bio-diesel product system
- 2) Yield of oil palm and bio-diesel productions
- 3) Fresh water consumption
- 4) Water footprint of product
- 5) Discussions

4.1 Life cycle of bio-diesel product system

-Oil palm cultivation

Life cycle of bio-diesel product started at the oil palm cultivation step. The product system of oil palm in oil palm plots at the Chaipattana- Mae Fah Luang Reforestation Project was started after 9 to 12 months nursery plants. Land preparing did not use any water because the soil was a sandy loam, called medium soil type (it was easily to improve the lands) and avoided the growth of weed. The land was prepared in dry season before plantation. After that dried soil by leaving the land about 15 days. In some lowland, the trench (2×1 meter) was necessary to prevent the flood water. The oil palm grew with triangle pattern (9×9×9 meter) and 22 plants /rai. For oil palm treatment meets the standards of the Department of Agriculture (DOA) method. The water system of oil palm was used precipitation in wet season and mini-springer

water system in dry season from the Wa Lai Along Korn reservoir; the frequency of irrigation was 1 time per 3 days (1.50 hour per field when did not had precipitation). In oil palm harvesting was did performed human labor only before transported the palm yield to bio-diesel mill by truck about 1 km. (Figure 4-1 and 4-2)

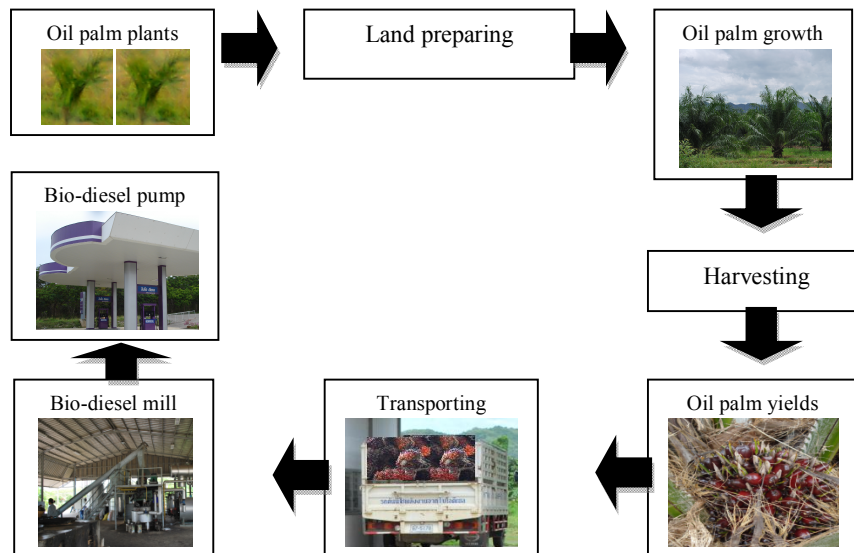


Figure 4-1 Production system of oil palm before transform to bio-diesel at the Chaipattana- Mae Fah Luang Reforestation Project

The fertilizer average was 54.3, 28.6 and 40.2 kg/rai or 0.33, 0.17 and 0.001 ton/ha of ammonium sulfate (21-0-0), rock phosphate (0-3-0) and potassium chloride (0-0-60) for plant 1 to 6 year.

- Palm oil

When factory accepted the FFB, palm oil extraction was first process before bio-diesel produced. The Hui Mai Tai reservoir was supported for water using.

This step was produced base on dry process. First stage, the oil palm extraction was produced with separation and mixture oil method. An oil palm yield (fresh fruit bunch) was threshed by cutting the fruit from bunch and cleaning by palm fruit cleaner before enter to dry process. After palm fruit was fired at temperature less than 120 degree Celsius for 1 hour (15 kg palm/pan). Fried palm was screw pressing and screen vibrating before oil was stored. Palm cake was by-product. The residual of

oil palm was removed by turning to filter press before storage crude palm oil (CPO) in CPO storage tank with free fatty acid 4-7 %.

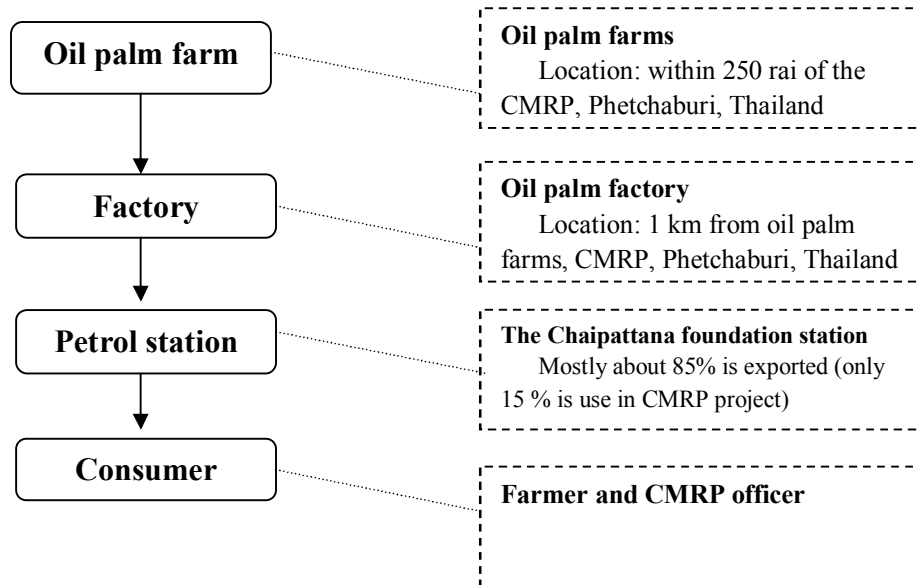


Figure 4-2 Simplified supply chain of bio-diesel palm

-Bio-diesel

In bio-diesel stage, the bio-diesel mill was produced oil which based on catalyze transesterification. The Hui Mai Tai reservoir will support for water using.

First stage, 400 L of CPO was cleaned by degumming and washing process. The added water in this step with ratio 1:1 L of CPO per water used. The end product was CPO 99.99% and 400 L of waste water. (Figure 4-3)

Second stage (bio-diesel processing), esterification of CPO was begun with mixed sulfuric acid and methanol in chemical mixing tank. Two reactions were done in the bio-diesel reactor; mixed potassium chloride with methanol in transesterification step. Then oil was separated by settle (output product raw was glycerol). The settle oil evaporated ethanol by re-heating; the recovery methanol was returned to system again. Output washing was sprayed by hot water at temperature 50 degree Celsius with ratio 1:1 L of CPO and water used. Oil was de-hydrated by re-heating and filters salting. When water in oil less than 0.05% that was separated by settle it in 10 degree Celsius of distribution tank and filter again. Oil storage in bio-diesel tank was distributed at the

bio-diesel station. The final product was pure bio-diesel (B100), bio-diesel wax and waste water (Figure 4-4).

For the residual matter (bio-diesel wax) was fueled in burning process. Waste water of process was treated by aeration method in the 7×7×3 meters soil pond. The polyethylene (PE) material was filled in the soil pond to prevent the soil from becoming toxic. The maximum capacity is 147 m³ of waste water.

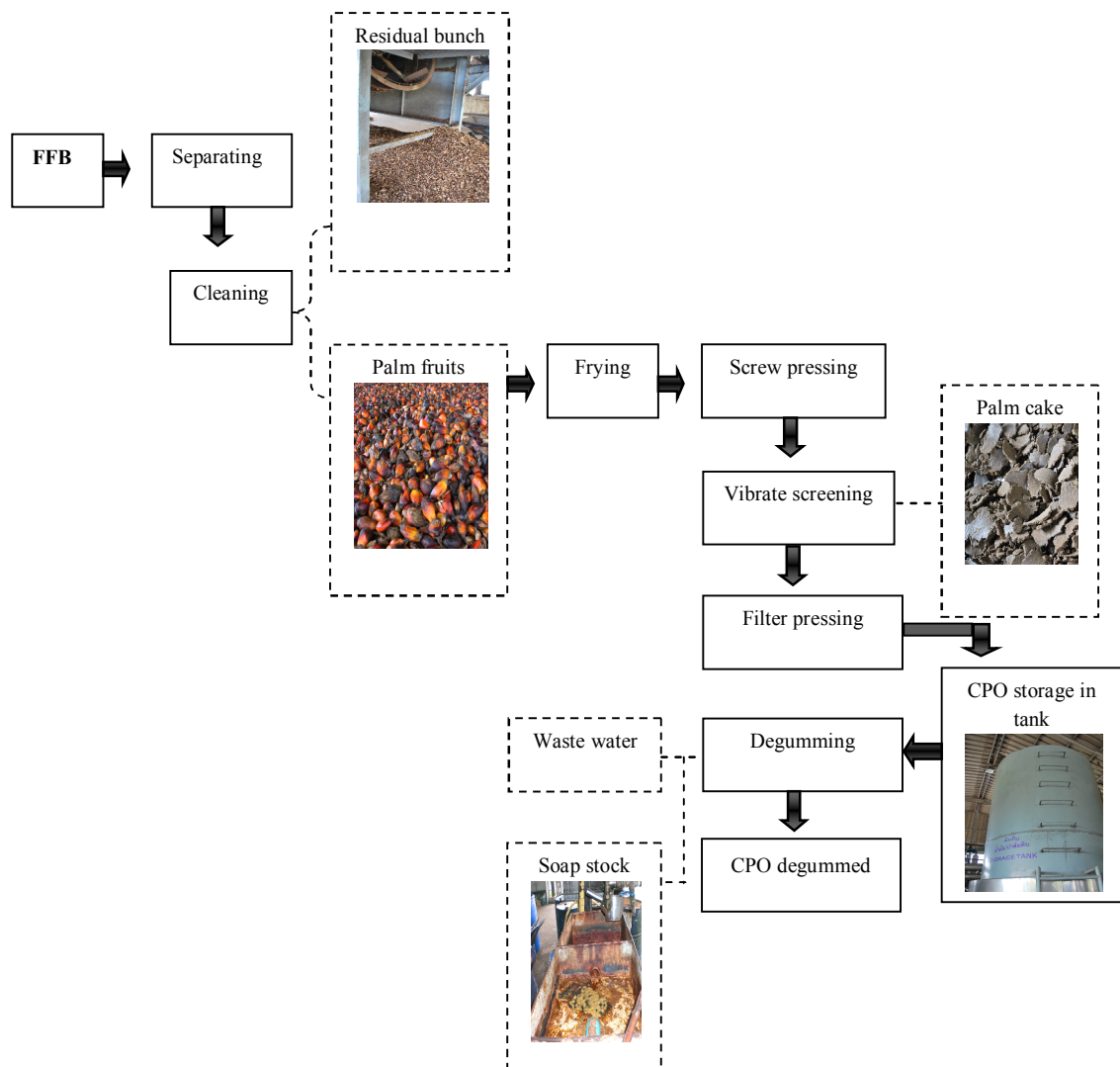


Figure 4-3 Palm oils extraction, ➡ (flow process) and ---- (output product)

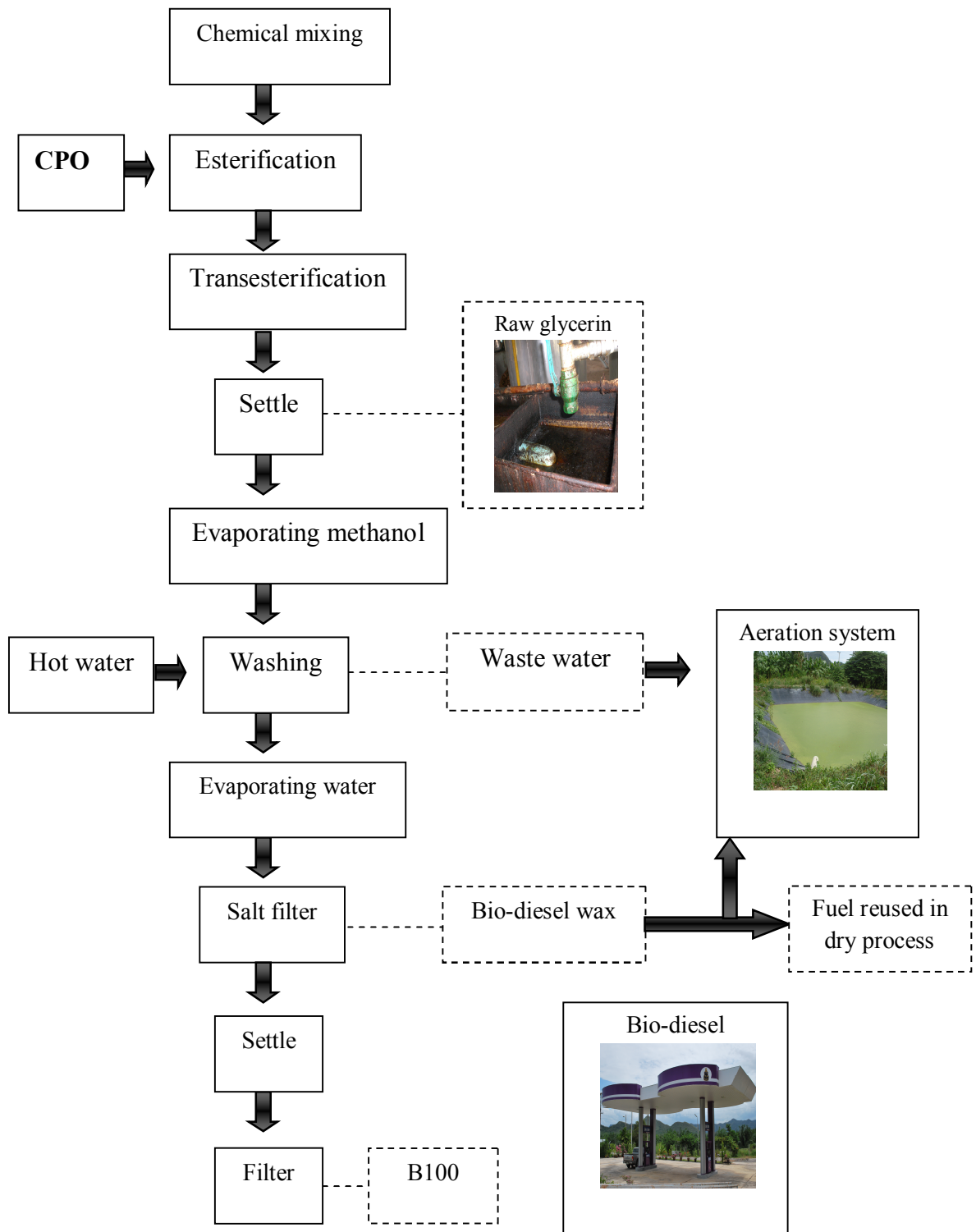


Figure 4-4 Bio-diesel supply chain to end use

4.2 Yield of oil palm and bio-diesel productions

- Oil palm harvesting

The size of area plantation was from 200 rai to 250 rai and only 100 rai of oil palm can be harvested. After 30 months or 2½ years of oil palm growth was staying in development stage. Firstly harvest yields of *Suratthani II* and *Compact Nigeria* were in 2005 and 2006, respectively as Figure 4-5. The oil palm yield can be harvested over the year and high season (May to August) can be kept about 15 days per time as Figure 4-6. In oil palm harvesting used human labor only and transported to the bio-diesel mill model by truck about 1 km. In the early of bio-diesel production used external oil palm from farmer more than palm harvesting from palm field. The oil palm yield of project had the low yield and did not completely grow up.

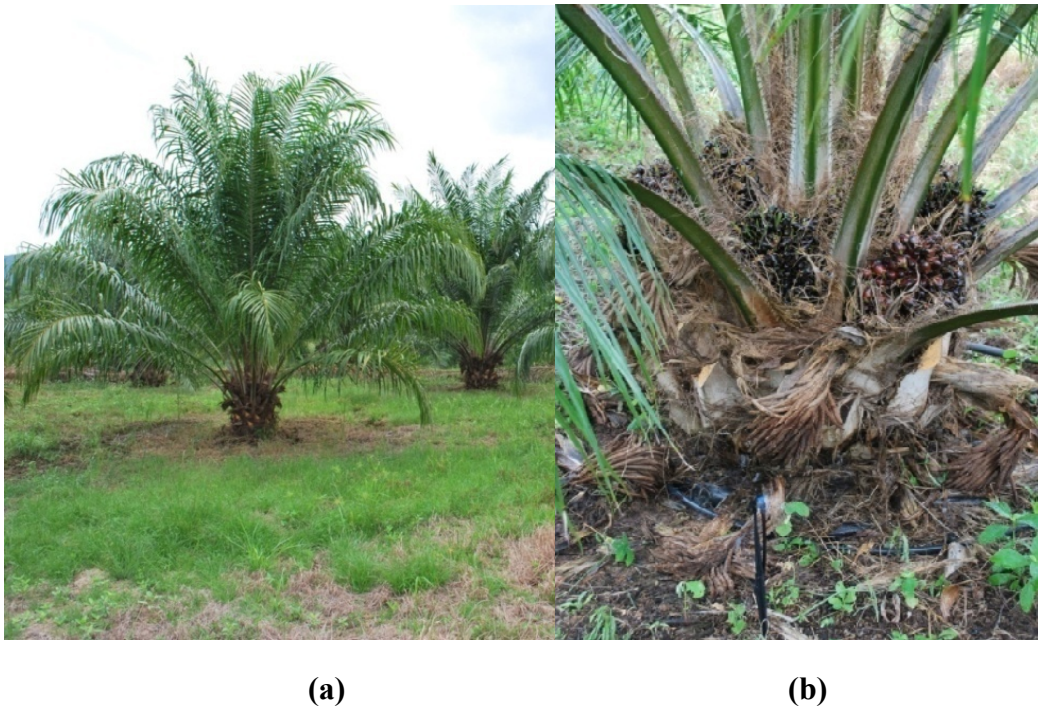


Figure 4-5 Oil palm tree (a) and oil palm fruit (b) in study area

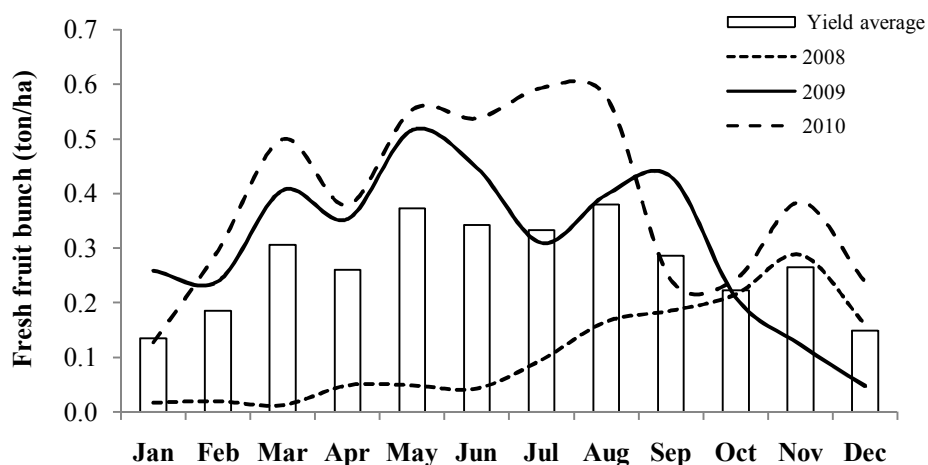


Figure 4-6 Total monthly yields of oil palm in 2008-2010 periods

Other fresh fruit bunch (FFB) and fresh fruit was showed in Table 4-1. Yield palm fruit had 70% of FFB in this study area.

Table 4-1 Oil palm yields

Country	Weather station location	Latitude /longitude	Yield FFB (kg/rai)	Yield FFB (kg/ha)	Yield average of full life span (ton/ha)	Yield fruit (ton/ha)
Thailand (2008-2010)	Nhong Plub, Prachuap Khiri Khan	12.35N, 99.44 E	490	3,063 ^a	7.8	5.5 ^b

***Remark** ^a Value calculates, FFB yield in oil palm pilots at the Chaipattana- Mae Fah Luang Reforestation Project, 2008-2010 periods. ^b Value calculates, yield fruit as 70% of average FFB yield of full life span.

Total oil palm yield in 2008-2010 period were 1.3, 3.7 and 4.9 ton/ha, respectively. Yield average was 3.3 ton/ha or 0.53 ton/rai and yield of 2010 was highest. The oil palm yield average of full life span was 7.8 ton/ha. Bio-diesel production was used only the oil palm fruit; the yield fruit was 5.5 ton/ha (palm fruit as 70% of FFB). The trend of total yield was increasing slightly as Figures 4-7. The oil palm yield in the study area was lower than oil palm world standard as Figures 4-8.

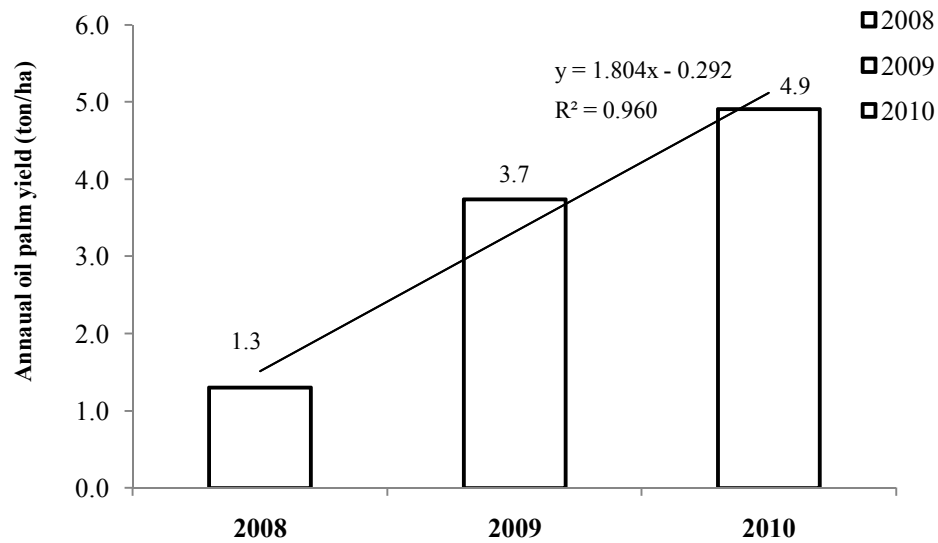


Figure 4-7 Annual whole FFB yield of the oil palm in 2008–2010 periods (ton/ha)

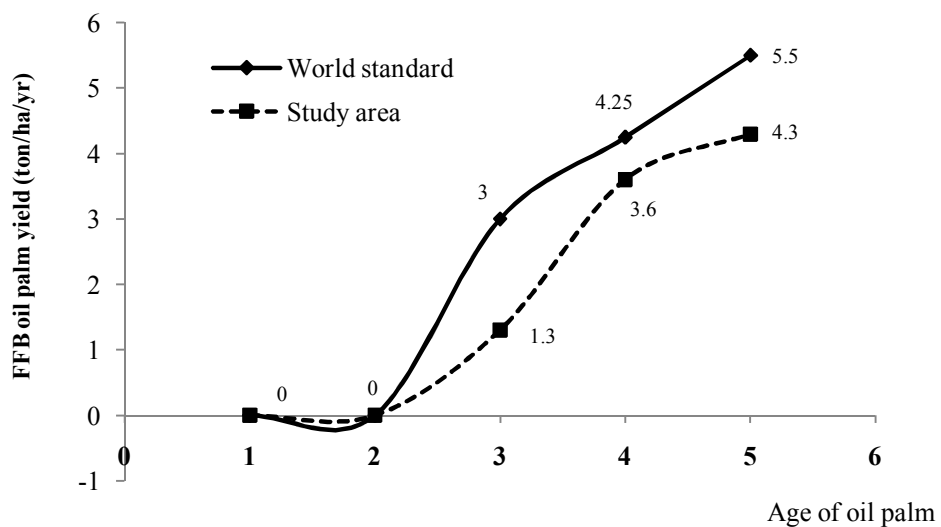


Figure 4-8 Annual whole FFB yield of oil palm in 2006–2010 periods (ton/ha/year), oil palm growth stage compared with world standard

- Bio-diesel production

As showed in Figure 4-9 the bio-diesel production in 2008-2010 periods was 36.3 thousand liters/year. 1 L CPO used 4 kg FFB (1.5 ton /800 L). The bio-diesel distribution was sold to people and used in project. The bio-diesel average was 28 and 5 thousand L/yr, respectively as Figure 4-9. The demand for bio-diesel export was higher

than bio-diesel used in project as 6 fold. Bio-diesel price average was 23 bath/L in 2008-2010 periods.

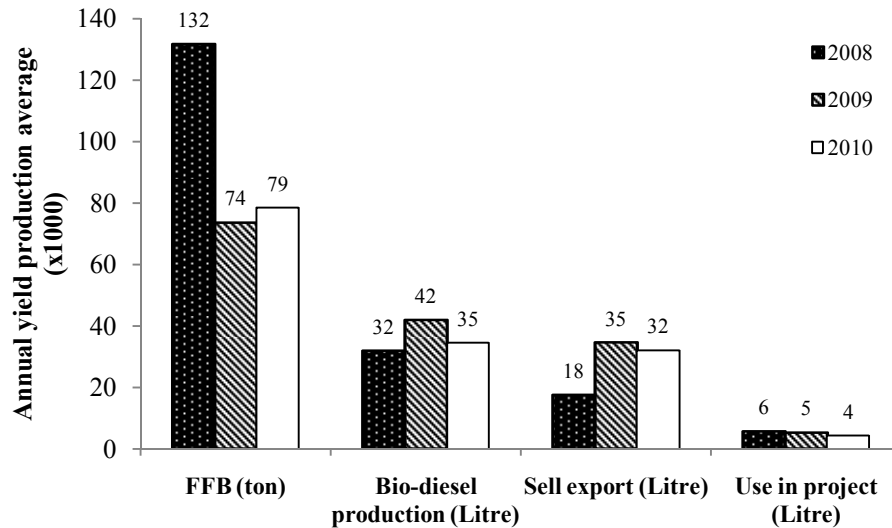


Figure 4-9 Demand for bio-diesel productions in terms of exporting and using in the project in 2008-2010 periods

4.3 Fresh water consumption

- Oil palm cultivation

As showed in Table 4-2 and Figure 4-10, crop water used (CWU) in 2006-2010 period was 2.2×10^4 m³/ha/year; CWU_{green} 2,880, CWU_{blue} 10,060 and CWU_{grey} 9,000 m³/ha (or 3.5×10^3 m³/rai) on the irrigation schedule option model. Result run with CWR option model was 2.4×10^4 m³/ha/ year. Total CWU ignored CWU_{grey} was 1.2×10^4 m³/ha.

CWU of oil palm which based on CWR option model was higher than Irrigation schedule option model result in all 3 periods. The CWU was calculated with vary climatic data, CWU in 2001-2010 periods was higher than both CWU in 1986-2010 and 2006-2010 periods on both the irrigation schedule and CWR option model, respectively as Figure 4-11. Efficiency water use in oil palm plantation was 0.23.

Table 4-2 Green, blue and grey oil palm water used (m^3/ton) in the reforestation project Chaipattana- Mae Fah Luang Royal, Thailand (in 3 periods; 2006-2010, 2001-2010 and 1986-2010). CWU results run based on the CWR and irrigation schedule option

CROPWAT option	ET _{green}	ET _{blue}	ET _a	CWU _{green}	CWU _{blue}	CWU _{grey}	CWU _{tot}	CWU _{green+blue}
	mm/growing period			m^3/ha			m^3/ha	
Oil palm (2006-2010)								
<i>Irrigation schedule option</i>	288	1,006	1,294	2,880	10,060	9,000	21,940	12,940
<i>CWR option</i>	704	802	1,506	7,040	8,020	9,000	24,060	15,060
Oil palm (2001-2010)								
<i>Irrigation schedule option</i>	318	1,051	1,369	3,180	10,510	9,000	22,690	13,690
<i>CWR option</i>	707	889	1,595	7,070	8,890	9,000	24,960	15,950
Oil palm (1986-2010)								
<i>Irrigation schedule option</i>	318	1,022	1,340	3,180	10,220	9,000	22,400	13,400
<i>CWR option</i>	675	883	1,557	6,750	8,830	9,000	24,580	15,570

***Remark** Result of CWU_{green} and _{blue} estimated by CROPWAT model, CWU grey result was calculated by AR equation.

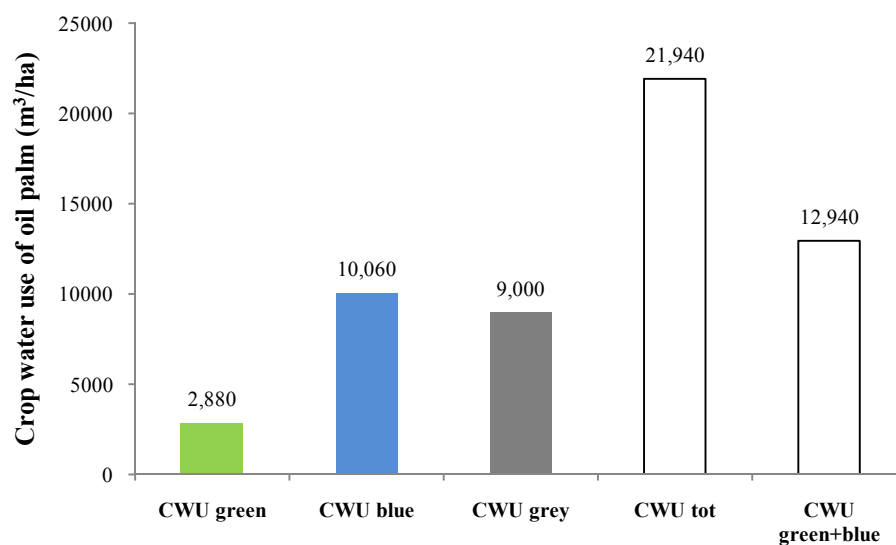


Figure 4-10 Crop water used of oil palm in 2006-2010 periods, results based on the irrigation schedule option

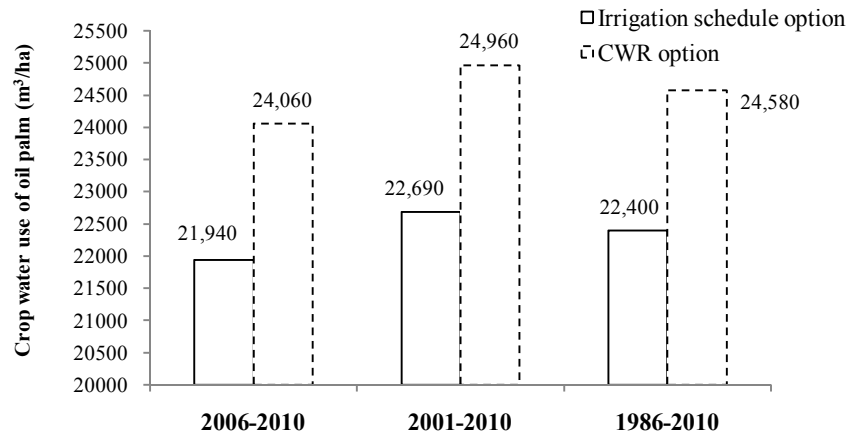


Figure 4-11 Total crop water used of oil palm in 3 periods; 2006-2010, 2001-2010 and 1986-2010 periods. Results run with the irrigation schedule and CWR option model

In the other hand, oil palm CWU results from Kc followed Chapagain & Hoekstra (2004) was 2.1×10^4 m³/ha/year in 2006-2010 period; CWU_{green} 2,520, CWU_{blue} 9,810 and CWU_{grey} 9,000 m³/ha (or 3.4×10^3 m³/rai) on the irrigation schedule option model. Total CWU ignore CWU_{grey} was 1.2×10^4 m³/ha as Table 4-3 and Figure 4-12.

Table 4-3 Green, blue and grey components of oil palm crop water used in 2006-2010 periods (m³/ton). Results of Kc value followed Chapagain & Hoekstra (2004)

CROPWAT option	ET_{green}	ET_{blue}	ET_a	CWU_{green}	CWU_{blue}	CWU_{grey}	CWU_{tot}	$CWU_{green+blue}$
	mm/growing period							
Oil palm (2006-2010)								
<i>Irrigation schedule option</i>	252	981	1,233	2,520	9,810	9,000	21,330	12,330
<i>CWR option</i>	673	807	1,480	6,730	8,070	9,000	23,800	14,800
Oil palm (2001-2010)								
<i>Irrigation schedule option</i>	257	1,016	1,273	2,570	10,160	9,000	21,730	12,730
<i>CWR option</i>	738	768	1,506	7,380	7,680	9,000	24,060	15,060
Oil palm (1986-2010)								
<i>Irrigation schedule option</i>	273	999	1,272	2,730	9,990	9,000	21,720	12,720
<i>CWR option</i>	690	796	1,486	6,900	7,960	9,000	23,860	14,860

***Remark** Result of CWU_{green} and $blue$ estimated by CROPWAT model, CWU grey result was calculated by AR equation.

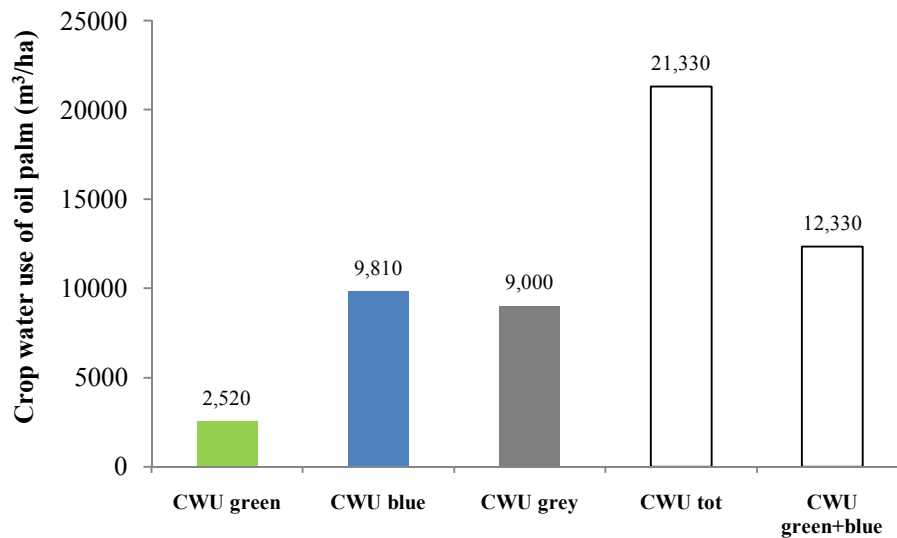


Figure 4-12 Crop water used of oil palm in 2006-2010 periods, results run based on Irrigation schedule option model. Results of Kc value followed Chapagain & Hoekstra (2004)

CWU result of CWR option model was 2.3×10^4 m³/ha/ year. In 2001-2010 periods CWU of oil palm in terms of the CWR and irrigation schedule option model were higher than 2 period; 1986-2010 and 2006-2010 period as Figure 4-13.

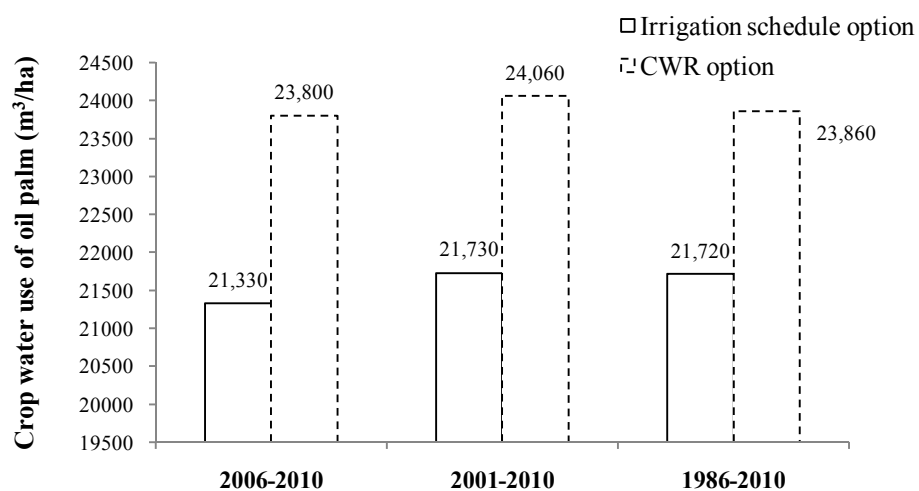


Figure 4-13 Crop water used total of oil palm in 3 periods; 2006-2010, 2001-2010 and 1986-2010 periods. CWU result run based on the irrigation schedule and CWR option model. Kc of oil palm followed Chapagain & Hoekstra (2004)

The CWU result of oil palm was calculated with Kc of oil palm followed Chapagain & Hoekstra (2004) and Lienden et al. (2010) source; Lienden et al. (2010) was a representative of study area. The CWU results calculating followed KC base on Lienden et al. (2010) was higher than Kc followed Chapagain & Hoekstra (2004) in all cases as Figure 4-14.

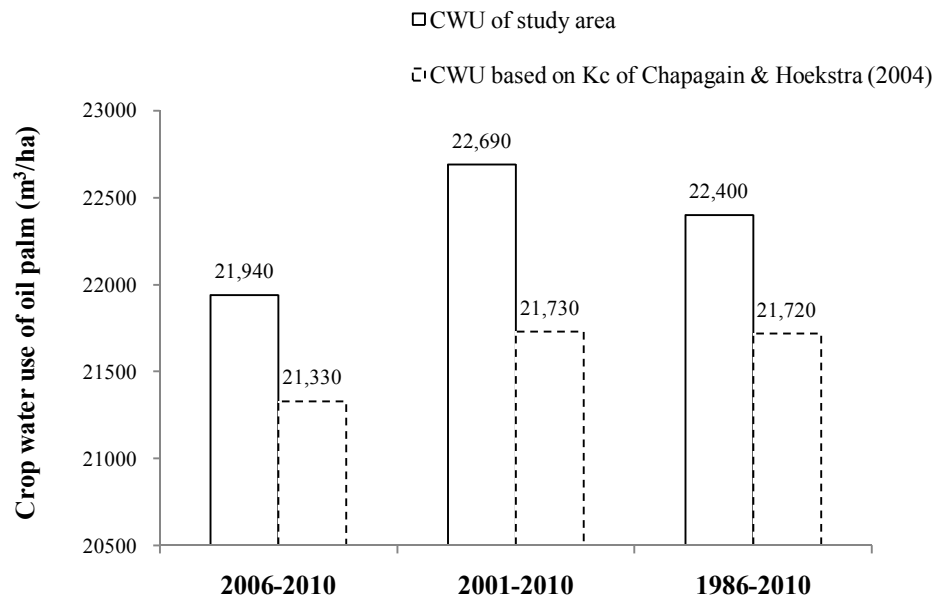


Figure 4-14 Total crop water used of oil palm which results run 2 Kc source; Lienden et al. (2010) this was representative of study area and Chapagain & Hoekstra (2004). The results run based on the irrigation schedule option model

For monthly crop water requirements of oil palm, the ET_{green} was lower than ET_{blue} in annual year. The ET_{green} was highest during wet season (April to October) and ET_{blue} was high demanded during dry seasons (January to March, November and December) between 2006-2010 and 1986-2010 period as Figure 4-15 and 4-16. The ET_{green} and ET_{blue} were conversely relationship in all periods.

As showed in Figures 4-17, when considerate data in 2006-2010 and 2001-2010 period, *trend of oil palm* in 2015; irrigation water will be increasing because the rainwater will be declining.

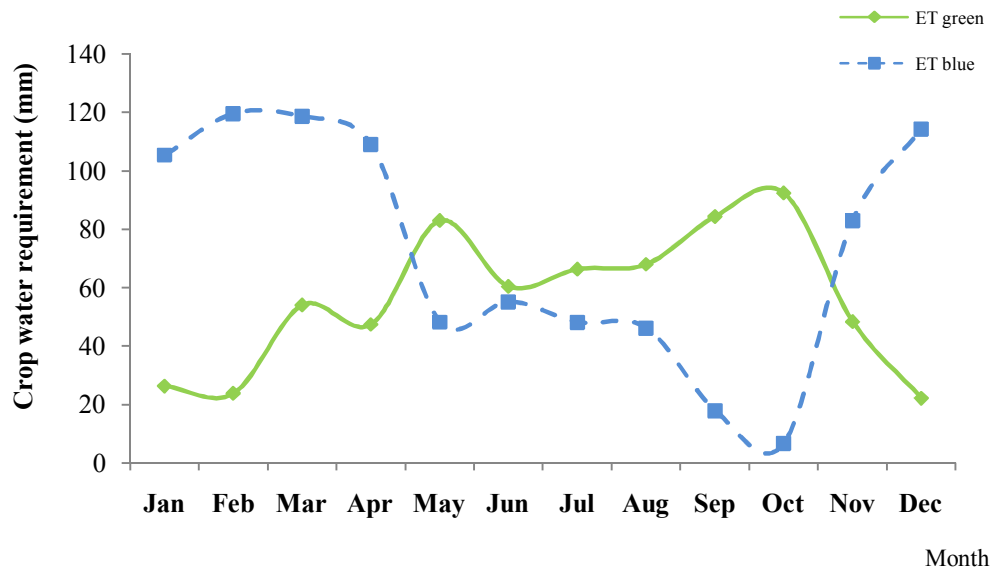


Figure 4-15 Monthly crop water requirements (ET_{green} and ET_{blue} , mm.) of oil palm cultivation in 2006-2010 periods

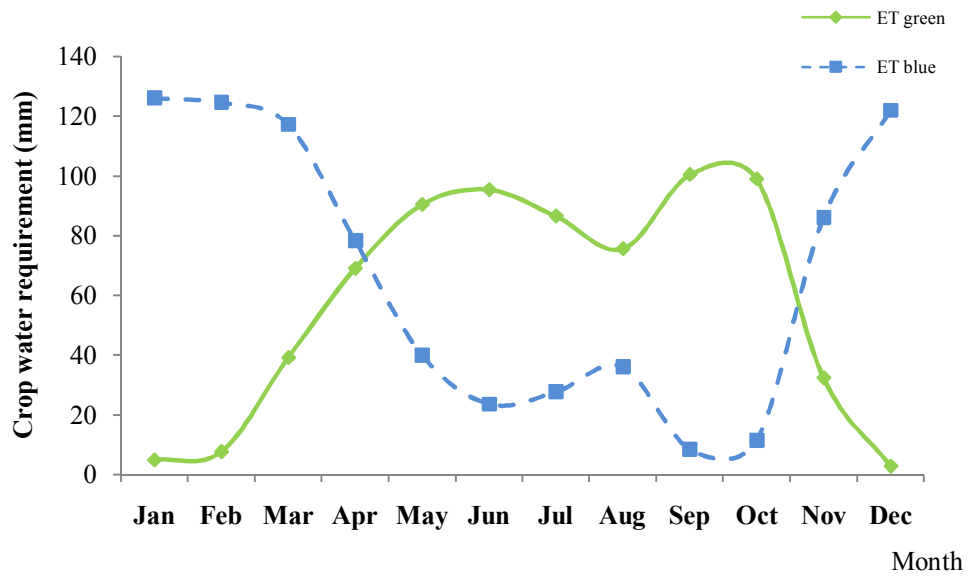
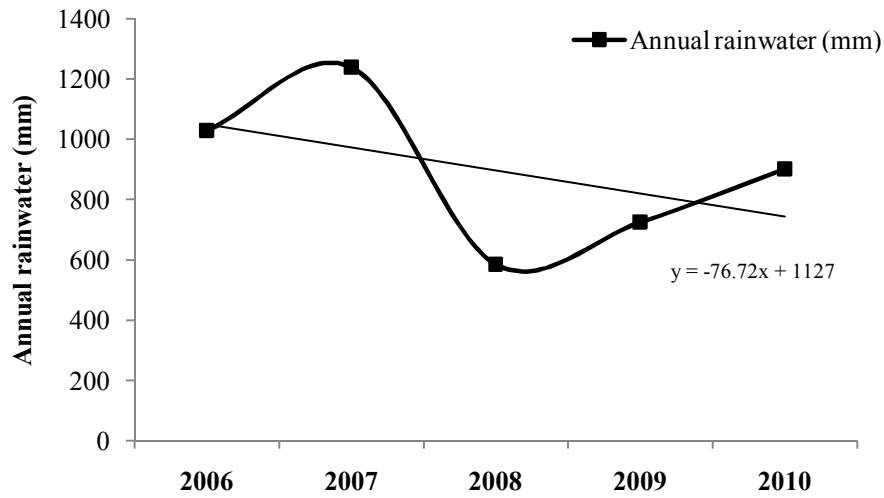
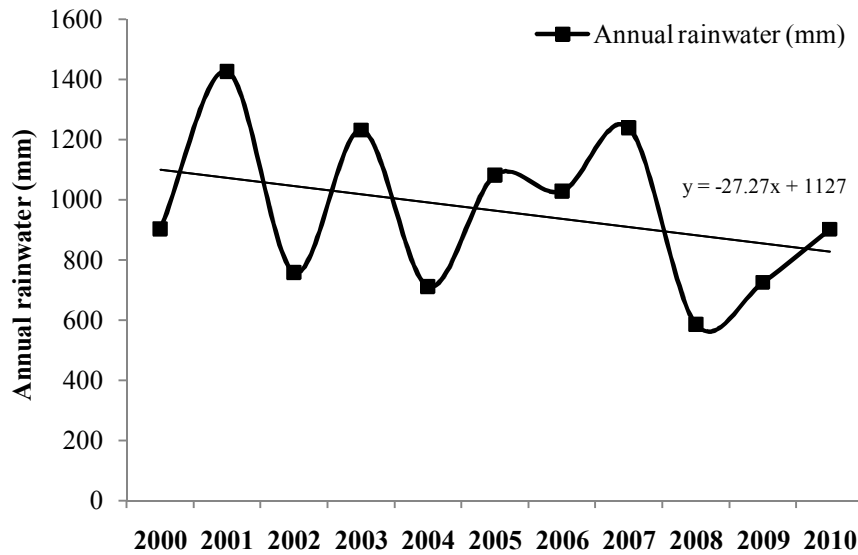


Figure 4-16 Monthly crop water requirements (ET_{green} and ET_{blue} , mm.) of oil palm cultivation in 1986-2010 periods



(a)



(b)

Figure 4-17 Annual rainwater of Nong Plub station since 2006-2010 (a) and 2001-2010 periods (b)

As Figure 4-18, in 2015 the trend of irrigation water from 1986-2010 periods of rainwater data of oil palm will be increase in 2015. The green water (precipitation) was limited by nature. Finally water used of oil palm was used in the cultivation step only. The other of production steps (land preparing, harvesting and transportation) did not used any water as Table 4-4.

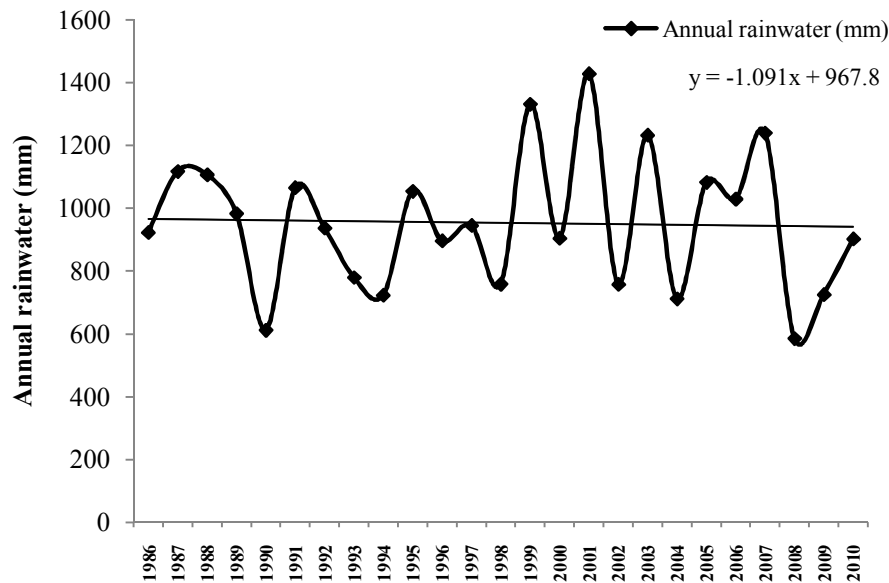


Figure 4-18 Annual rainwater since 1986-2010 periods

Table 4-4 Freshwater use of bio-diesel process steps

Production step	Crop water use (CWU)			
	Green water	Blue water	Grey water	Total
• Land preparation	0	0	0	0
• Cultivation (m ³ /ha)	2,880	10,060	9,000	21,940
• Harvest	0	0	0	0
• Transportation	0	0	0	0
• Palm oil (<i>Dry process</i>)	0	0	0	0
• Bio-diesel (<i>catalyze transesterification</i>) (L water/ 1,383 L bio-diesel)*	0	2,767	0	2,767

Remark* 2 L water per 1 L CPO in one round bio-diesel production.

- Palm oil and bio-diesel production

Dry process method was selected in palm oil producing. Water used of crude palm oil (CPO) did not used any freshwater in process. Bio-diesel water used was used in degumming and trans-esterification. The degumming process used 400 L palm oil per 400 L freshwater; output product was CPO. The trans-esterification step used

400 L CPO degummed per 400 L freshwater; bio-diesel B100 was output product. 5.5 ton/ha FFB can be produced 1,383 L bio-diesel; bio-diesel water used was 2,767 L water (ratio of bio-diesel process as 1 L bio-diesel/2 L water used) as Figure 4-19.

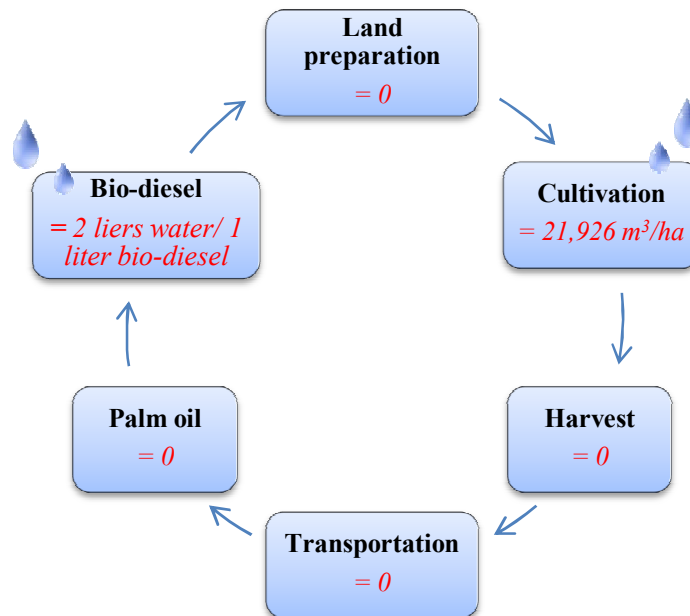


Figure 4-19 Freshwater used in bio-diesel process step

4.4 Water footprint of products

- Water footprint of oil palm crop

In the first section had described the *grey WF* of oil palm. Due to rainwater scarcity and runoff from palm in the Hui Mai Tai reservoir was evaporated so water quality data has not been collected after 2006. It is reported from RID that nitrate-nitrogen (NO₃-N) concentration of water quality was 1.7 mg/L (2010).

Fertilizer used in the study area based on water quality of Thailand and world standard, which 1,636 and 545 m³/ton, respectively. Otherwise grey WF calculated with FertiStat from FAO (2007b) was 545 m³/ton water quality Thailand standard and 181 m³/ton world standards as Figure 4-20.

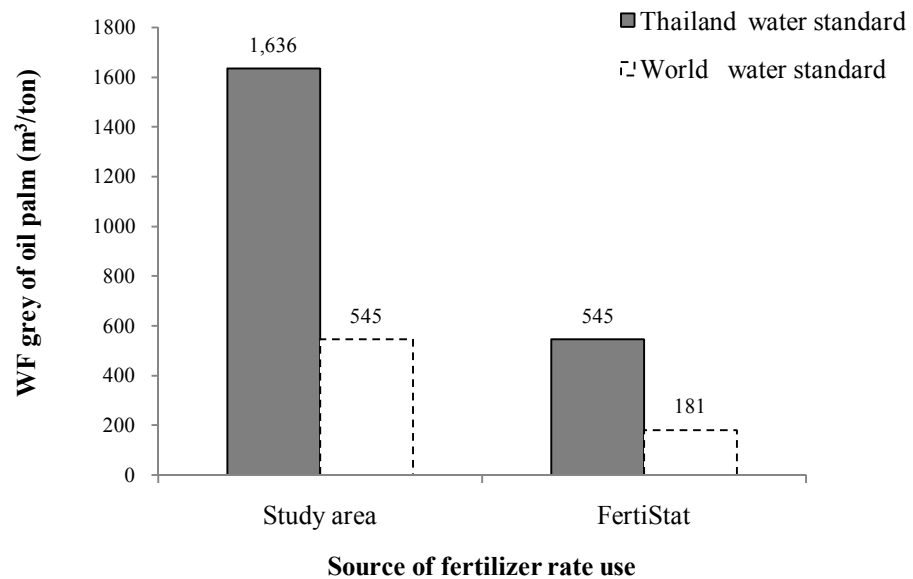


Figure 4-20 The grey water footprint (N-nitrate used only) of oil palm cultivation on water quality of Thailand and world standard in 2006-2010 periods. Fertilizer rate used base on study area and FertiStat, FAO (2007b)

Secondary section was the *green and blue WFs*. The evapotranspiration from the field was referred from previous section. The water percolation was not including in the blue WF. Harvested crop had the green and blue water incorporated. Incorporated water fraction of oil palm with 3.8%; the WF of oil palm was 0.038 m³/ton. The WF related to evaporated water which was less than 1 %. The total WFs of oil palm result with WF_{grey} base on Thailand standard can be explained as follows.

The WFs of oil palm in 2006-2010 periods were typical in study area. Total WFs of oil palm were 3,989 m³/ton (green WF 524, blue WF 1,829 and grey WF 1,636 m³/ton) by the irrigation schedule option model. WF of the CWR option model was 4,374 m³/ton as Figure 4-21 or 699 m³/rai as Table 4-5. Generally WF research was reported about green and blue WFs only; ignored the grey WF. WFs of oil palm without grey WF was 2,353 m³/ton as Table 4-6.

Oil palm WFs were compared among 3 periods; on the irrigation schedule option model were 4,125 and 4,072 m³/ton of WFs in 2001-2010 and 1986-2010 periods, respectively. Oil palm WFs of CWR option was higher than 2006-2010 periods as Table 4-6.

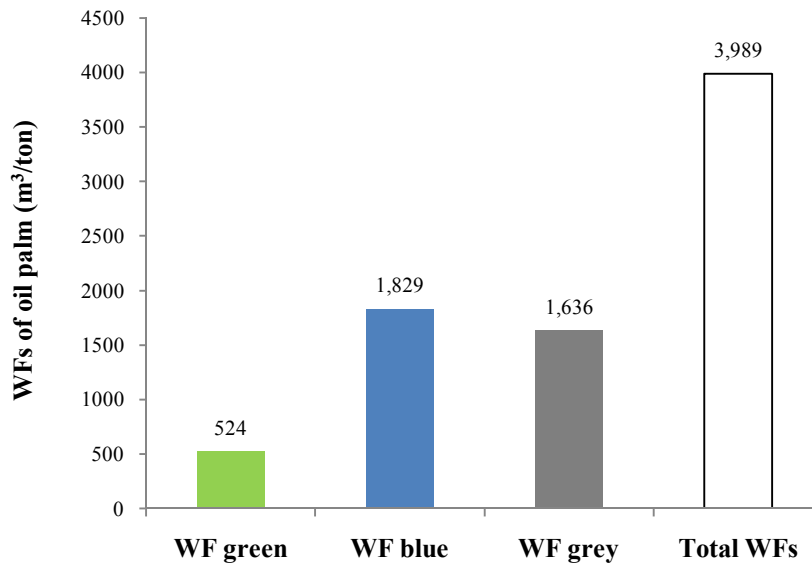


Figure 4-21 WFs of oil palm cultivation in study area, the results run based on the irrigation schedule option model in 2006-2010 periods

Table 4-5 Oil palm yields, water use, effective rainfall, irrigation water, pollution water volume and WFs of oil palm

Water used of oil palm (m³/rai)	Oil palm yield (ton/rai)	Effective rainfall (m³/rai)	Irrigation water (m³/rai)	pollution water volume (m³/rai)	WFs of oil palm (m³/ton)
3.5×10^3	0.88	461	1,610	1,440	262

WFs was calculated with vary climatic data, WFs of oil palm in 2001-2010 periods was higher than WFs in 1986-2010 and 2006-2010 periods with both the option model as Figure 4-22.

In the other hand, WFs of oil palm results in 2006-2010 period was calculated by Kc of Chapagain & Hoekstra (2004) which was 3,878 m³/ton; WF_{green} 458, WF_{blue} 1,784 and WF_{grey} 1,686 m³/ha on the irrigation schedule option model. WFs of CWR option model was 4,327 m³/ton as Figure 4-23. Total WFs of oil palm without grey WF was 2,242 m³/ton as Table 4-7.

Table 4-6 Green, blue and grey WFs of oil palm (m^3/ton) in the Royal of reforestation project Chaipattana-Mae Fah Luang, Thailand (in 3 periods; 2006-2010, 2001-2010 and 1986-2010)

CROPWAT option	Y* ton/ha	WF _{proc,green}	WF _{proc,blue}	WF _{proc,grey}	WF _{proc,total}	WF _{proc, green+blue WF}
		m^3/ton			m^3/ton	
Oil palm (2006-2010)						
Irrigation schedule option	5.5	524	1,829	1,636	3,989	2,353
CWR option		1280	1,458	1,634	4,374	2,738
Oil palm (2001-2010)						
Irrigation schedule option	5.5	578	1,911	1,636	4,125	2,489
CWR option		1,285	1,616	1,636	4,537	2,901
Oil palm (1986-2010)						
Irrigation schedule option	5.5	578	1,858	1,636	4,072	2,436
CWR option		1,227	1,605	1,636	4,468	2,832

***Remark** Result of WF_{green} and WF_{blue} estimated by CROPWAT model, WF_{grey} result was calculated by AR equation. *Oil palm yield data from study area.

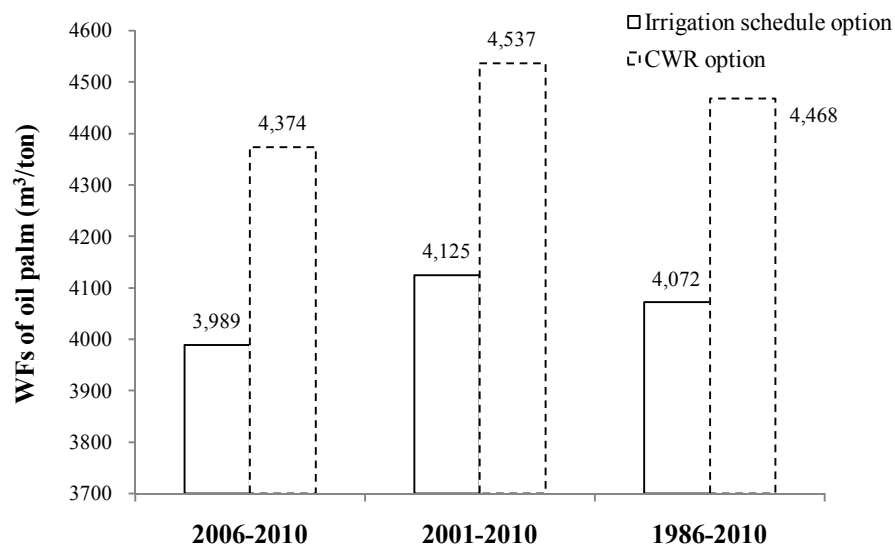


Figure 4-22 Water footprint total of oil palm in 3 periods; 2006-2010, 2001-2010 and 1986-2010 periods. Results with the irrigation schedule and CWR option model

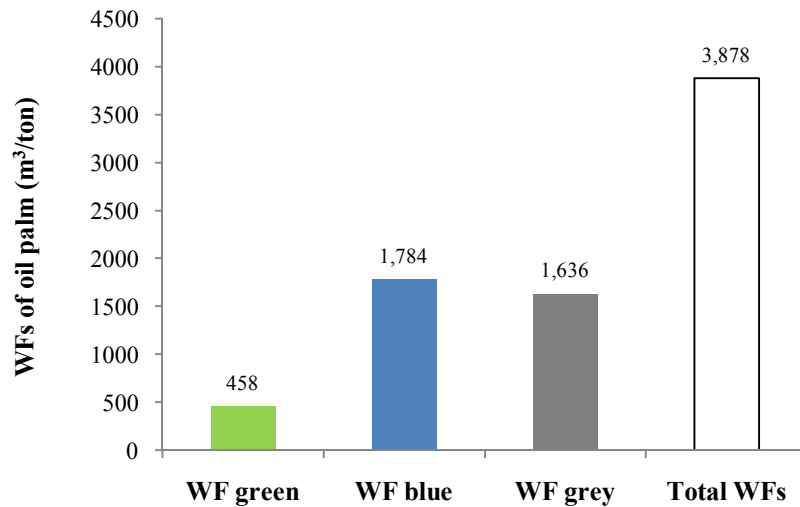


Figure 4-23 WFs of oil palm cultivation, results run based on the irrigation schedule option model in 2006-2010 periods. Results run Kc value followed Chapagain & Hoekstra (2004)

Oil palm WFs which calculated from both option models compared among 3 periods. WFs of oil palm in 2001-2010 and 1986-2010 periods were 3,950 and 3,948 m³/ton, respectively on the irrigation schedule option model. The WFs result from CWR option was higher than 2006-2010 periods as Table 4-7.

Table 4-7 Green, blue and grey components of oil palm water footprint in 2006-10 periods (m³/ton). Results run Kc value followed Chapagain & Hoekstra (2004)

CROPWAT option	Y* ton/ha	WF _{proc,green}	WF _{proc,blue}	WF _{proc,grey}	WF _{proc,total}	WF
						proc,green+blue
Oil palm (2006-2010)						
<i>Irrigation schedule option</i>	5.5	458	1,784	1,636	3,878	2,242
<i>CWR option</i>		1,224	1,467	1,636	4,327	2,691
Oil palm (2001-2010)						
<i>Irrigation schedule option</i>	5.5	467	1,847	1,636	3,950	2,314
<i>CWR option</i>		1,342	1,396	1,636	4,374	2,738
Oil palm (1986-2010)						
<i>Irrigation schedule option</i>	5.5	496	1,816	1,636	3,948	2,312
<i>CWR option</i>		1,255	1,447	1,636	4,338	2,702

***Remark** Oil palm yield data obtained from study area (Y)

WFs was calculated with vary climatic data, in 2001-2010 periods WFs of oil palm was higher than WFs in 1986-2010 and 2006-2010 periods on both the irrigation schedule and CWR option model as Figure 4-24.

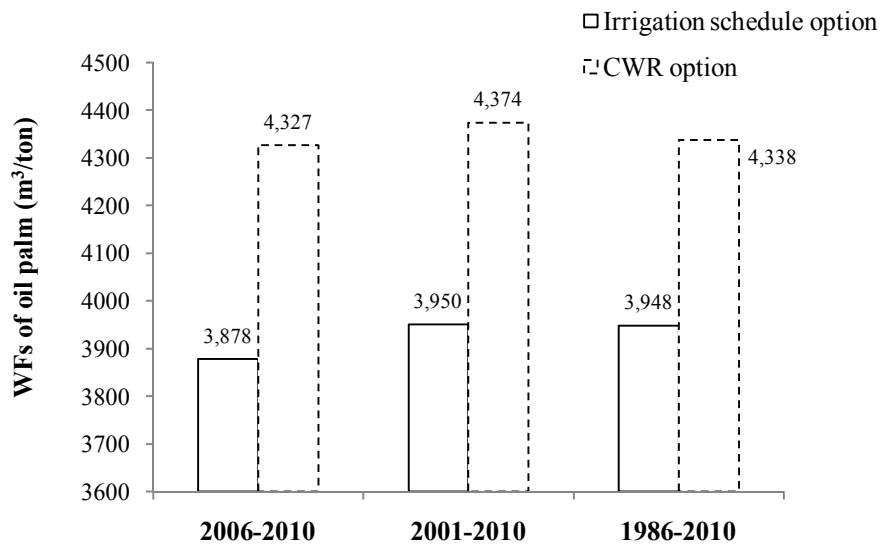


Figure 4-24 Water footprint of oil palm in 3 periods; 2006-2010, 2001-2010 and 1986-2010 periods. Results based on the irrigation schedule and CWR option model. Results run Kc value followed Chapagain & Hoekstra (2004)

Calculation of oil palm WFs based on 2 sources Kc of oil palm; followed Lienden et al. (2010) (representative of study area) and Chapagain & Hoekstra (2004) source. WFs of study area with Kc followed Lienden et al. (2010) was higher than Chapagain & Hoekstra (2004) in all case and all periods as Figure 4-25.

WF (green, blue and grey) of oil palm (output based on the CWR option model) in study area were higher than Thailand and global average included other countries as Figure 4-26. Blue WF of study area was highest among countries as Figure 4-27.

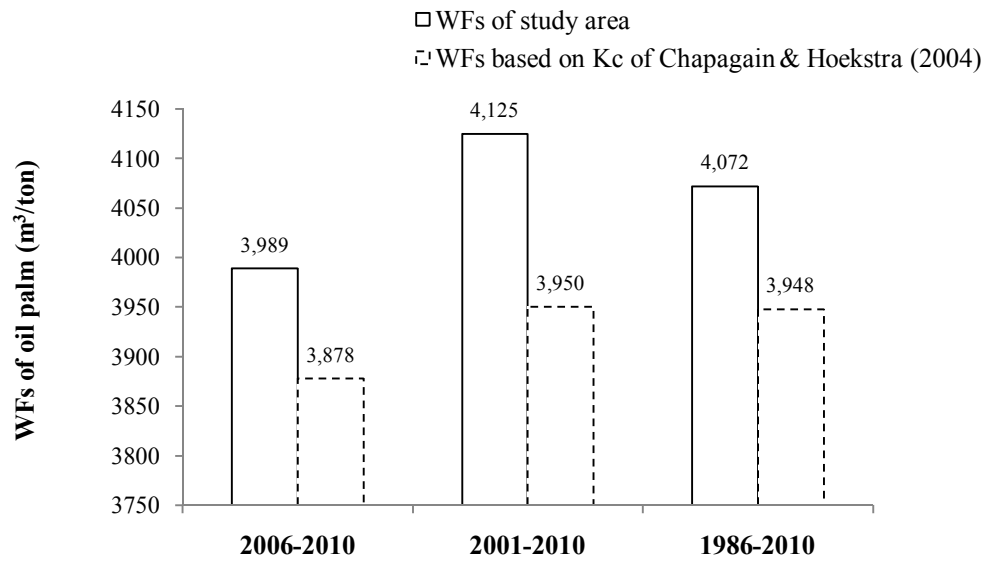


Figure 4-25 The WF of oil palm run on 2 Kc source; Lienden et al. (2010) (representative of study area) and Chapagain & Hoekstra (2004). Results run based on the irrigation schedule option model

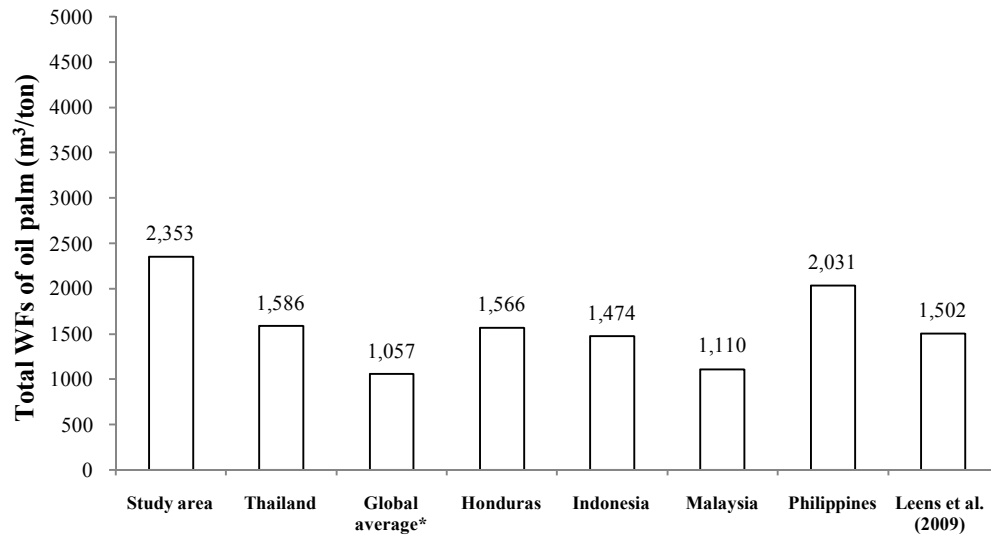


Figure 4-26 WFs (green and blue WFs) of oil palm in study area (rain-shadow area) compared with Thailand and other countries followed Lienden et al. (2010), Mekonnen and Hoekstra (2011)* and Leens et al. (2009); the output based on CWR option model.

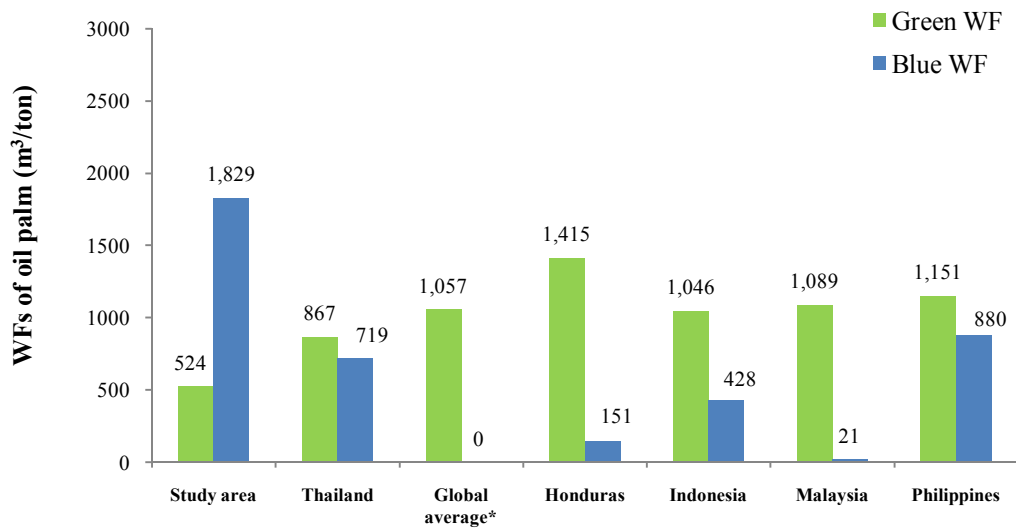


Figure 4-27 The WF of oil palm (green and blue WFs) in study area, Thailand and other countries followed Lienden et al. (2010) and Mekonnen and Hoekstra (2011)*; the output of the CWR option model

- Water footprint of palm oil production

In palm oil extracting, 100 kg FFB can be made 25.2 kg palm oil output by dry process method as Figure 4-28 and 4-29.

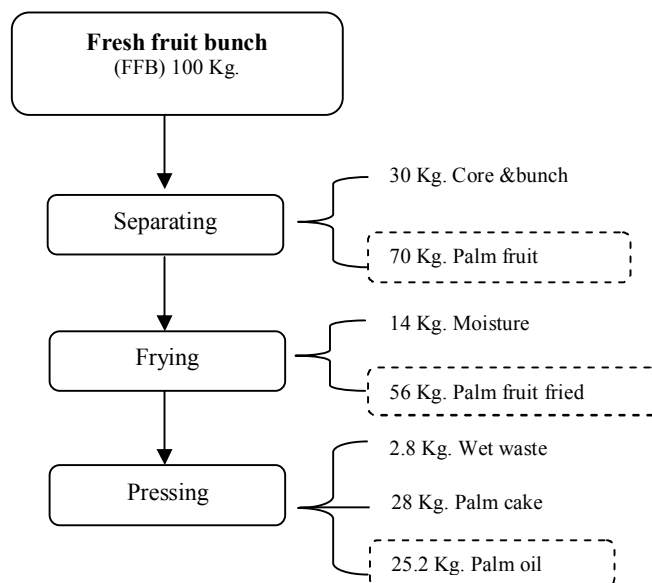


Figure 4-28 Mass balance of palm oil production

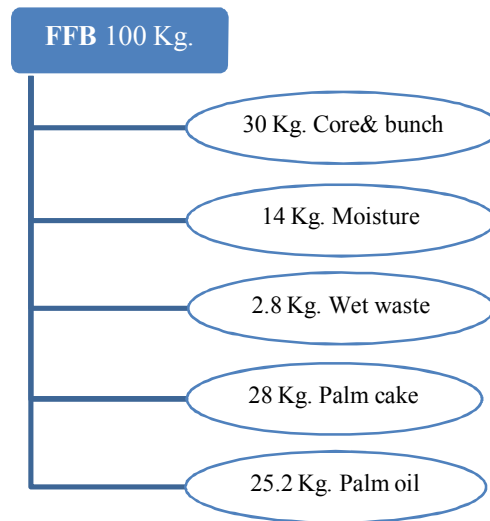


Figure 4-29 Output flow of palm oil production by dry process

WF of palm oil was 13,249 L water/L palm oil in 2006-2010 periods; 1,740 WF green, 6,075 WF blue and 5,434 L water/L palm oil of WF grey, respectively as Figure 4-30. Blue of palm oil WF was higher than green and grey WFs.

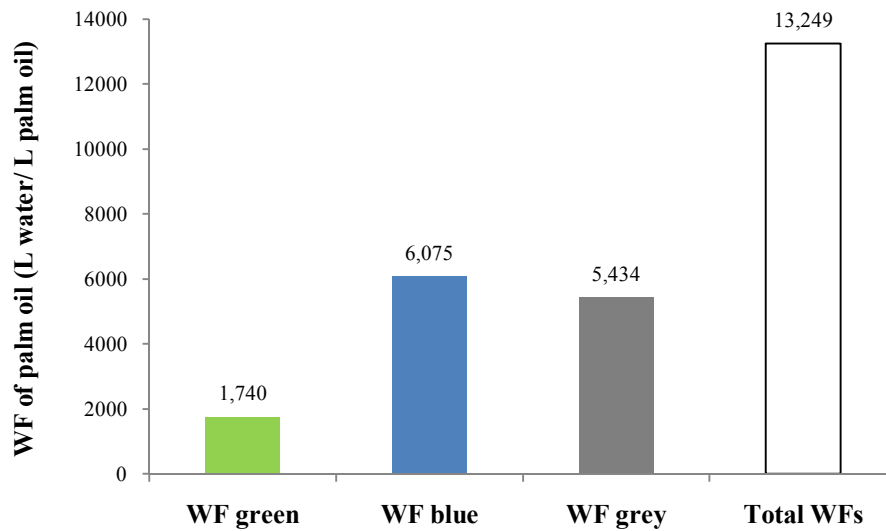


Figure 4-30 Palm oil WFs of study area in 2006-2010 periods; in termed green, blue and grey WF

- Water footprint of bio-diesel production

After palm oil was full at 400 L which can be made 312.8 L Bio-diesel (B100) as Figure 4-31 and 4-32.

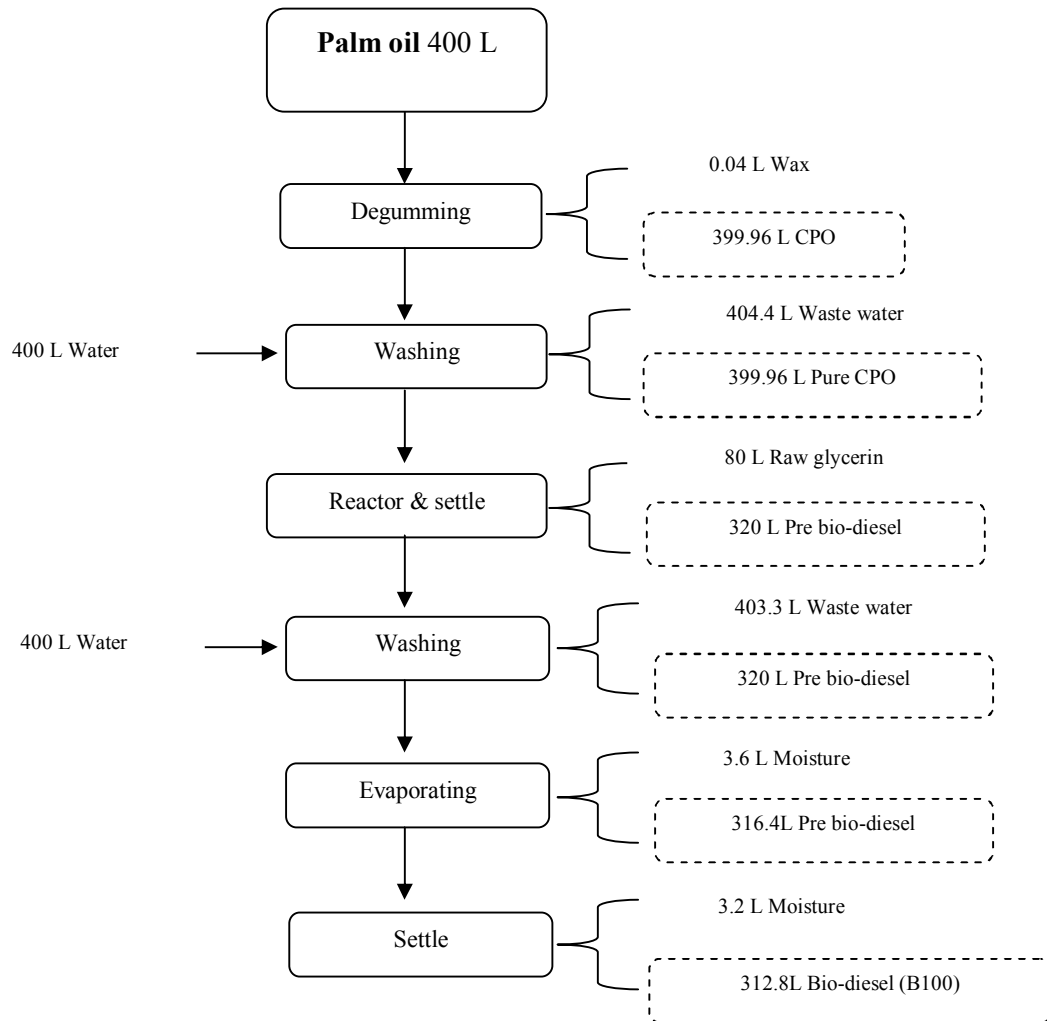


Figure 4-31 Mass balance of bio-diesel product (B100)

The output product in this step was the wax, waste water, raw glycerin, moisture and B100 as Figure 4-33. Waste water volume of bio-diesel product was followed by freshwater used.

As Figure 4-34, Bio-diesel WFs was 15,249 L water/L B100 in 2006-2010 periods; 2,003 WF green, 6,992 WF blue and 6,254 L water/L B100 of WF grey, respectively. Blue of bio-diesel WF was higher than green and grey WF. The water use efficiency in bio-diesel production was 0.47

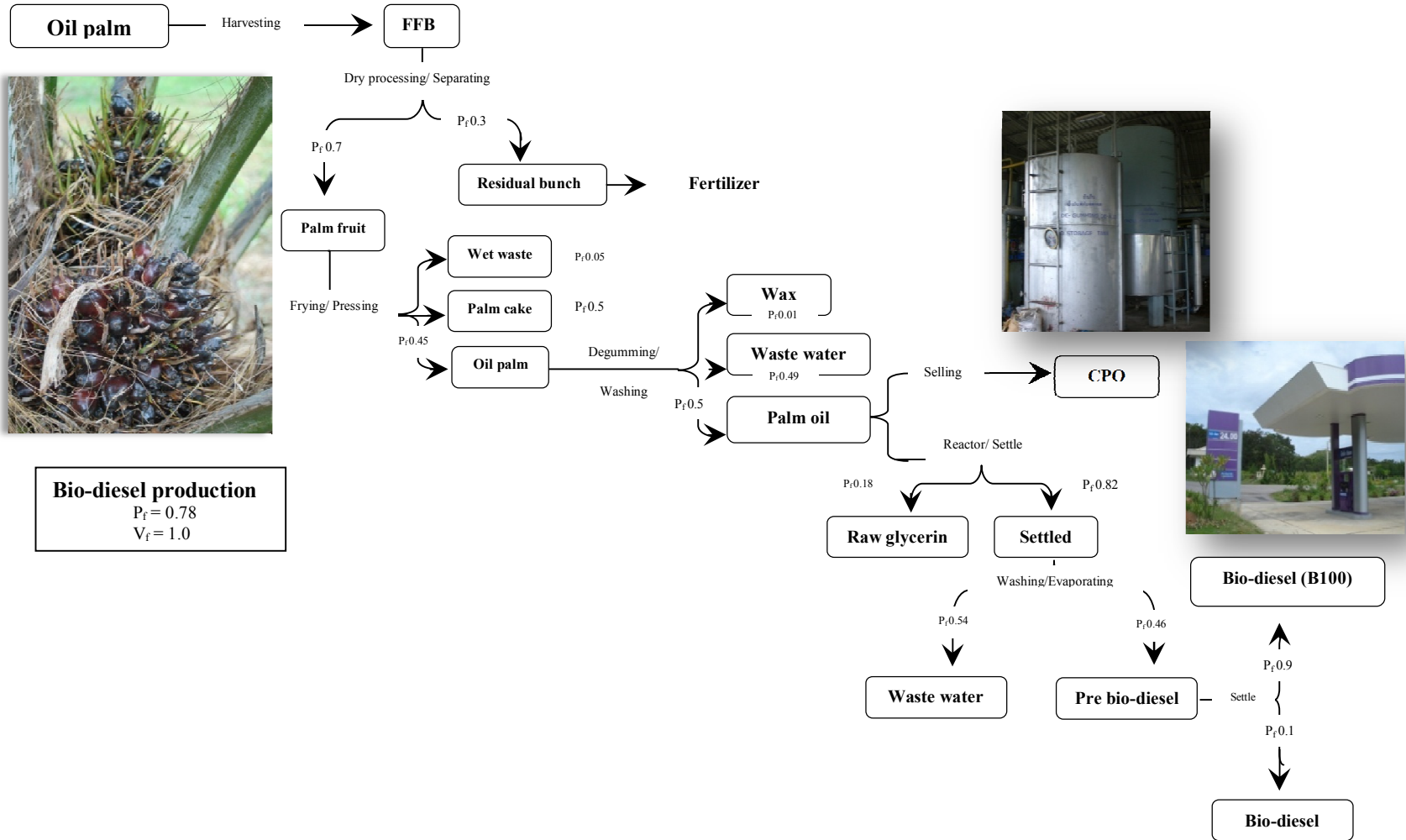


Figure 4-32 Product chain of bio-diesel production from oil palm diagram including product fraction

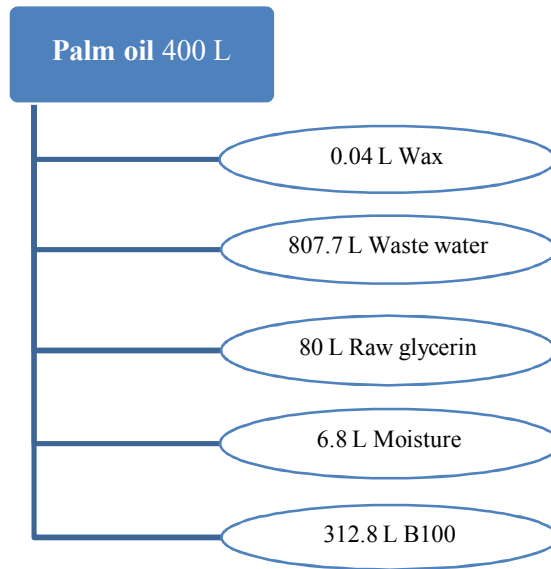


Figure 4-33 Output flow of bio-diesel production by 2 reaction methods

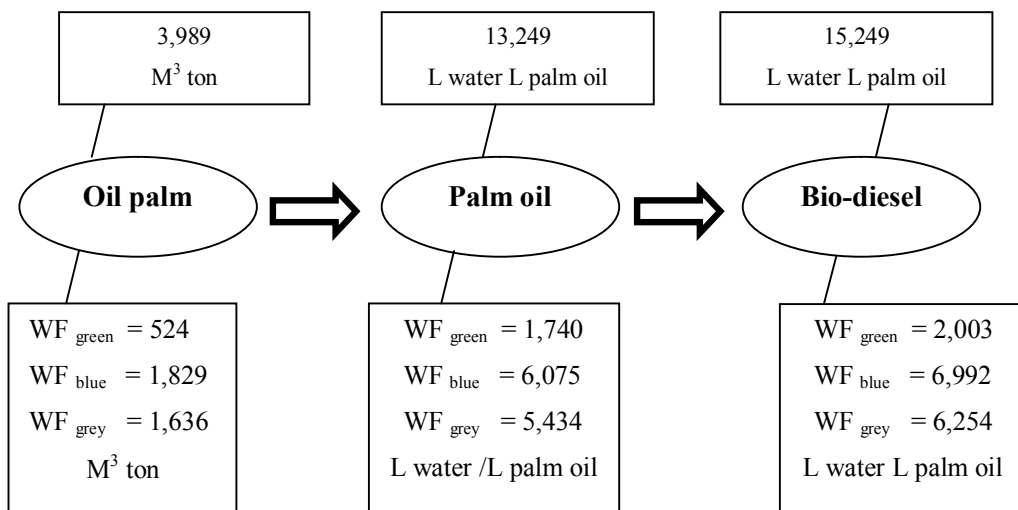


Figure 4-34 The WFs of bio-diesel production steps in 2006-2010 periods; oil palm, palm oil and bio-diesel steps.

4.4.1 The ways to reduction of water footprint

Results of WFs from the study area, WFs of cultivation oil palm step were higher than the bio-diesel process because of the oil palm yield had lower than normal standard of *Suratthani II* strain. The advice for WFs of oil palm reduction was

increasing an oil palm yield per rai or hectare to highest; by improving the practice cultivation of system and maintain the soil fertilizer the same as Chumpathong et al. (2011) and Pongpinyopap and Mungcharoen (2011) studied.

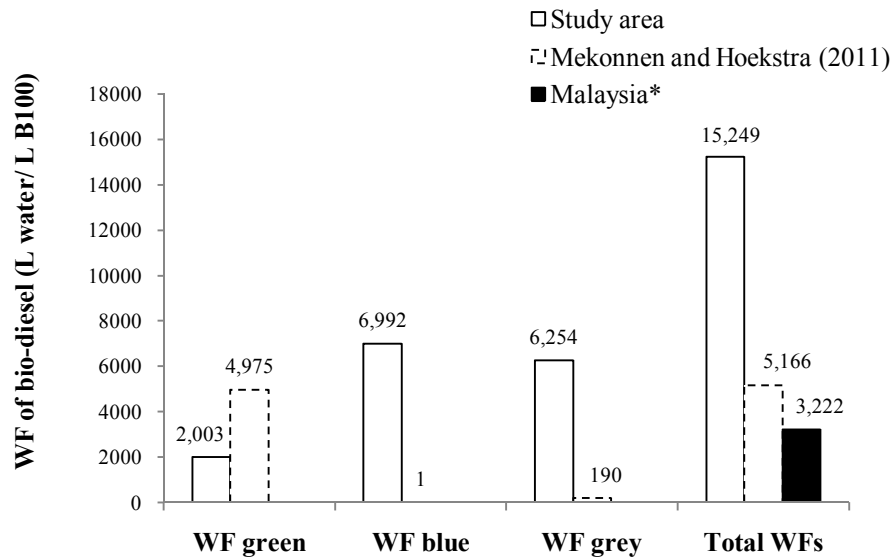


Figure 4-35 Total WFs of bio-diesel production in 2006-2010 periods that compared with Mekonnen and Hoekstra (2011) and Amarasinghe (2011)*

As for the bio-diesel process, the dry process was good method for palm oil extraction but bio-diesel based on catalyzed tran-esterification was not the best technology. So, the bio-diesel production which based on catalyzed reaction in complete tank was a better new choice in the future because it helped to reduce acid in process as Chaipattana Foundation (2007) that advised.

4.5 Discussion

4.5.1 Oil palm yield

The oil palm yield was an important factor; the low harvested yield could give high WFs value because the fertilizer used for oil palm cultivation was not enough as followed Juntaraniyoom (2008) method so oil palm yield was low. Another reason of

lower oil palm yield was in the early stage of development and the oil palm in other countries had grown longer than Thailand. Harvested oil palm was not full productivity. Ratio of plantation per area in other countries had differed. Average FFB of the study area in 2006-2010 periods was lower than 1.3 fold of world standard from FAO (2006) as same oil palm yield average of full life span too. The water efficient use of oil palm cultivation step was less than 1. Then it should be more improved for water use and yield. *Suratthani II* and *Compact Nigeria* oil palm were a hybrid of *Tenera* variety. *Suratthani II* had more tolerance than *Compact Nigeria*. *Compact Nigeria* gave higher productivity than *Suratthani II*; but it was very sensitive drought. (Chorawis, 2005; Juntaraniyoom, 2007)

Properties of the study area (oil palm plantation) compared with Juntaraniyoom (2007) standard was 1,059 mm/year rainfall, 35.0, 18.9 and 27.0 degree Celsius for maximum, minimum and average temperature (Thai Metrological Department, 2010). The slope area at 2-20 % was medium to fast draining and medium infiltration rate (Office of Soil Survey and Land Use Planning, 2010). Topography of oil palm plantation in study area was rather suitability for oil palm plant. In part of climatic parameter, rainfall and rain-shadow area were serious limiting factor. On the other hand, temperature factor was the unlimited factor. Infertility soil was the main cause of oil palm yield damage.

4.5.2 Fresh water used in product system

The crop water used, the study area was higher irrigation system (blue water resource) than rain water (green water resource). Because of these areas were located in rain shadow area, lack of soil fertility from pineapple plantation for a long time (Office of Soil Survey and Land Use Planning, 2010), and oil palm plant consumed high water (Chorawis, 2005 and Juntaraniyoom, 2007). So the blue WF of study area was higher than green WF. The study area used high fertilizer rate, the result of grey WF was high. Although the topography factor of the study area was rather suitability for oil palm cultivation but climatic parameter, rainfall and drought period were serious limited factor as same as Hoekstra et al. (2009), Leens et al. (2008, 2009), Bultink et al. (2010) and Lienden et al. (2010). The water used (green and blue water volume) of oil palm

cultivation was simulated by CROPWAT model so the output was a water demand in terms of the theory only. Water management in this step was not completely so you might collect actual water used in site. A water percolation was not including in this research. The efficiency of water strategy need to improve for water saved and water optimize for plant. (Chapagain & WWF, 2009)

The trend of irrigation water demand in 2015 will be increase because the annual rainwater of study area will be decline and effected from global warming as same as Lienden et al. (2010) studies.

Because the technologies and methods provided by Chaipattana Foundation (2007) were easy methods to reduce water loss and appropriate to farmers, the amounts of water used to grow palm oil and to produce bio-diesel in this area were less than water used for general cultivation. Water used in oil palm transportation and contribution had not any water used. Waste water per one round process was 0.8 m³. Capacity of aeration treatment pond was enough for over a year. Water polluted in this step was assumed to zero in Table 4-4 because the waste water was treated before leave it to nature. Palm oil and bio-diesel production, dry process was good process but was not the best technology to produce. For the better output, we had changed from the catalyze trans-esterification technology to 2 steps reaction in completely tank for reduce acid as same Chaipattana Foundation (2007) that advised.

4.5.3 Water footprint in product system

Water footprint of oil palm plantation was raw material which produced palm oil and bio-diesel. The higher of WFs in root product, the higher of WFs output product too. Blue WFs was higher than grey and green WFs because rain water was not enough for crop's water need and affected from rain shadow location. Because of unnourished soil, the grey WF had value nearly blue WF. Then the oil palm plantation was high fertilizer rate used. The total WFs of oil palm results in the study area was higher than Lienden et al. (2010) results; 2 fold of Thailand, Honduras and Indonesia and Malaysia. For total WFs of study area had value nearly the WF of Philippines. The study area had high blue water resource used while the other countries and Thailand's oil palm had high green water resource used. Due to location, climate, topography, soil

condition, crop type and agricultural production system were different so the WFs of oil palm was depend on these factors significantly as same as Hoekstra et al. (2009), Leens et al. (2008 and 2009), Bulsink et al. (2010) and Lienden et al. (2010).

WF of palm oil in this studied was higher more 3 fold of Mekonnen and Hoekstra (2011) studied; because the different of palm oil technology in each countries and high WFs in root product. Bio-diesel WF of the study area was higher than Mekonnen and Hoekstra (2011) and Amarasinghe (2011) studied. Green WF of these studied was lower than Mekonnen and Hoekstra (2011). The different of input data used did not identify type and detail (Kc crop, yield, agriculture practice and technology of product etc.). It was not clearly when we have to compare WFs value in other countries.

Grey WF of oil palm, grey WFs in cultivation stage was higher and nearly the green and blue WFs that were affected from low oil palm yield and high fertilizer used. The grey WF in Thailand water quality standard was high 3 fold of world standard. All grey WF results which based on water quality of Thailand standard was higher concentrated than world standard both of the study area and FAO (2007b) results. The grey WF of study area was 3 fold of grey WF which based on FertiStat, FAO (2007b). Oil palm chemically fertilizer used in Thailand had high water pollution than global average so this disadvantage of Thailand's oil palm WF reported. Natural water quality of Thailand and global had different standard. Water quality in Thailand standard (5.0 mg/L) was lower than the global standard (10.0 mg/L) as 2 fold. Water pollution in the study area which based on Thailand standard was critically level than the global standard. High fertilizer used and bad water quality were a major environmental bottleneck as same as Amarasinghe (2011). The grey WF of CPO and bio-diesel plus the grey WF value from plantation the same as WF concept, although in this stage was assume water pollution equal zero.

Kc of oil palm value from Lienden et al. (2010) was higher than Chapagain & Hoekstra (2004) so WF and water used were high followed Kc data. Result from the CROPWAT model which based on the CWR option model was higher than irrigation schedule option model. The CWR and irrigation schedule option model were different criteria; example the application and irrigation timing of the irrigation schedule option. The irrigation schedule of WF resulted could be better represent the WF of study area

than the CWR option. Water used and WF of product was calculated output from 2001-2010 period was higher than the result in 1986-2010 and 2006-2010 periods, respectively because in 2001-2010 periods had the flooding and drought situation. So the WF output in these periods was highest value. Then, the results were depended on variable of data which was chosen.

4.5.4 The ways to reduction of water footprint

The yields of oil palm and palm oil were less than that produced by *Suratthani II*. Thus, oil palm yield should be increased in this area. In addition, cultivation practices, including the ways to maintain soil fertility and to reduce deep water percolation, must be improved. A variety of energy crops could also be used as raw materials for making more benefit. In terms of the grey WF, the answer was adopted the suitable fertilizer application strategy. The fertilizer was almost full recovery in crop and supporting an organic fertilizer used in cultivation as Chapagain & WWF (2009), Chumpathong et al. (2011), Hoekstra et al. (2009), Leens et al. (2008 and 2009), Lienden et al. (2010) and Pongpinyopap & Mungcharoen (2011).

CHAPTER V

CONCLUSION AND RECOMMENDATION

In this chapter consists of a conclusion of water footprint, fresh water use, yield harvest, answer for reduce to WF and recommendation for the next study. The results from the study can be concluded as follows:

5.1 Conclusion

5.1.1 Water footprint of product

In period 2006-2010 in the rain-shadow area, water footprint of bio-diesel, palm oil and oil palm cultivation were 15,249 L water/ L bio-diesel, 13,249 L water/ L palm oil and 3,987 m³/ton, respectively. The blue WF of all step products was higher than grey and green WFs; 13% green WF, 46% blue WF and 41% grey WF.

5.1.2 Fresh water consumption

In period 2006-2010, 4 kg of fresh fruit bunch was produced 1 kg of palm oil. Irrigation water used (blue water) was the domain source for water used in dry season; blue > grey > green water. Crop water used was 1.3 km³ per hectare per year; oil palm plantation was highest water pollution. 38.4 m³ per year was water pollution of bio-diesel but palm oil extraction step did not use any water and water pollution. Rain water and soil condition were limited factor in this location. The trend of irrigation water demand will be increasing in 2015 and oil palm yield was lower than the *Ternara* species standard.

5.1.3 Input model data and time period

As the results of a WF study which based on Kc from Lienden et al. (2010) was higher than Kc from Chapagain & Hoekstra (2004). Water used and WF of

product (based on both Irrigation schedule and CWR option model) in 2000-10 period were higher than result in 1986-2010 and 2006-10 periods, respectively. WF result which based on CWR option model was higher than irrigation schedule option model; but irrigation schedule option of WF result was better representative than CWR option model.

5.1.4 Answer for reduce to water footprint

Oil palm cultivation in the rain-shadow area can be reduced a WF by increasing an oil palm yield per area as possible. Bio-diesel production can be reduced a WF by changing the technology from catalyze trans-esterification method to 2 reaction step in complete tank.

5.2 Recommendations

For the future research, it is recommended as follows:

5.2.1 To analyze the WFs of oil palm and bio-diesel production in all seasonal.

5.2.2 The WFs of oil palm and bio-diesel analyzed should be assay in terms of direct and indirect water used of product system.

5.2.3 Monitoring and sampling the blue and grey water data in each season of oil palm cultivation and should be included study the true Kc of oil palm in Thailand (*Tarnera* species).

5.2.4 Researching for WF label of bio-diesel and oil palm in the study area.

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APPENDICES

APPENDIX A

DEFINITION

Water footprint of bio-diesel is the total volume of freshwater used to produce the bio-diesel production. It also looks to where and when the water used (summed overall production step) (Hoekstra et al. 2009 and 2011).

Green water is the volume of rainwater on land and consumption by crop growth and stored in the soil or top and plant and evaporated. That does not runoff or recharges into the groundwater (Hoekstra et al. 2009 and 2011).

Blue water is the fresh surface and ground water such as the water in freshwater lakes, river and stream (Hoekstra et al. 2009 and 2011).

Grey water is the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards (Hoekstra et al. 2009 and 2011).

Crop water requirement (CWR) is the total water need for evapotranspiration, from planting to harvesting for a give crop in a specific climate region. Adequate soil water is maintained by rainfall and or irrigation (Hoekstra et al. 2009 and 2011).

CWR option model is the crop evapotranspiration equals the crop water requirement, assuming optimal condition (well-fertilized plants, disease-free, under optimum soil water conditions and perfecting full production) and calculated crop water requirement based on FAO Penman Montieith on the CROPWAT model (Hoekstra et al. 2009 and 2011).

Irrigation schedule option model is the crop evapotranspiration is calculated on both optimal and non-optimal conditions over planting period by the daily soil water balance approach on the CROPWAT model (Hoekstra et al. 2009 and 2011).

Fresh fruit bunch (FFB) is the bunch harvested from oil palm or refers to the oil palm fruit harvested over the bunch (EPPO, 2011).

Crude palm oil (CPO) is the oil extracted from oil palm fruit for the materials of bio-diesel production (Ngamkanokwan (2006).

APPENDIX B

Table 1 Composition of fresh weight (g/100g) of oil palm mesocarp

Nutrients of oil palm	percent
Carbohydrates	8.2
Proteins	2.1
Fats	45.4
Lignins	0.0
Organic acids	0.6
Minerals (K,Ca,P,S)	1.2
Fibers	4.3
Moisture	3.8

Source: Lienden et al. (2010)

Table 2 Applications rate of palm oil in Thailand on 2001

Area	Area %	Rate N	Rate P	Rate K	Cons N	Cons P	Cons K
204	98.0	105.0	35.0	170.0	20.99	7.00	33.99

*Note : Area is expressed in '000 ha; Area % = percentage of area dedicated to respective crop on which farmers apply fertilizers. Rate is expressed in kg nutrients/ha. Consumptions, i. e. area multiplied by application rate is expressed in '000 tons.

Source: (FAO, 2007b)

Table 3 Estimated FFB yield (*Ternera* variety) ton per hectare after planting

Year	1	2	3	4	5	6	7	8	9	10	Average
Estimated yield (tons)	-	-	3.0	4.25	5.5	6.0	7.25	8.2	8.6	9.5	6.5
Study area	-	-	1.3	3.7	4.9	6.9	8.7	10.5	12.3	14.1	7.8

Source: FAO (2006)

Table 4 CROPWAT of oil palm growth profile

Parameter	Value	Remark
Crop coefficients	1.0,1.0,1.0	Lienden et al. (2010)
(<i>Kc ini, Kc mid, Kc end</i>)	0.9,0.95,0.95	Chapagain & Hoekstra (2004)
Growth period stages	91, 91, 92, 91	Lienden et al. (2010)
(<i>Init., dvlmnt., mid., late</i>) (days)	120,60.180,5	Chapagain & Hoekstra (2004)
Rooting depth (<i>Init., final</i>) (meters)	1.0, 1.0	-
Depletion factor (<i>all stages</i>)	0.65	-
Yield response factor (<i>Ky I, II, III, IV</i>)	1.0, 1.0, 1.0, 1.0	Default
Planting day/month		
- <i>Suratthani II</i>	Aug 05	Existing plantation, year-round
- <i>Compact Nigeria</i>	Sep 06	harvesting

Source: Chapagain & Hoekstra (2004) and Lienden et al. (2010)

Table 5 Total fertilizer used of palm oil in study area

Age of palm oil (year)	Chemical fertilizer (kg/plant/year)		
	ammonium sulfate (21-0-0)	rock phosphate (0-3-0)	potassium chloride (0-0-60)
Before planting	0.00	0.50	0.00
1	1.55	1.00	1.00
2	3.00	1.50	2.50
3	ND	ND	ND
4	ND	ND	ND
5	2.67	4.00	2.00
Average	2.47	1.33	1.83
Kg/rai	54.34	28.60	40.26
Kg/ha	339.6	178.7	11.43

Remark ND (No data)

Source: The Chaipattana- Mae Fah Luang Reforestation Project (2010)

Table 6 Evaluation criteria for the cultivation of oil palm➤ *Topography*

Properties	Appropriate	Semi-appropriate	Inappropriate
-Slope area (%)	0-12	12-20	>20
-Detention of flood water	No-few	Few	Very
-Draining water	Medium	Good	Good/so bad
-Infiltration rate	Medium	Fast/slow	Very fast/slow
-Soil texture	Mold to clay	Sandy loam	Sandy loam to sand
-Depth of soil (cm.)	> 75	40 -75	< 40

➤ *Climatic factor*

Properties	Level of limiting factor				
	No limiting factor	Few limiting factor	Medium limiting factor	Serious limiting factor	Very serious limiting factor
Rainfall/year (mm.)	> 2000	1700 - 2000	1450 - 1700	1250 - 1450	< 1250
Drought period (month)	-	1-2	2-3	3-4	4+
Maximum Tem.	> 29 (°c)	27-29 (°c)	24-27 (°c)	22-24 (°c)	<22 (°c)
Minimum Tem.	>20 (°c)	18-20 (°c)	16-18 (°c)	14-16 (°c)	<14 (°c)
Average Tem.	>25 (°c)	22-25 (°c)	20-22 (°c)	18-20 (°c)	<18 (°c)

Source: Juntaraniyoom (2007)

APPENDIX C

Table 7 Annual crop water requirement; ET_{green} and ET_{blue} of oil palm in the study area by CWR and irrigation schedule option used, in 1986-2010 periods

Year	Crop water requirement			
	CWR option (mm)		Irrigation schedule option (mm)	
	<i>ET_{green}</i>	<i>ET_{blue}</i>	<i>ET_{green}</i>	<i>ET_{blue}</i>
1986	535	1023	381	1,002
1987	520	1037	464	906
1988	761	796	351	996
1989	613	944	367	977
1990	630	927	341	1,004
1991	616	941	453	898
1992	606	951	457	910
1993	669	889	296	1,031
1994	650	907	359	1,005
1995	695	863	401	953
1997	648	910	378	946
1998	717	841	338	1,001
1999	658	900	207	1,124
2000	849	708	264	1,044
2001	847	711	284	1,067
2002	670	888	338	986
2003	795	763	183	1,150
2004	619	939	322	1,024
2005	673	885	323	993
2006	783	775	203	1,129
2007	831	727	158	1,170
2008	649	908	361	965
2009	669	889	339	997
2010	647	911	382	958
Average	681	876	331	1,010

Table 8 Annual crop water requirement; ET *green* and ET *blue* of oil palm (Kc value base on Chapagain & Hoekstra (2004)) by the CWR and irrigation schedule option used in 1986-2010 periods

Year	Crop water requirement			
	CWR option (mm.)		Irrigation schedule option (mm.)	
	ET <i>green</i>	ET <i>blue</i>	ET <i>green</i>	ET <i>blue</i>
1986	526	954	331	982
1987	512	968	417	882
1988	740	740	312	967
1989	601	878	317	957
1990	624	856	290	987
1991	604	875	401	881
1992	596	883	412	886
1993	661	818	246	1,013
1994	641	839	312	984
1995	674	806	357	928
1997	637	843	333	922
1998	705	774	293	979
1999	645	835	160	1,102
2000	701	779	216	1,026
2001	697	783	235	1,048
2002	658	821	287	969
2003	781	699	139	1,127
2004	612	868	258	1,019
2005	663	817	275	973
2006	772	708	165	1,100
2007	824	656	131	1,129
2008	643	837	312	946
2009	663	816	290	979
2010	637	843	336	935
Average	659	821	284	988

Table 9 Grey water footprint calculates of the process water footprint (m³/ton) for oil palm in the Royal of Chaipattana-Mae Fah Luang reforestation project , 2006-10 periods (Thailand)

Standard waste Water Quality Fertilizer value source	Thailand		World	
	Study area	FertiStat*	Study area	FertiStat*
Average fertilizer application rate (kg/ha)	339.6 ^a	105.0 ^b	339.6 ^a	105.0 ^b
Area (ha)	1	1	1	1
Total fertilizer applied (ton/yr)	0.3	0.1	0.3	0.1
Nitrogen leaching or running off to water bodies 10% (ton/yr) ^c	0.03	0.01	0.03	0.01
Max. ,nat. conc. (mg/l) ^d	5.0,1.7	5.0,1.7	10,1.7	10,1.7
Total WF _{proc, grey} oil palm (10 ⁶ m ³ /yr)	0.009	0.003	0.003	0.001
Production (ton/ha) ^a	5.5	5.5	5.5	5.5
WF_{proc, grey} oil palm (m³/ton)	1,636	545	545	181

Source* : ^a Date in field (data in 2006-2010 period); palm yield average of full life span.

^b Fertistat(FAO, 2007)

^c (Hoekstra etal., 2009 and 2011)

^d (RID, 2008)

Table 10 Calculation of the green, blue and grey components of water footprint (m³/ton) process for oil palm in the Royal of reforestation project Chaipattana- Mae Fah Luang (Thailand) by using the CWR option and irrigation schedule option for a medium soil

CROPWAT option	ET_{green}	ET_{blue}	ET_a	CWU_{green}	CWU_{blue}	CWU_{grey}	CWU_{tot}	Y*	WF_{proc,green}	WF_{proc,blue}	WF_{proc,gray}	WF_{prc,totl}
	mm/growing period			m ³ /ha				ton/ha	m ³ /ton			
Oil palm (2006-2010)												
<i>Irrigation schedule option</i>	288	1,006	1,294	2,880	10,060	9,000	21,926	5.5	524	1,829	1,636	3,989
<i>CWR option</i>	704	802	1,506	7,040	8,020	9,000	24,046		1,280	1,458	1,636	4,374
Oil palm (2001-2010)												
<i>Irrigation schedule option</i>	318	1,051	1,369	3,180	1,0510	9,000	22,676	5.5	578	1,911	1,636	4,125
<i>CWR option</i>	707	889	1,595	7,070	8,890	9,000	24,946		1,285	1,616	1,636	4,537
Oil palm (1986-2010)												
<i>Irrigation schedule option</i>	318	1,022	1,340	3,180	10,220	9,000	22,386	5.5	578	1,858	1,636	4,072
<i>CWR option</i>	675	883	1,557	6,750	8,830	9,000	24,566		1,227	1,605	1,636	4,468

***Remark** Result of CWU_{green} and blue estimated by CROPWAT model, CWU grey result was calculated by AR equation.

Kc value of oil palm followed Lienden et al. (2010), this representative of study area.

Table 11 Calculation of the green and blue components of the process water footprint (m^3/ton) and crop water used (m^3/rai) for oil palm in the area of Royal of reforestation project Chaipattana- Mae Fah Luang (Thailand) by using the CWR option and irrigation schedule option for a medium soil

CROPWAT option	ET_{green}	ET_{blue}	ET_a	CWU_{green}	CWU_{blue}	CWU_{grey}	CWU_{tot}	Y*	WF_{proc,green}	WF_{proc,blue}	WF_{proc,grey}	WF_{proci,total}
	mm/growing period			m^3/rai			ton/rai	m^3/ton				
Oil palm (2006-2010)												
<i>Irrigation schedule option</i>	288	1,006	1,294	461	1,610	1,440	3,511	0.9	512	1,789	1,600	3,901
<i>CWR option</i>	704	802	1,506	1,126	1,283	1,440	3,849		1,251	1,426	1,600	4,277
Oil palm (2001-2010)												
<i>Irrigation schedule option</i>	318	1,051	1,369	509	1,682	1,440	3,631	0.9	566	1,869	1,600	4,035
<i>CWR option</i>	707	889	1,595	1,131	1,422	1,440	3,993		1,257	1,580	1,600	4,437
Oil palm (1986-2010)												
<i>Irrigation schedule option</i>	318	1,022	1,340	509	1,635	1,438	3,584	0.9	566	1,817	1,600	3,983
<i>CWR option</i>	675	883	1,557	1,080	1,413	1,438	3,933		1,200	1,570	1,600	4,370

***Remark** Result of $\text{CWU}_{\text{green}}$ and blue estimated by CROPWAT model, CWU_{grey} result was calculated by AR equation.

Kc value of oil palm followed Lienden et al. (2010), this representative of study area.

Table 12 The water footprint of product in bio-diesel production from the Royal of reforestation project Chaipattana- Mae Fah Luang (Thailand)

Process step	Oil palm cultivation				Palm oil extraction				Bio-diesel production			
	WF _{proc,green}	WF _{proc,blue}	WF _{proc,gray}	WF _{proc,total}	WF _{proc,green}	WF _{proc,blue}	WF _{proc,gray}	WF _{proc,total}	WF _{proc,green}	WF _{proc,blue}	WF _{proc,gray}	WF _{proc,total}
CROPWAT option	m ³ /ton				L water/ L CPO				L water/ L bio-diesel			
Oil palm (2006-2010)												
<i>Irrigation schedule option</i>	524	1,829	1,636	3,989	1,740	6,075	5,434	13,249	2,003	6,992	6,254	15,249
<i>CWR option</i>	1,280	1,458	1,636	4,374	4,251	4,843	5,434	14,528	4,892	5,574	6,254	16,720
Oil palm (2001-2010)												
<i>Irrigation schedule option</i>	578	1,911	1,636	4,125	1,920	6,347	5,434	13,701	2,210	7,305	6,254	15,769
<i>CWR option</i>	1,285	1,616	1,636	4,537	4,268	5,367	5,434	15,069	4,912	6,177	6,254	17,343
Oil palm (1986-2010)												
<i>Irrigation schedule option</i>	578	1,858	1,636	4,072	1,920	6,171	5,434	13,525	2,210	7,102	6,254	15,566
<i>CWR option</i>	1,227	1,605	1,636	4,468	4,075	5,331	5,434	14,840	4,690	6,135	6,254	17,079

***Remark** Kc value of oil palm followed Lienden et al. (2010), this representative of study area.

Table 13 Calculation of the green, blue and grey components of water footprint (m^3/ton) process for oil palm in the Royal of reforestation project Chaipattana- Mae Fah Luang (Thailand) by using the CWR option and irrigation schedule option for a medium soil

CROPWAT option	ET_{green} mm/growing period	ET_{blue} mm/growing period	ET_a	CWU_{green} m^3/ha	CWU_{blue} m^3/ha	CWU_{grey} m^3/ha	CWU_{tot}	Y* ton/ha	WF_{proc,green} m^3/ton	WF_{proc,blue} m^3/ton	WF_{proc,grey}	WF_{proct,land}
Oil palm (2006-2010)												
<i>Irrigation schedule option</i>	252	9,81	1,233	2,520	9,810	9,000	21,330	5.5	458	1,784	1,636	3,878
<i>CWR option</i>	673	807	1,480	6,730	8,070	9,000	23,800		1,224	1,467	1,636	4,327
Oil palm (2001-2010)												
<i>Irrigation schedule option</i>	257	1,016	1,273	2,570	10,160	9,000	21,730	5.5	467	1,847	1,636	3,950
<i>CWR option</i>	738	768	1,506	7,380	7,680	9,000	24,060		1,342	1,396	1,636	4,374
Oil palm (1986-2010)												
<i>Irrigation schedule option</i>	273	999	1,272	2,730	9,990	9,000	21,720	5.5	496	1,816	1,636	3,948
<i>CWR option</i>	690	796	1,486	6,900	7,960	9,000	23,860		1,255	1,447	1,636	4,338

***Remark** Kc value of oil palm followed Chapagain & Hoekstra (2004)

Table 14 The water footprint of product in bio-diesel production from the reforestation project Chaipattana- Mae Fah Luang Royal (Thailand)

Process step	Oil palm cultivation			Palm oil extraction			Bio-diesel production		
	WF <i>procgreen</i>	WF <i>procblue</i>	WF <i>proctotal</i>	WF <i>procgreen</i>	WF <i>procblue</i>	WF <i>proctotal</i>	WF <i>procgreen</i>	WF <i>procblue</i>	WF <i>proctotal</i>
CROPWAT option	m ² /ton			L water/ L CPO			L water/ L bio-diesel		
Oil palm (2006-2010)									
<i>Irrigation schedule option</i>	458	1,784	3,878	1,521	5,925	12,880	1,751	6,819	14,824
<i>CWR option</i>	1,224	1,467	4,327	4,065	4,873	14,372	4,678	5,608	16,540
Oil palm (2001-2010)									
<i>Irrigation schedule option</i>	467	1,847	3,950	1,551	6,135	13,120	1,785	7,061	15,100
<i>CWR option</i>	1,342	1,396	4,374	4,457	4,637	14,528	5,130	5,337	16,721
Oil palm (1986-2010)									
<i>Irrigation schedule option</i>	496	1,816	3,948	1,647	6,032	13,113	1,896	6,942	15,092
<i>CWR option</i>	1,255	1,447	4,338	4,168	4,806	14,408	4,797	5,331	16,582

***Remark** Kc value of oil palm followed Chapagain & Hoekstra (2004)

➤ **Water footprint of palm oil calculation**

$$\text{WF proc. green} = 0$$

$$\text{WF proc. blue} = 0 \text{ m}^3 \text{ water/ 100 Kg oil palm}$$

$$\text{WF proc. grey} = 0$$

$$\begin{aligned} -\text{WF palm oil (green)} &= \{0+(524/0.252^*)\} \times 0.93^{**} \\ &= 1,933.80 \text{ m}^3 \text{ water/ ton CPO} \times 0.9 \text{ weight of palm oil mass} \\ &= 4427 \text{ L water/ L CPO} \end{aligned}$$

$$\begin{aligned} -\text{WF palm oil (blue)} &= \{0+(4,657/0.252^*)\} \times 0.93^{**} \\ &= 17,186.54 \text{ m}^3 \text{ water/ ton CPO} \times 0.9 \text{ weight of palm oil mass} \\ &= 1,740 \text{ L water/ L CPO} \end{aligned}$$

$$\begin{aligned} -\text{WF palm oil (grey)} &= \{0+(1,636/0.252^*)\} \times 0.93^{**} \\ &= 6,037.61 \text{ m}^3 \text{ water/ ton CPO} \times 0.9 \text{ weight of palm oil mass} \\ &= 5,434 \text{ L water/ L CPO} \end{aligned}$$

$$\text{WF palm oil Total} = 13,249 \text{ L water/ L CPO \#}$$

$$\begin{aligned} -\text{Product faction of palm oil} &= \{\text{output product/ input product}\} \\ &= \text{Pre-palm oil 25.2 kg/ FFB 100 kg} \\ &= 0.252 \# \end{aligned}$$

Remark * Product faction calculated from study area
 ** Value faction obtain from Chapagain & Hoekstra (2004)
 This result was calculate followed equation [6]

➤ **Water footprint of bio-diesel**

$$\text{WF } \textit{proc. green} = 0$$

$$\begin{aligned} \text{WF } \textit{proc. blue} &= 0.8 \text{ L water/ } 400 \text{ L CPO} \\ &= 2 \text{ m}^3 \text{ water/ ton bio-diesel} \end{aligned}$$

$$\text{WF } \textit{proc. grey} = 0$$

$$\begin{aligned} -\text{WF } \textit{palm oil (green)} &= \{0+(1,740 /0.782^*)\} \times 1^{**} \\ &= 2,225.06 \text{ m}^3 \text{ water/ ton CPO} \times 0.9 \text{ weight of palm oil mass} \\ &= 2,003 \text{ L water/ L Bio-diesel} \end{aligned}$$

$$\begin{aligned} - \text{WF } \textit{palm oil (blue)} &= \{0+(6,075 /0.782^*)\} \times 1^{**} \\ &= 7,768.54 \text{ m}^3 \text{ water/ ton CPO} \times 0.9 \text{ weight of palm oil mass} \\ &= 6,992 \text{ L water/ L Bio-diesel} \end{aligned}$$

$$\begin{aligned} - \text{WF } \textit{palm oil (grey)} &= \{0+(5,434 /0.782^*)\} \times 1^{**} \\ &= 6,948.84 \text{ m}^3 \text{ water/ ton CPO} \times 0.9 \text{ weight of palm oil mass} \\ &= 6,253.9 \text{ L water/ L Bio-diesel} \end{aligned}$$

$$\text{WF } \textit{bio-diesel Total} = 15,249 \text{ L water/ L CPO \#}$$

$$\begin{aligned} - \text{Product faction of bio-diesel} &= \text{Bio-diesel } 312.88 \text{ L/ CPO } 400 \text{ L} \\ &= 0.782 \# \end{aligned}$$

Remark * Product faction calculated from study area
 ** Value faction obtain from Chapagain & Hoekstra (2004)
 This result was calculate followed equation [6]

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