HYBRID WATER FOOTPRINT AND LIFE CYCLE ASSESSMENT OF CRUDE PALM OIL PRODUCTION

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ABSTRACT

The purpose of this study was to evaluate water footprint (WF) of 1 ton crude palm oil (CPO) production from nursery, plantation, and palm oil mill. WF is one of the methods that can be used as a tool for calculating volume of water consumption through the processing of the product. Moreover, this study integrated WF methods for quantifying water volume and used life cycle assessment approach as a tool to evaluate potential impacts through the supply chain. In addition, geo informatics system method was used to illustrate topography and land surface of study locations. Furthermore, this study also determined water deprivation from freshwater used in producing per ton of crude palm oil. The amount of WF at nursery stage ranges from 1.02 to 1.07 m^3/seedling. Meanwhile, the WF at plantation stage ranges from 685 m^3/ton of fresh fruit bunches (FFB) to 1528 m^3/ ton of FFB. The total water foot print for various mill processes ranges from 6.90 m^3 to 9.00 m^3/ton. Therefore, the average WF in this study is equivalent to 4391 m^3/ton of CPO. The significant environmental impacts from this study are freshwater ecotoxicity (kg 1,4-DB eq.), marine eutrophication (kg N-eq.), water depletion (m^3), fossil depletion (kg oil eq.), and climate change (kg CO_2-eq.). For water deprivation results at nursery range from $8x10^{e-6}$ to $5x10^{e-4}$ H_2O eq. Meanwhile at plantation stage, it ranges from $6x10^{e-2}$ H_2O eq. to $5.5x10^{e-1}$ H_2O eq. At mill stage, water deprivation ranges from 1.18 H_2O eq. to 1.55 H_2O eq. This study has highlighted the outcomes to the environment, governance, and economic sector.

ABSTRAK

Kajian ini dilakukan bertujuan untuk mengkaji jejak air (WF) bagi penghasilan 1 tan minyak sawit mentah (CPO) bermula dari tapak semaian, ladang kelapa sawit hingga ke kilang. WF ialah salah satu kaedah dalam mengira jumlah air yang digunakan sepanjang proses penghasilan sesuatu produk. Selain itu, kajian ini menggabungkan antara kaedah WF dalam mengira jumlah air sepanjang proses penghasilan produk dan kaedah penilaian kitaran produk untuk menilai potensi impak melalui penghasilan produk ini. Tambahan pula, kaedah sistem maklumat geografi digunakan untuk memaparkan topografi dan permukaan tanah bagi lokasi kajian. Selain itu, kajian ini juga mengenalpasti jumlah kehilangan air dari penggunaan bekalan air tawar bagi penghasilan satu tan minyak sawit mentah. Jumlah anggaran WF di peringkat tapak semaian ialah 1.02 hingga 1.07 m^3/biji benih. Manakala jumlah anggaran WF di peringkat ladang kelapa sawit ialah dari 685 m^3/tan bagi setiap tan tandan buah segar (FFB) hingga 1528 m^3/tan FFB. Jumlah WF untuk pelbagai proses kilang dalam julat 6.90 m^3 hingga 9.00 m^3/tan. Justeru, purata WF untuk kajian ini setara 4391 m^3/ tan CPO. Impak alam sekitar penting yang diperoleh dari kajian ini ialah tahap ketoksikan air tawar (kg 1,4-DB eq.*)*, eutrofikasi air laut (kg N-eq.), kekurangan air (m^3), kehabisan fosil (kg oil eq.), dan perubahan iklim (kg CO_2-eq.). Bagi kajian ke atas kehilangan air dari penggunaan air tawar di tapak semaian dari 8x10^{e-6} hingga 5x10^{e-4} H_2O eq. Di ladang kelapa sawit pula, ia dalam julat dari 6x10^{e-2} H_2O eq. sehingga 5.5x10^{e-1} H_2O eq. Di peringkat kilang, jumlah kehilangan air ialah dari 1.18 H_2O eq. dan 1.55 H_2O eq. Kajian ini juga menekankan hasil kajian pada alam sekitar, pentadbiran dan sektor ekonomi.

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LIST OF ABBREVIATIONS

UN	-	United Nations
MPOB	-	Malaysian Palm Oil Board
WFN	-	Water Footprint Network
VW	-	Virtual Water
WF	-	Water Footprint
LCA	-	Life Cycle Assessment
DOSM	-	Department of Statistic Malaysia
GDP	-	Gross Domestic Product
POME	-	Palm Oil Mill Effluent
CPO	-	Crude Palm Oil
ET	-	Evapotranspiration
GIS	-	Geo Informatics System
FFB	-	Fresh Fruit Bunches
WSI	-	Water Stress Index
DB	-	Dichlorobenzene
mil	-	Million
SPAN	-	Suruhanjaya Perkhidmatan Air Negara
ML	-	Mega litre
DOSM	-	Department of Statistic Malaysia
GDP	-	Gross Domestic Product
MPOC	-	Malaysian Palm Oil Council
°C	-	Celsius Degree
FFA	-	Free Fatty Acids
EFB	-	Empty Fruit Bunches
OECD	-	Organization for Economic Co-operation and Development
FAO	-	Food and Agriculture Organization
CO_2	-	Carbon Dioxide
N_2O	-	Nitrous Oxide
CH_4	-	Methane

N	-	Nitrogen
P	-	Phosphorus
K	-	Potassium
GHG	-	Greenhouse Gas
BMP	-	Best Management Practices
RSPO	-	Roundtable of Sustainable Palm Oil
POME	-	Palm Oil Mill Effluent
L	-	Litre
WSI	-	Water Stress Index
CF	-	Characterisation Factor
WFN	-	Water Footprint Network
m^3	-	Cubic Meter
Gm^3	-	Giga Cubic Meter
UNDP	-	United Nations Development Programme
SDG	-	Sustainable Development Goals
UTM	-	Universiti Teknologi Malaysia
UKM	-	Universiti Kebangsaan Malaysia
UMP	-	Universiti Malaysia Pahang
VW	-	Virtual Water
EFA	-	Environmental Footprint Assessment
EEIOA	-	Environmentally Extended Input-Output Analysis
AWSI	-	Agricultural Water Stress Index
E-W-C	-	Energy-Water-Carbon
WULCA	-	Water Use Life Cycle Assessment
LCI	-	Life Cycle Inventory
NO_3-N	-	Nitrate Nitrogen
LCIA	-	Life Cycle Impact Assessment
ISO	-	International Organization for Standardization
ET	-	Evapotranspiration
mm	-	Millimetre
TOC	-	Total Organic Carbon
Mg	-	Magnesium
C_{max}	-	Maximum Acceptable Concentration

C_{nat}	-	Natural Concentration
ArcGIS	-	Aeronautical Reconnaissance Coverage Geographic Information System
SCP	-	Sustainable Consumption and Production
Kc	-	Crop Coefficient
ha	-	Hectares
C_{eff}	-	Concentration of Pollutant
C_{act}	-	Actual Concentration of the Intake Water
mg	-	Milligram
DALY	-	Daily Adjusted Life Years
GPS	-	Global Positioning System
RS	-	Remote Sensing
Lat.	-	Latitude
Long.	-	Longitude
IDW	-	Inverse Distance Weighted
DEM	-	Digital Elevation Models
MWh	-	Megawatt Hour
kg	-	Kilogram
PET	-	Potential Evapotranspiration
MOP	-	Muriate of Potash
m	-	Meter
NES	-	Nucleus Estate Schemes
km	-	Kilometre
m^3H_2O eq.	-	Cubic Meter Water Equivalents
IPCC	-	Intergovernmental Panel on Climate Change
PR	-	Phosphate Rock
Ca	-	Calcium
CI	-	Chlorine
Bt	-	Bacillus Thuringiensis
HTP	-	Human Toxicity Potential
SA	-	Sensitivity Analysis
OAT	-	One-At-Time
GAP	-	Good Agriculture Practices

IDW	-	Inverse Distance Weighted

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Water demand is predicted to rise as a result of continued population and economic growth, but water availability is diminishing in many regions, making it even more critical to address water shortages (Distefano, 2017). According to the UN (2018), over 2 billion people live in countries experiencing high water stress (UN, 2018). Excessive water use threatens food security, energy production, and socioeconomic development in many parts of the world (Mekonnen, 2016).

The food and agriculture sectors are the largest water consumers compared to domestic and industrial needs. Globally, from the total amount of freshwater, 70% of the water demand is from the agriculture sector, 10% is used in domestic applications and 20% in industry (Chen and Chen, 2017; FAO, 2018), and it seems that it will increase continuously as shown in Figure 1.1. Moreover, sustainable water management in agriculture is crucial in increasing agricultural production while ensuring that water can be shared with other users and maintaining the environmental and social benefits of water systems.

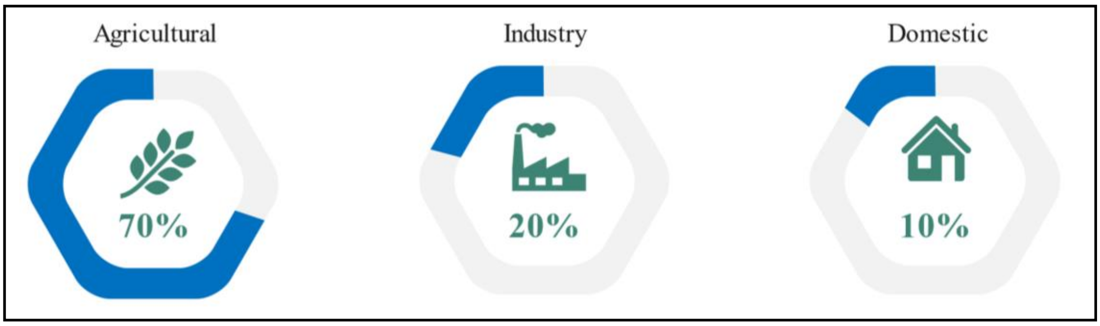

Figure 1.1 Global sum of Withdrawals Based on Several Countries with Very High Water Withdrawals (Chen and Chen, 2017).

Malaysia is one of the countries where the commodities that contribute to the main economy come from the agriculture industry, especially oil palm, rubber, and paddy. Since the 1960s, the cultivation of oil palm or the scientific name, Elaeis *guineensis jacq*. has increased, and in 2019, the oil palm planted area increased to 5.90 million hectares. Sarawak remains as the state with the largest number of oil palm planted in Malaysia, with 1.59 million hectares of the total Malaysian oil palm planted area (MPOB, 2020). Oil palm is one of the world's leading fruit crops that grow in tropical climates with an average temperature of 25–33°C and distributed rainfall of around 2000 mm/year (Malaysian Meteorological Department (2014). Due to tropical climates regions, Malaysia and Indonesia have become one of the largest producers of palm oil (Sumathi et al.,2007).

Water quality and water quantity are among the significant issues related to palm oil industries. For example, in palm oil mills, water has been an issue due to the huge water consumption and wastewater effluent, especially during the sterilisation process in producing crude oil. Without proper water use management, effects on the river basin and water resources in the country will take place. Based on Industrial Processes and The Environment Handbook of Crude Palm Oil (1999), even plantations may cause adverse typical environmental problems from pesticides and other chemical applications for crop growth.

After soy, palm oil is the second most traded vegetable oil crop in the world, and about 90% of the world's palm oil export comes from Malaysia and Indonesia (Sumathi et al., 2007; Tan et al., 2007). This oil is internationally known for its price competitiveness and ready supply to meet the growing world demand for vegetable oils. Lately, the usage of vegetable oils as renewable fuel has grown in importance with the depletion of fossil fuels. In Malaysia, the palm oil industry is one of the main contributors to the economy. Being a plantation-based industry, most of the palm oil mills are located within the estates that supply fresh fruit bunches, and these estates may stretch far into interior parts of the country. As a result, the discharge from palm oil mills has the potential to pollute the receiving waterways from all the way upstream. Thus, river communities and users may vulnerably be affected due to the potential adverse pollution. This is supported by the Department of Environment

(2006), which states that agriculture and livestock are major contributors to river pollution (Oksel et al., 2009).

To cope with the water use issue in the palm oil industry in this country, a way of calculating water consumption is implemented by the sector. The concept is called the water footprint guideline, also known as the WFN guideline. The term 'consumption in WF' refers to water that is 'lost' from the system and therefore cannot be used for other purposes at that particular time and location. Arjen Y. Hoekstra introduced this concept of WFN in 2003 as a water withdrawal indicator which is closely linked to the virtual water (VW) concept by Allan (1998). Later, with the expansion by Hoekstra and Chapagain (2008), they provided a framework to analyse the link between human consumption and the appropriation of the globe's freshwater. Generally, the WF of a product which is expressed in water volume per unit of product (usually m^3/t), is the sum of the water footprints of the process steps taken to produce the product. Current practices show the hybrid combination between WFN and life cycle assessment (LCA) approach in assessing potential environmental impacts from water use. Hence, by implementing this concept, the holistic view of the life cycle perspective and addressing all relevant environmental impacts globally and locally can be identified (Hauschild et al., 2005).

1.2 Problem Statement

In the past 25 years, the Malaysian palm oil industry has become very important and has contributed immensely to the nation's economy. Malaysia is the second largest after Indonesia as the largest producer of palm oil (Sumathi et al., 2007). Palm oil is the major contributor to the value added in the gross domestic product (GDP) by 37.7% of the agriculture sector (DOSM, 2020). According to Thani et al. (1999), about half of the water used in the extraction process will result in palm oil mill effluent (POME), and without proper treatment, this effluent will flow into the river basin. As a result, it leads to reducing good water quality, and it is no longer available for other water usage. Therefore, it is crucial to optimise water consumption in this industry.

Previous studies in agriculture separated the methods by using the WFN method to evaluate WF in volumetric value and using the ISO 14046 to assess the impacts of WF. As a result, there is room for improvement in the preceding approach. This is due to previous research limitations, such as limited water management assessment to blue water and ignoring green and grey water. The purpose of this study is to use a hybrid method that evaluates both volumetric and impact assessments to estimate the WF of CPO production.

The utilisation of the hybrid technique by following the ISO 14046 framework from cradle to gate distinguishes this research from earlier investigations. As in this study, the hybrid method combines the WFN guideline by Hoekstra and the LCA approach. This hybrid method focuses primarily on water quantity in volumetric measurement and also emphasises the environmental impact of water use (ISO, 2013; Ridoutt et al., 2013). From a technology selection perspective, the combination of WFN & LCA will also contribute to better management and technical management path.

Moreover, this study uses potential evapotranspiration (ET) from the Penman-Monteith approach, while the previous study used CROPWAT 8.0. ET value is important, especially when calculating the WF in green and blue. This research shows detailed calculations by comparing the ET value with the rain feed and the WF value with the rain feed and crop yield against the rain feed.

By taking into consideration of the water scarcity issue, this study focuses on the WF blue stress index. To interpret the results in visual impact, this research combines the output with geoinformatics system (GIS) interpretation data to demonstrate the distribution of WF and water stress results in the study area.

1.3 Research Aim and Objectives

Since water accounting and environmental impact assessment are gaining prominence, this study proposes the development of a methodological framework for a comprehensive product potential impact assessment on water use based on an integrated WFN & ISO 14046 approach.

This research aims to determine the WF through CPO production by utilising a hybrid technique. These are the study's objectives set to attain this goal.

1. To build WF inventory of crude palm oil production through extensive data collection and analysis.
2. To assess the potential environmental impacts of direct and indirect water consumption in crude palm oil production.
3. To identify the hotspot and interpret the result towards better water management in crude palm oil production.
4. To integrate the findings of the Geo-Informatics System (GIS) platform to demonstrate areas of water stress and the results of WF from the study.

1.4 Scope

In this study, the WF is assessed using a hybrid method. The hybrid method is the integration of the WFN guideline by Hoekstra and the life cycle assessment (LCA) approach. WFN is primarily concerned with volumetric assessment, whereas LCA is concerned with the impact of water consumption during the process of CPO production. Most importantly, the hybrid concept in this study is to study a system and learn about its improvement potential.

This study is focused on water use in the palm oil industry in Johor, Negeri Sembilan, and Pahang, Malaysia. There are only four (4) nurseries involved; Machap Nursery, Kluang Nursery, Felda Raja Alias 04 Nursery, and Felda Kota Gelanggi Nursery, three (3) plantations; Kahang Plantation, Bukit Bujang Plantation and Felda Raja Alias 04 Plantation and two (2) mills; Kahang Mill and Bukit Bujang Mill.

These are the representatives that were willing to share their data and information regarding this study.

The study's functional unit is per ton of CPO production. As a result, some data is required for the WF assessment of 1 ton CPO production. For example, land area, yield production of fresh fruit bunches (FFB), and values of ET for each location are crucial information for assessing WF, especially for green and blue WF. The type and amount of fertilisers, pesticides, and herbicides used at nursery and plantation stages are important for assessing the grey component of WF. Rainfall data is important in comparing total WF at the end of the analysis. While at the mill stage, direct water input through the CPO process, steam input and palm oil mill effluent in producing per ton CPO are recorded. To obtain an accurate WF value for the entire process, data from electricity and diesel use at each stage are essential.

Extensive data collection was done through site visits to the study area, dissemination of questionnaires, and interviews with the assistant manager at nurseries, plantations, and mills. Moreover, there are extensive data reviews and analyses carried out from other previous research related to the study. All the information from inventories was analysed and calculated using ISO 14046 as a framework. It is stressed that this study applies the hybrid method of both WFN and LCA approaches to get more accurate results in a holistic view of the process of CPO production.

Next, the analysed data was inserted into the LCA software, GaBi, to assess the potential impact. LCI assessment was used as a management tool to identify the potential environmental impact of this industry in a holistic view, which includes direct and indirect water usage throughout the entire process, from nursery until CPO production at palm oil mills. Several main impact categories were assessed in this study. They are; freshwater and marine ecotoxicity, freshwater and marine eutrophication, water depletion, fossil depletion, climate change, and human toxicity. These impacts are chosen because they are closely related to the impact of water consumption in CPO production.

Then, the result of WF and water stress is demonstrated using the GIS approach. Moreover, the location of each study area was plotted using this approach to examine the relationship between topography for each area with the total WF. Usually, GIS is used to make land use planning decisions, monitor environmental remediation sites, and comply with environmental regulations. One of the aims of this study is to integrate the findings with the GIS platform to demonstrate areas of water stress and the results of WF from the study.

For accurate readings, several data are needed, such as the GIS layers of the cultivated crops and a drainage pipe system installed in the study area, meteorological data, and crop parameters (yield and irrigation recommendations). Due to the time constraints, the usage of GIS in this study is limited to demonstrating areas of water stress and WF results.

1.5 Significance of Study

Since the emergence of the WFN concept, a group of studies has been done with different methods and foci which mainly aim to determine the volume of water use in various sectors and industries. Most WF studies come from agriculture sectors as exemplified in oil palm industries (Sabli et al., 2017; Vijaya et al., 2018; Safitri et al., 2019), paddy (Chapagain et al., 2011; Roberto et al., 2015; Yoo et al., 2014; Wu et al., 2018), manufacturing industries (Gu et al., 2014; Chen et al., 2015; Handayani et al., 2018), and tourism sector (Cazcarro et al., 2014; Jun Li, 2017; Zhang et al., 2017; Wang et al., 2017).

In Malaysia, current WF studies are mostly in the palm oil, paddy, and manufacturing sectors. For WF in oil palm, recent studies mostly use CROPWAT as their tool in assessing water footprint in the palm oil industry. In contrast, this study uses the value of evapotranspiration according to the location of the oil palm. Details on previous studies are elaborated in Chapter 2. Therefore, this study is significant because the methods chosen and used are suitable due to the condition and limited data available in Malaysia.

The importance of the hybrid approach is in how WF can assess both dimensions of volumetric measurement and the potential environmental impact beginning from oil palm as a raw material until the end of the product. The assessment can be used to determine a product's hotspot. As a result, the management can adapt to existing conditions by using less water, ensuring fewer environmental consequences. Malaysia has started initiatives to introduce this approach. For example, the National Sustainable Consumption and Production (SCP) Blueprint 2016 – 2030 has included WF in Pathway 9, page 11. The Roadmap for the National Agenda on Water Sector Transformation 2040 has also included the study of WF and VW for main commodities in Malaysia. This study is expected to become more critical and demanded in the future, particularly in promoting our local products to the international market.

This study will also serve as a decision-making tool for authorities, raising awareness among stakeholders and the government about the current water usage in the palm oil industry. The potential environmental impact of the WF assessment will serve as a guideline for them in suggesting and implementing appropriate water management solutions.

1.6 Thesis Outline

The background of the study and the problem statement are included in Chapter 1 of this thesis. This study's research objectives are also identified and listed in this chapter, followed by the study's scope and significance. The literature review for this study is included in Chapter 2. Among the topics covered are WF, LCA, and oil palm plantation literature. In addition, literature on crop production, water irrigation, and rainfall in the study area were reviewed. The differences and relationships between WF on oil palm plantations in three Asian countries are also discussed: Malaysia, Thailand, and Indonesia. In Chapter 3, the methodology of this study is discussed. The research design, data sampling details such as sampling procedures, and methodologies chosen are all discussed in Chapter 3. Next, the results are discussed in Chapter 4 and will be supported by previous studies. Finally, Chapter 5 provides the conclusion and recommendations for future research and implementation.

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2. Noor Salehan Mohammad Sabli, Zainura Zainon Noor, Kasturi Devi A/P Kanniah, Siti Nurhayati Kamaruddin. 2020. Estimating Water Footprint of Palm Oil Production: Case Study in Malaysia. Journal of Environmental Treatment Techniques. 8 (3). 1163-1167