ESTIMATING THE COUNTRY-LEVEL WATER CONSUMPTION FOOTPRINT OF SELECTED CROP PRODUCTION

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Abstract. Agriculture has become a major user of global freshwater resources. This study measured the consumptive water use of 15 selected crops (cash crops, vegetables, and fruits) in Malaysia. The results indicated that the green water consumption footprint (129.8 m^3/ton -1586.0 m^3/ton) was higher compared to the blue water consumption footprint (21.0 m^3/ton - 931.0 m^3/ton) for all 15 crops in Malaysia. Paddy crop had the highest total water consumption footprint for both off and main seasons with 2265 m^3/ton and 2255 m^3/ton, respectively, due to the cultivation practices under flood conditions. The water consumption footprint depends on the crop yield, implying that the higher the crop yield, the lower the value is. This paper provides a comprehensive review of the assessment of the water consumption footprint of crop production in Southeast Asia from 2007 to 2017 (10 years). The paper also highlights and discusses a feasibility study for the water consumption footprint of crops and future outlooks in Southeast Asia following an LCA-based approach.
Keywords: *water footprint, water scarcity, agriculture water management, sustainability, Malaysia*

Introduction

In line with the increasing world population, increased water use and management issues have become a major global sustainability debate in recent years. A large amount of water is required to satisfy the needs of various sectors. A better understanding of water use and management is necessary to improve water resource stewardship and management at the local, regional, and global levels. The agriculture sector has become a major global freshwater consumer due to the irrigation sector, which consumes about 70% of freshwater around the world (Scanlon et al., 2007; Gordon et al., 2010; WWAP, 2012). Some regions, such as Southeast Asia, have a tropical climate and receive a sufficient amount of rainfall throughout the year, which allows for growing a variety of crops and has made the region a major global agriculture producer. The agriculture sector also makes a significant contribution to economic growth, as there is a high exportation of agricultural products, such as palm oil and rice; however, intensive anthropogenic activities and unforeseen natural events have affected the availability of surface and groundwater. The water footprint (WF) is a sustainability indicator that has been introduced to assess water consumption and the availability for different sectors (e.g., industrial, agricultural, domestic, etc.) and levels (global, national, regional, watershed, etc.). The WF was introduced to assess and quantify the water required for the production of a product and to assess the potential environmental impacts related to water use (Hoekstra, 2017, 2003; Babel et al., 2011; Chapagain and Hoekstra, 2004). WF is categorized into three components (green, blue, and grey)

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based on a spatial and temporal water consumption evaluation of the source (Hoekstra et al., 2011; Aldaya et al., 2010).

Development of the water footprint concept

The concept of virtual water and the WF indicator were developed over the last decade. The virtual water concept was first introduced by Allan (1998), who defined it as the volume of freshwater used to produce a product. In other words, virtual water is the volume of water required to produce a product at the consumption level. WF is defined as the volume of water used in the production of a product or service consumed by an individual or group (Hoekstra, 2017). Hoekstra (2003) introduced the concept of WF by developing a framework to analyse the ratio of spatially and temporally explicit water consumption per water availability. The focus of the WF in early studies was quantifying the WF of processes, products, companies, and consumer groups. The WF consists of three components, which are specified geographically and temporally: green, blue, and grey water. The green WF refers to the total rainwater evapotranspiration and water incorporated into harvested crops used in the production of goods or services. The blue WF is defined as the volume of surface and groundwater consumed during the production of a product. The grey WF refers to the volume of freshwater required to dilute pollutants so that the quality of the polluted water complies with ambient water quality standards.

In the 2000s, Hoekstra and Hung (2002), Chapagain and Hoekstra (2003), Hoekstra (2003), Oki et al. (2003), Zimmer and Renault (2003), and De Fraiture et al. (2004) conducted studies to assess virtual water at a global scale. Hoekstra and Hung (2002) and Chapagain and Hoekstra (2004) provided global WF statistics of the agricultural, domestic, and industrial sectors and virtual water flows between nations due to international trade. Early studies of the WF focused on blue and green water consumption, and later, the grey WF was included to assess how much water is needed to dilute the pollutants in a body of water (Chapagain and Hoekstra, 2008). The WF has been further improved in terms of its definition and methodology for the agriculture, industry, and domestic sectors at a global scale by applying high spatial and resolution aspects (Mekonnnen and Hoekstra, 2011). Hoekstra et al. (2011) also developed the Global WF Standard to ensure that a reliable method is applied and a fair comparison can be formed between various WF studies.

ISO 14046 is the standard guideline for reporting WF, and it was launched by the International Standard Organization (ISO) in 2014. The factors that must be considered when applying ISO 14046 include societal, environmental, legal, cultural, and organizational diversity as well as differences in economic conditions (ISO, 2014). The framework consists of four phases: goal and scope definition, WF inventory, analysis, and water impact assessment. WF assessments can be performed either individually or as part of the Life Cycle Assessment (LCA) to identify the hot spots of the process throughout its supply chain; thus, significant environmental impacts from water consumption can be reduced (Sabli et al., 2017). *Figure 1* provides a brief description of the development of the WF assessment concept.

Although several WF studies have been conducted in many developed countries, this approach is still nascent in Southeast Asian countries, especially Malaysia. For the WF of agriculture, few studies have been conducted in Malaysia for cash crops (Harun and Hanafiah, 2017) and palm oil (Aminordin et al., 2014; Vijaya et al.,

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2014; Zulkifli et al., 2014; Muhammad et al., 2012). Therefore, the present study aimed to assess the water consumption footprint of selected crops in Malaysia and to provide a comprehensive review of the current state of the water consumption footprint of crops in Southeast Asia from 2007 to 2017 (10 years). Recommendations and potential approaches to the sustainability of water resources in Malaysia are discussed as well.

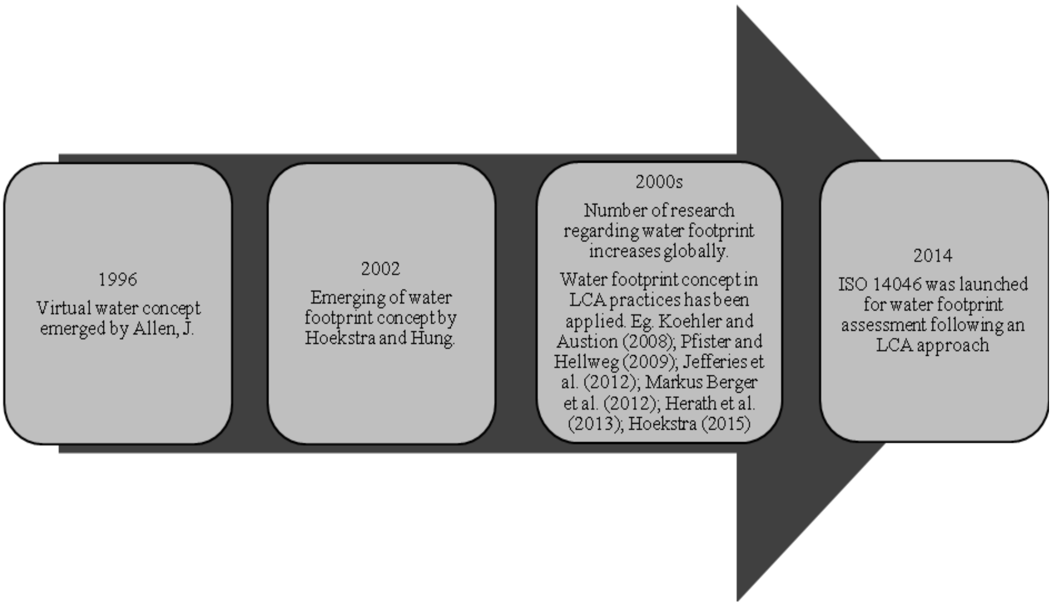

Figure 1. *Development of WF assessment concept*

Assessment of the water consumption footprint of selected crops in Malaysia

Malaysia receives a high amount of rainfall, with an average of 3,000 mm per year, implying a high dependence on rainfall for its water resources (GWP, 2017; WHO, 2011). The area of Malaysia's water supply is around 566 km^2 and includes catchment areas, rivers, lakes, and reservoirs. In Malaysia, the agriculture sector recorded an annual growth rate of 5.6% in 2015 compared to 2010 with a contribution of 8.9% to the Gross Domestic Product (GDP). Palm oil was a major contributor to the GDP of the agriculture sector, followed by other agriculture, livestock, fishery, rubber, and forestry and logging sectors, as shown in *Figure 2*.

According to the World Wildlife Fund (WWF), inefficient agricultural water use is a major issue that must be addressed to ensure the sustainability of water resources, as agriculture consumes about 68% of total water use in Malaysia. The agriculture sector plays an important role in national economic development by securing national food security and also contributes to public incomes, especially for people living in rural areas. Therefore, farmers in Malaysia as well as across the world have taken a step further to strengthen food security, and the government has also allocated billions of Ringgit Malaysia (RM) to maximise Malaysian agriculture production over the past 50 years (Zaim et al., 2013).

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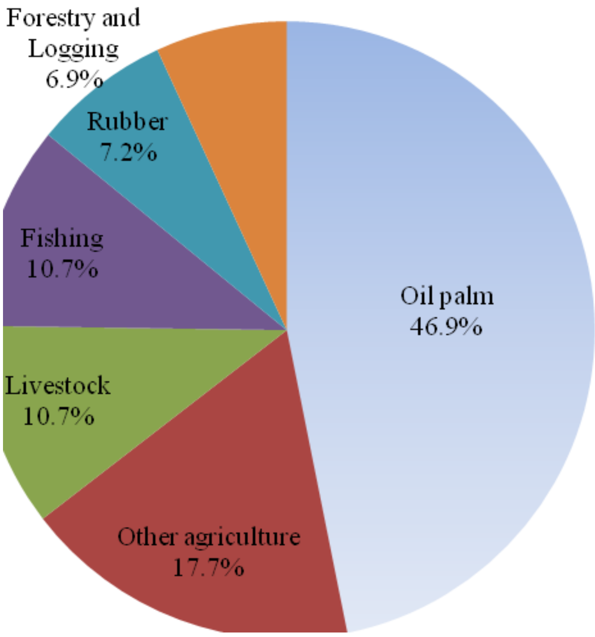

Figure 2. *Malaysia Gross Domestic Products (GDP) 2015 (Department of Statistics Malaysia, 2016)*

Methodological framework

In an agricultural context, the water consumption footprint (WCF) is used to quantify how much water has been consumed to grow a crop, and it is applicable to both annual and perennial crops (Hoekstra, 2011). In the present study, the WCF of three crop categories (cash crops, vegetables, and fruits) in Malaysia was assessed. Fifteen crops from the three crop categories grown in Peninsular Malaysia were selected: cassava, maize, sugarcane, sweet potato, pomelo, mandarin, banana, mango, pineapple, watermelon, cucumber, eggplant, green bean, lettuce, and rice. These 15 crops were chosen based on the high demand and their major contributions to the Malaysian economic sector. The total WCF of the crop cultivation process (WCF_{crop}) was adapted from the general formula of Hoekstra et al. (2011), as shown in *Equation 1*.

$$WCF_{crop} = WCF_{green,crop} + WCF_{blue,crop} \ m^3/ton \quad \text{(Eq.1)}$$

where,

WCF_{crop} = total water consumption footprint
$WCF_{green,crop}$ = green water consumption footprint
$WCF_{blue,crop}$ = blue water consumption footprint

The green water used in the process of the WCF of a crop ($WCF_{green,crop}$, m^3/ton) was calculated by dividing the green component in the water use of a crop with the crop yield (Y, ton/ha) as shown in *Equation 2*. The blue component ($WCF_{blue,crop}$) was calculated similarly to the green WF and is expressed in m^3/ton.

$$WCF_{crop} = \frac{CWU_{green,crop}}{Y_{crop}} + \frac{CWU_{blue,crop}}{Y_{crop}} \ \left(\frac{m^3/ha}{ton/ha}\right) \quad \text{(Eq.2)}$$

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where,

$CWU_{green,crop}$ = crop water use (green component)
$CWU_{blue,crop}$ = crop water use (blue component)
Y = crop yield

The crop evapotranspiration (ET), which is the combination of the two processes whereby water is lost from the soil surface and from crops by transpiration, was calculated using the following formulae (*Eqs. 3* and *4*) to determine the WCF_{green} and WCF_{blue}:

$$CWU_{green} = 10 \times \sum_{d=1}^{lgp} ET_{green}\ (m^3/ha) \quad \text{(Eq.3)}$$

$$CWU_{blue} = 10 \times \sum_{d=1}^{lgp} ET_{blue}\ (m^3/ha) \quad \text{(Eq.4)}$$

where,

ET_{green} = green water evapotranspiration
ET_{blue} = blue water evapotranspiration

A factor 10 was applied to convert water depths in millimeters into water volumes per land surface in m^3/ha, and lgp is the length of the growing period in days. The Penman-Monteith method by Allen et al. (1998) was used to calculate the evapotranspiration of crops (*Eqs. 5* and *6*). Crops coefficient used in this study was based on the length of crop development stages according to Food Agriculture Organization (FAO).

$$ET_{crop} = K_c \times ET_0\ (mm/day) \quad \text{(Eq.5)}$$

where,

ET_{crop} = crop evapotranspiration (mm/day)
K_c = crop coefficient
ET_0 = Penman-Monteith crop evapotranspiration (mm/day)

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad \text{(Eq.6)}$$

where,

ET_o = reference evapotranspiration (mm day^{-1})
Rn = net radiation at the crop surface (MJ m-2 day^{-1})
G = soil heat flux density (MJ m-2 day^{-1})
T = air temperature at 2 m height (°C)
u2 = wind speed at 2 m height (m s^{-1})
es = saturation vapour pressure (kPa)
ea = actual vapour pressure (kPa)
es – ea = saturation vapour pressure deficit (kPa)
D = slope vapour pressure curve (kPa $°C^{-1}$)
G = psychrometric constant (kPa $°C^{-1}$)

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A statistical analysis was also used to estimate the rainfall deficit for irrigation water requirements based on long-term rainfall records. This analysis was determined as part of the rainfall, which effectively contributes to cover crop water requirements (CWR). Information from the inventory database was compiled, and all data were used to model the WCF of the selected crop cultivation in Malaysia. Finally, a set of recommendations and suggestions was developed. The conceptual framework of the present study is shown in *Figure 3*.

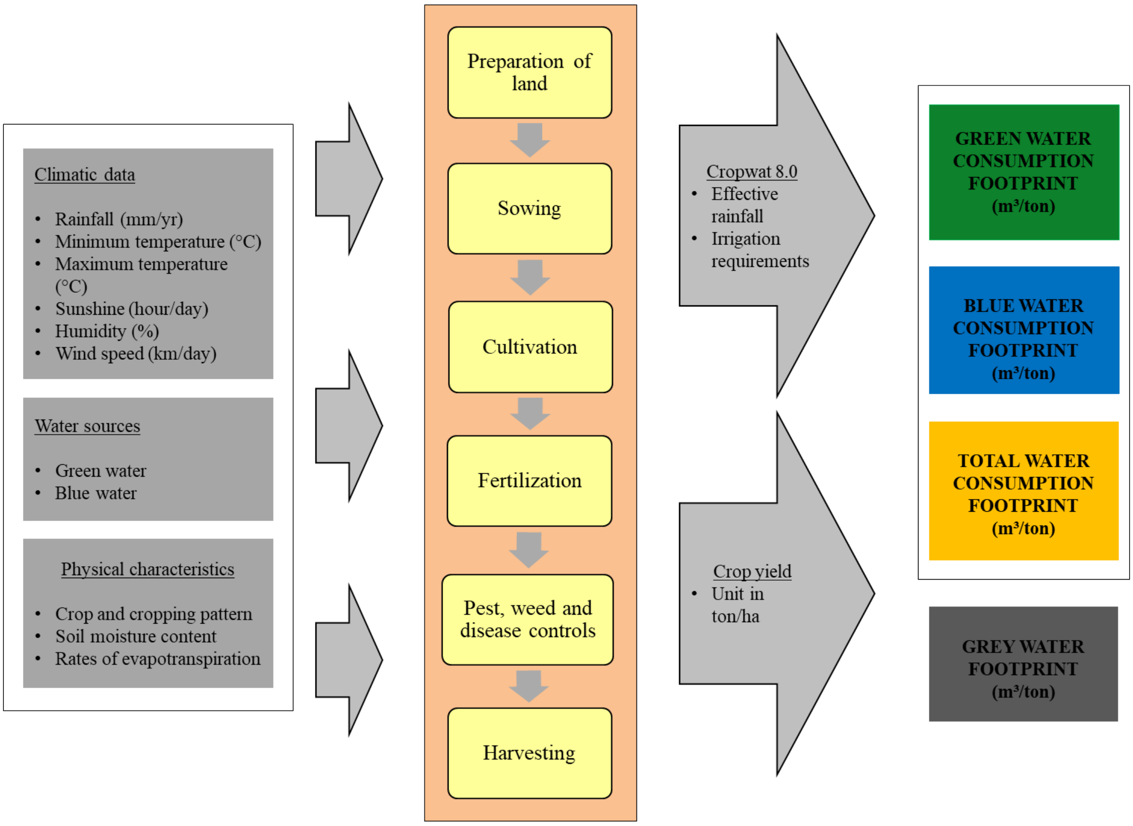

Figure 3. *Conceptual frameworks for WCF study of crop cultivation in Malaysia*

For this research study, data were compiled from various secondary data sources, such as books, publications, reports, government agencies related to the field of studies, including the Department of Irrigation and Drainage (DID), Malaysian Meteorological Department (MMD), Department of Agriculture for Peninsular Malaysia (DOA), Department of Statistics, Malaysian Agricultural Research and Development Institute (MARDI), and National Water Services Commission (SPAN), Malaysian rice cultivation, and Malaysian hydrological information. Foreground data were obtained through a series of site visits by communicating with data providers and administering questionnaires.

Result and discussion

Climatic data

For the WCF analysis, the climatic data provided by Malaysian Meteorological Department (MMD) consisted of minimum and maximum temperature, humidity,

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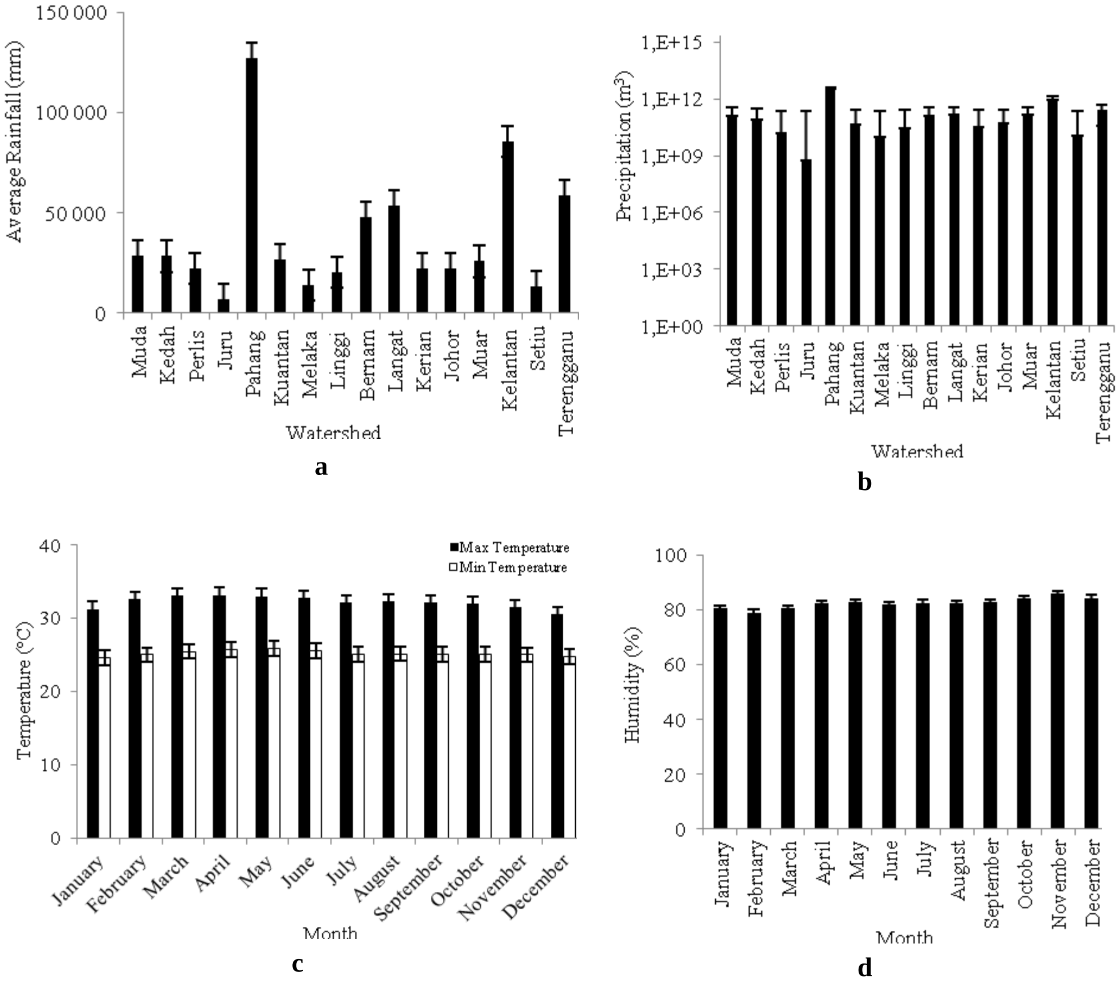
sunshine, rainfall rate, and wind speed for nine years (2005 to 2013), which were used to estimate the water use for crops. Crop water requirements and irrigation requirements were calculated using the CROPWAT 8.0 Model, which is a decision support tool developed by the Land and Water Development Division of FAO. In addition to climatic data, other parameters, such as crop data and soil conditions, were included in the CROPWAT 8.0 model to estimate crop performance under both rain-fed and irrigated conditions.

Peninsular Malaysia experienced a uniform temperature throughout the year and ranged from 24 to 34 °C, while the average temperature over a period of nine years (2005 to 2013) recorded in this study was 28.7 °C. Due to the high evaporation rate, Malaysia’s humidity ranged between 80% to 86%, with an average humidity of 82%, which can be considered high with an average of six hours of sunshine per day. In this study, the highest humidity rate was found in November at 85.8%, while the lowest humidity at 78.9% was observed in February. On the other hand, the highest wind speed rates were recorded in January and February at 155.5 and 146.9 km/day, respectively. The lowest wind speed rate of 121.0 km/day was recorded from April to July and September to November. *Figure 4* shows the average temperature, relative humidity, wind speed, and monthly sunshine for Malaysia over the nine-year period.



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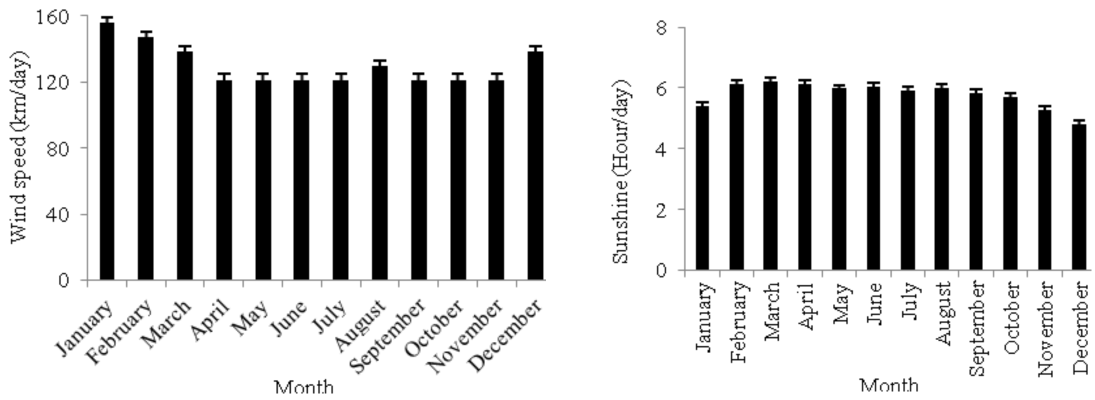

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Figure 4. *Average a) rainfall, b) precipitation, c) temperature, d) humidity, e) wind speed, and f) monthly sunshine hours in Peninsular Malaysia over nine years (2005–2013)*

Water consumption footprint of selected crops

The green, blue, and total WCF for each crop along with the average yield from the year 2005 to 2013 are shown in *Figure 5*. The results indicated that perennial trees (banana, mango, and pineapple) require the highest amount of water per ton of crop production because perennial trees require water year-round, unlike annual trees. Variations in the blue and green WCF of crop production were related to the volume of water use, consumption patterns, climate factors, and agricultural management practices (Le Roux et al., 2017; Mekonnen et al., 2011). The evapotranspiration rate, which is mostly determined by climate conditions, is another factor that affects the WCF of crops.

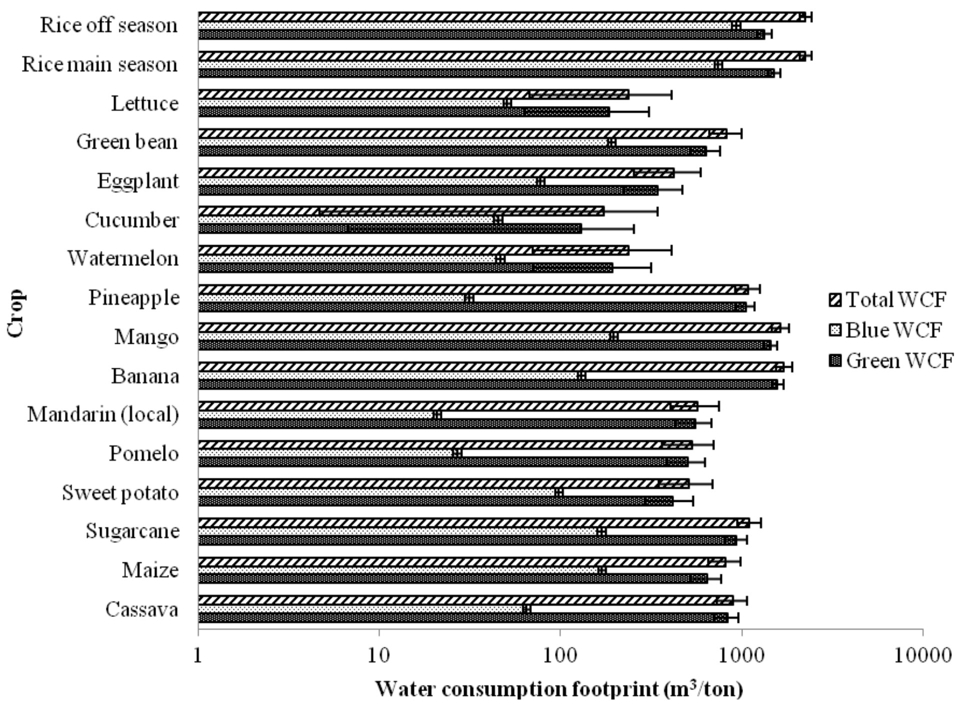

Figure 5. *Average blue, green, and total WCF of 15 crops for nine states in Peninsular Malaysia*

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Green WCF had the highest value compared to blue WCF for all 15 crops in Peninsular Malaysia over the nine-year period. In Malaysia, 80% of irrigation water originates from green water, contributing to a higher green WCF compared to the blue WCF of crop production. In the agricultural sector, the blue water used depends on the crop, crop tolerance to water deficits, irrigation efficiency and green water availability (Lovarelli et al., 2016). If the evapotranspiration rate is higher than the rainfall rate, WCF_{blue} is potentially equal to the difference between evapotranspiration and rainfall (Bochiolla et al., 2013). Crop irrigation systems in Malaysia highly depend on rainwater, especially during the wet season (November to March), and there is a uniform temperature and high humidity throughout the year. It has been shown that the average of the green WCF was higher compared to the blue WCF for nine cultivated crops in Malaysia Ghazali and Hanafiah, 2016). Malaysia usually uses rainfall to meet crop water requirements, and the irrigation supply is only needed when rainfall is not sufficient (Abdul Samad et al., 2017; Ghazali and Hanafiah, 2016). Green water consumption causes less damage to the environment compared to blue water consumption (Falkenmark and Rockström, 2004) because high blue water usage will eventually lead to water scarcity (Gheewala et al., 2014). Terengganu has the highest average of green and total WCF among nine states in Peninsular Malaysia, and the lowest WCF was found for Selangor (*Figure 6*). This is because Terengganu has the lowest yield value compared to all crops included.

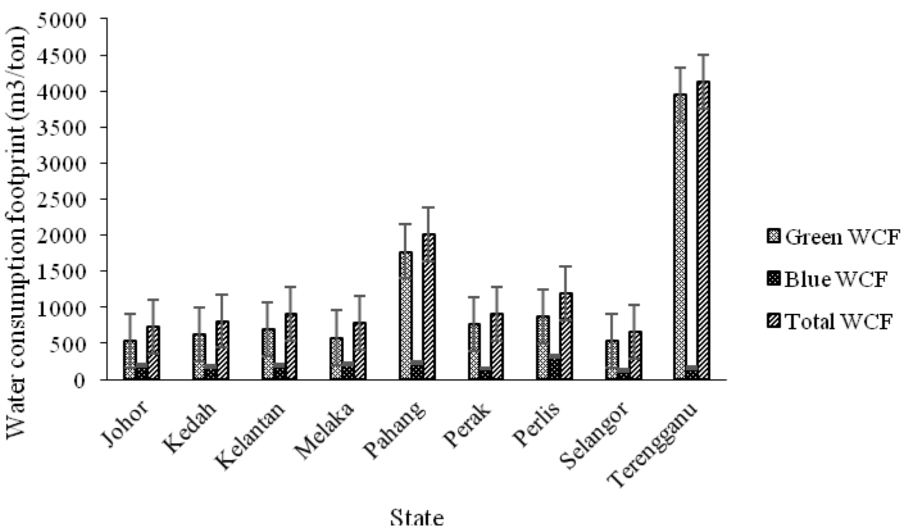

Figure 6. *Average of WCF (nine years) of 15 crops for nine states in Peninsular Malaysia*

The results for total WCF indicate that the cultivation of rice requires the highest amount of irrigation in both seasons compared to other crops, i.e., 2265 m^3/ton and 2255 m^3/ton in the off-seasons and main seasons, respectively, followed by mangoes and green beans. Based on this study, in the off-season, rice has the highest WCF values and contributes 15% of the total WCF of 15 crops in Peninsular Malaysia (*Fig. 7*). Rice requires two or three times more water than any other crop because paddy fields are cultivated under flood conditions (Gheewala et al., 2014; Maclean et al., 2013). Chapagain and Hoekstra (2011) reported that rice is one of the largest water consumers in the world, and large areas are required to irrigate paddy fields. Compared to other

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selected Southeast Asian countries, Malaysia was ranked 8^{th} for the highest paddy production at 2674.4 tons after Indonesia (recorded the highest paddy production), Vietnam, Thailand, Myanmar, Philippines, Cambodia, and Laos in 2015 (Economic Planning Unit, 2016).

Cucumbers had the lowest WCF (175.07 m^3/ton) compared to other crops due to the higher production yield (19.66 ton/ha). WCF is based on several factors; however, the most important factor is related to crop yield (Gheewala et al., 2014; Bulsink et al., 2010). A higher crop yield results in a lower WCF of crops (Gheewala et al., 2014; Bulsink et al., 2010; Chu et al., 2017). To reduce the WCF, the productivity of the crop per hectare of area must be improved. For instance, improving agriculture practices, such as by using organic fertilizer and regular weed control, can be applied. The results of the total WCF of the present study are similar to the previous study presented by Mekonnen et al. (2014), which reported the average of WCF for crops at the global scale; however, there are some crops that have different WCF values due to regional and climate factors, including climate variability, productivity, and agriculture practices (Gheewala et al., 2014; Mekonnen and Hoekstra, 2014; Bulsink et al., 2010; Hoekstra and Chapagain, 2006).

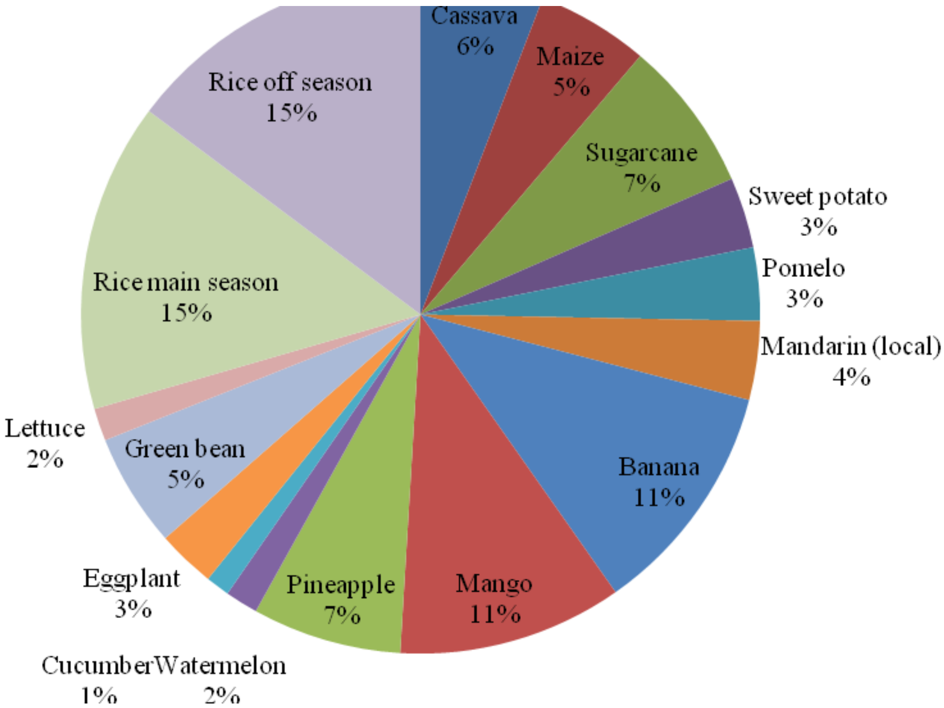

Figure 7. *Percentages of total WCF of 15 crops in Malaysia*

Previous studies of the WCF of crops in Southeast Asia

The next sections of this paper discuss previous studies of the WF of crops conducted in the Southeast Asian region that were published from 2007 to 2017 (10 years). The keywords used to search for published studies included water footprint, blue water, green water, water consumption, water use, water scarcity, agriculture, crop production, and Southeast Asia. Literature from several established databases, such as Scopus and Science Direct, were included. Southeast Asia has a tropical humid climate

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and consists of 11 countries: Brunei, Cambodia, East Timor, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand, and Vietnam. Agriculture is the primary economic activity in Southeast Asia, and approximately 16% of the land area is planted with crops. Many Southeast Asian countries heavily depend on the export of plantation crops, such as coconut, sugar, rubber, tea, bananas, and abaca, to maintain the balance of trade. Southeast Asian countries are among the largest exporters of commodity crops, such as palm oil and rice. Furthermore, rice is one of the staple foods of Malaysia, Thailand, and Indonesia.

Aim and scope

WF is a new approach used to assess water use in the agricultural sector of Southeast Asia, and few studies have been conducted in this region. *Table 1* provides an overview of studies on the WCF of crops that have been conducted in Southeast Asia. To satisfy the growing demand for food, feed, and biofuel production in the future, information related to water resource availability and crop water requirements is needed for water resource sustainability planning (Gheewala et al., 2014).

Table 1. *Previous study on WCF of crops in Southeast Asia from 2010-2017*

Authors	Location	Phases assessed	Functional unit	WCF (m^3/ton)			
				Blue	Green	Grey	Total
SUGARCANE							
Babel et al. (2011)	KhlongPhlo sub-basin, Rayong province, Thailand	Production	m^3/GJ	81	147	n.a	228
Kongboon and Sampattagul (2012)	Northern provinces, Thailand	Cultivation	m^3/ton	31	146	49	226
Sangchan (2015)	Eastern Thailand	Cultivation	m^3/ton	Rain-fed 0.0 Irrigated 10.21	153.31 136.18	18.17 15.90	171.48 162.29
Gheewala et al. (2014)	Thailand	Cultivation	m^3/ton	2442	7920	n.a	10362
Kongboon and Sampattagul (2012)	Thailand	Cultivation, production	m^3/ton	31	146	49	226
Present study	Malaysia	Cultivation	m^3/ton	168.40	941.60	n.a	1109.50
OIL PALM							
Silalertruksa et al. (2017)	Thailand	Cultivation	m^3/ton	773.2	1145.8	n.a	1919
Suttayakul et al. (2016)	Thailand	Cultivation, Mill	m^3/ton	191.34	722.84	148.82	1063
Babel et al. (2011)	KhlongPhlo sub-basin, Rayong province, Thailand	Production	m^3/GJ	421	756	62	1239
Seewiseng et al. (2012)	Chaipattana-Mae FahLuang Reforestation Project, Phetchaburi province, Thailand	Oil palm production	m^3/ton	1829	524	1636	3989

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Mungkalasiri et al. (2015)	Thailand Pathumthani and Chonburi	Cultivation	m^3/ton	Pathumthani 92.22 Chonburi 302.70	Pathumthani 423.77 Chonburi 635.65	Pathumthani 92.22 Chonburi 131.96	Pathumthani 678.84 Chonburi 1070.65
Bulsink et al. (2010)	Indonesia	Cultivation Trading	m^3/ton	0	802	51	853
Seewiseng et al. (2012)	Thailand (Phetchaburi province)	Production (land preparation, cultivation, harvesting and transportation steps)	m^3/ton	4657	1333	4160	10150
Gheewala et al. (2014)	Thailand	Cultivation	m^3/ton	5405	8323	n.a	13728
Muhammad et al. (2012)	Malaysia	Nursery (seedling)	m^3/ton	0.157	0.310	0.002	0.469
Vijaya et al. (2014)	Malaysia	Cradle-to-gate (from nursery and ends in the palm oil mill.	m^3/ton	21.48	5275.00	535.30	5831.78
Zulkifli et al. (2014)	Malaysia	Fresh fruit bunch	m^3/ton	17.00	5273.45	535	5825.45
PADDY							
Shrestha et al. (2017)	Thailand	Cultivation	m^3/ton	600	1678	585	3209
Bulsink et al. (2010)	Indonesia	Cultivation Trading	m^3/ton	735	2527	212	3473
Gheewala et al. (2014)	Thailand	Cultivation	m^3/ton	Major rice 1275 Second rice 3948	Major rice 4079 Second rice 1179	n.a	Major rice 5354 Second rice 5127
Chatpanyacharoen et al. (2015)	Thailand (Nan Province)	Cultivation 4 stages of rice development namely, land preparation and vegetative growth, reproductive growth, grain development and harvest	m^3/ton	0	1470.33	788.49	2258.82
Present study	Malaysia	Cultivation	m^3/ton	Main Season: 747.33 Off season: 931.82	Main Season: 1508.40 Off season: 1333.20	n.a	Main Season: 2255.8 Off season: 2265.10
CORN							
Cheroennet and Suwanmanee (2017)	Thailand	Cultivation, Ethanol production	m^3/ton	0	0.77	0.63	1.4
Present study	Malaysia	Cultivation	m^3/ton	170.6	649.3	n.a	819.9
COCOA							
Bulsink et al. (2010)	Indonesia	Cultivation Trading	m^3/ton	0	8895	519	9414
PINEAPPLE							
Gheewala et al. (2014)	Thailand	Cultivation	m^3/ton	5402	8323	n.a	13725
Present study	Malaysia	Cultivation	m^3/ton	31.34	1060.20	n.a	1091.60
CASSAVA							
Bulsink et al. (2010)	Indonesia	Cultivation Trading	m^3/ton	8	487	19	514

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Tiewtoy et al. (2013)	Eastern Thailand	Cultivation	m^3/ton	Rain-fed 0.0 Irrigated 23.8	Rain-fed 335.8 Irrigated 393.9	Rain-fed 58.5 Irrigated 58.9	Rain-fed 386.8 Irrigated 413.2
Babel et al. (2011)	Thailand	Production	m^3/GJ	n.a	n.a	n.a	103
Gheewala et al. (2014)	Thailand	Cultivation	m^3/ton	1297	6529	n.a	7827
Namchancharoen et al. (2015)	Thailand	Cultivation and harvesting of feedstock, feedstock transport, feedstock processing, ethanol conversion, by products processing and on-site waste management.	m^3/ton	0	178.08	78.58	256.96
Present study	Malaysia	Cultivation	m^3/ton	65.42	853.56	n.a	900.98

n.a = not available

Functional unit

The WCF is expressed in terms of water volume per unit of product or as water volume per unit of time (Hoekstra et al., 2011). In an agricultural context, the functional unit frequently used is the volume of water per ton of crop product (m^3/ton); however, m^3/GJ is sometimes used as a functional unit when an analysis of energy crops is conducted. For example, Babel et al. (2011) examined the WCF of the biofuel energy production of palm oil, cassava, and sugarcane.

Component

The WCF considers both the direct and indirect water use of a process or product, which includes water consumption and water pollution throughout the full production cycle. The green, blue, and grey WCF were calculated separately, as they measure different types of water appropriation. The green and blue WCF are quantified to assess water quantity, while the grey WCF focuses on water quality.

Type of crops

Figure 8 shows the type of crops analyzed by the reviewed papers. CROPWAT 8.0 was applied to calculate the water used to cultivate crops. Most reviewed WCF studies assessed the WF of palm oil, followed by sugarcane and cassava, due to the promotion of biofuel in many countries, such as the US, Brazil, China, India, Thailand, and Malaysia. Biofuel use is promoted to reduce fossil fuel consumption, oil imports, and greenhouse gas emissions as well as to decrease the poverty rate of rural communities (Dufey, 2006; De Fraiture et al., 2008).

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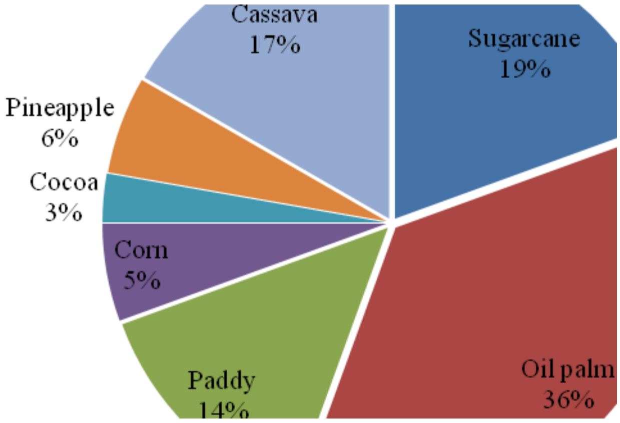

Figure 8. *Type of crops analysed in the reviewed papers*

The government of Thailand has planned to increase the share of renewable energy in the total energy consumption from 0.5% in 2002 to 20.3% by 2022 (Preechajarn and Prasertsri, 2010), many studies on biofuel crops have been carried out in Thailand (e.g., Silalertruksa et al., 2017; Suttayakul et al., 2016; Mungkalasiri et al., 2015; Pongpinyopap et al., 2014; Tiewtoy et al., 2013; Babel et al., 2011; Seewiseng et al., 2012; Gheewala et al., 2014; Namchancharoen et al., 2015; Kongboon and Sampattagul, 2012). In Thailand, biofuel is projected to replace 4928 million liters of fossil fuel annually by the year 2022 (Preechajarn and Prasertsri, 2010). The increase in biofuel crops will lead to land use changes and the replacement of native rainforests and wetlands due to shortages of land for agricultural purposes (Muller et al., 2007). Land use changes affect water resources and the aquatic environment. In addition, the changes can influence evapotranspiration and interception, thus reducing effective rainfall sources and affecting surface runoff and groundwater recharge (Stephan et al., 2001). As biofuel crops are crucial to supporting renewable and sustainable energy, it is necessary to determine which crop is produced in the most water-efficient manner (Babel et al., 2011). Several researchers, such as Gerbens-Leenes et al. (2009), Yang et al. (2009), and Mekonnen and Hoekstra (2011), conducted WCF studies on biofuel production. For instance, Yang et al. (2009) investigated the water requirements of biofuel in China based on the government's biofuel development plans.

Agriculture is a major source of livelihood in Southeast Asia. The Asian Development Bank (ADB) (1999) reported that there are approximately 115 million ha of land that are devoted to the production of rice, maize, palm oil, and natural rubber. Rice is a staple food for about 557 million people in Southeast Asia (Manzanilla et al., 2011); hence, this region is one of the largest producers and exporters of rice at a global scale. An assessment of the WCF of rice was carried out by Chatpanyacharoen et al. (2015) to evaluate water requirements for rice cultivation in the Wang Pha district, Nan Province, Thailand. The WCF of rice in the Nan province was 2258.82 m^3/ton. The green WCF accounted for 1470.33 m^3/ton, and the grey WCF was 788.49 m^3/ton. The results indicated that the value of WCF was within the range of the WCF of rice found by Mekonnen and Hoekstra (2014) (range from 638-2874 m^3/ton). The blue WCF was not assessed because cultivation occurs under rain-fed conditions. The results of the WCF were affected by the maximum evapotranspiration (ET_o) and rice maximum coefficient (K_c). Only two components of WCF (green and grey WCF) were used for

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the study because the green WCF was related to rainfall data, and for grey WCF, the phosphate was selected as the other pollutant (nitrate, ammonia) reduction parallel to the reduction of phosphate concentrations during the cultivation process. Numerous studies have been conducted on the WCF of rice across the globe, including studies by Chapagain and Hoekstra (2011), Bulsink et al. (2010), Aldaya et al. (2010), Yoo et al. (2013), Shresta et al. (2013), Gheewala et al. (2014), Marano and Filippi (2015), and Su et al. (2015). Shresta et al. (2013) estimated the WCF of rice and other crops in different districts, development regions, and physiographic divisions of Nepal. Marano and Filippi (2015) determined the WCF for rice production in two areas in Argentina located in the central-east Entre Rios and Santa Fe regions.

The volumetric WCF indicator does not provide the actual impact of water use directly (Wichelns, 2010); thus, it underestimates the water scarcity or water stress of a specific area. Water scarcity generally varies based on geographical, climate condition, environmental, social, economic, and political factors. The water stress index (WSI) developed by Pfister (2009) is a commonly applied method used to measure water scarcity. The WSI can serve as a characterization factor for freshwater deprivation. The evaluation of the impacts of crop water use in different regions or watersheds using the water stress index and the indication of water deprivation potential was studied by Gheewala et al. (2014) for 10 crops, including rice, maize, soybeans, mung beans, peanuts, cassava, sugarcane, pineapple, and palm oil. The highest amount of water use in irrigation was rice farming, which amounted to 10,489 million m^3/year volume of water used, followed by maize, sugarcane, palm oil, and cassava. In addition, major rice cultivation contributes to the highest water deprivation rate, which is around 1862 million m^3H_2Oeq/year, followed by sugarcane, second rice, and cassava. Crops such as rice, maize, cassava, soybeans, groundnuts, coconut, palm oil, bananas, coffee, and cocoa, which were analyzed by Bulsink et al. (2010), accounted for 86% of total Indonesian water use.

The factors that generally determine the WCF are volume of consumption, consumption patterns, climate, and agricultural practices (Hoekstra and Chapagain, 2008). Several studies have compared the WCF value of crops among provinces. Mungkalasiri et al. (2015) conducted a study to evaluate the WCF of palm oil and fresh fruit bunches (FFB) in two provinces in Thailand (Pathumthani and Chonburi). The results showed that the WCF of palm oil in Chonburi province (1070.65 m^3/ton of FFB) was higher than Pathumthani (678.84 m^3/ton of FFB) due to the lower yield and annual precipitation. The green and blue water WCF mainly depend on climate conditions. Areas with higher precipitation and yield rates have lower WCF values compared to areas with lower precipitation and yield rates (Mungkalasiri et al., 2015). Agricultural practices vary depending on farmers and the technology used and thus influence the yield and WCF values of the crops studied. Bulsink et al. (2010) found that the WCF of the population of Java was low due to high yields, the average consumption rate was just below average, and the evapotranspiration rate was lower compared to other regions.

Water management in Southeast Asia: future outlook following an LCA-based approach

Urbanization and industrialization have grown rapidly in Southeast Asia, thus affecting water resources. Other factors, such as water-related disasters, climate change,

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and poor governance, have worsened the water sustainability issue. In acknowledgement of the importance of managing water resources for sustainability, Global Water Partnership (GWP) Southeast Asia was established to develop and influence sustainable water management policies at the national and regional levels (Lautze et al., 2011). The GWP drafted the water vision and framework, which is comprised of at least five countries (Cambodia, Indonesia, Philippines, Thailand, and Vietnam), and has incorporated Integrated Water Resources Management (IWRM). At the regional level, GWP Southeast Asia is working with ASEAN and has contributed to adding water sustainability to the ASEAN agenda through the creation of the ASEAN Working Group on Water Resources Management (AWGWR) (Global Water Partnership, 2017).

Agriculture is a primary sector that contributes to economic growth in Southeast Asian countries; however, it has a significant impact on water consumption. This could lead to water deprivation and scarcity if water resources are not managed properly. As mentioned, considerable efforts have been devoted to improving water management as well as to promoting green and sustainable development. As part of the initiative to sustain water resources, the WCF approach has been adopted in Southeast Asia. As shown by previous studies, Southeast Asian countries have begun to implement WCF in water resource management.

For Malaysia, the country has sufficient water to supply the needs of the agriculture, domestic, industrial, energy production, and environmental sectors; however, water resources must be managed properly to ensure that the resource is sustainable for future generations. The government of Malaysia has put forth various efforts to manage water resources. In the 11th Malaysia Plan (2016-2020), water resources and the agriculture sector were two primary focuses due to the awareness of global climate change (Economic Planning Unit, 2015). The National Water Resources Policy was launched by the Malaysian government in 2012, which provides holistic strategies for water resource management in Malaysia. The policy includes governance collaboration to ensure water security and continued sustainability. In addition, the federal government prioritized the restoration program for water resources by enhancing the IWRM program. Improvements in water quality in some rivers in Malaysia and the water shortage issue in Klang Valley were addressed through this program.

Moreover, a water demand management master plan was established by the Ministry of Energy, Green Technology, and Water (KeTTHA), which provides Malaysia with a better approach to water demand management and a tool to forecast water demands. For the river basin, agencies at the state level (i.e., Lembaga Urus Air Selangor [LUAS], Syarikat Air Kelantan [SAK], Syarikat Air Negeri Sembilan [SAINS], Pengurusan Air Pahang Berhad [PAIP], etc.) that have been established are responsible for effectively managing the river basins due to various legislations related to water management. In addition, communication, public awareness, and education programs for all ages were increased to promote a more efficient and prudent use of water. Awareness campaigns and activities with the cooperation of the relevant non-governmental organizations (NGOs) have also been implemented to promote the efficient use of water and river conservation for local commodities.

The WCF assessment is a nascent approach in Malaysia, especially in the agriculture sector. The actual impact of water use cannot be provided directly through a volumetric WCF indicator because water scarcity issues vary based on geographical, climate condition, environmental, social, economic, and political factors (Gheewala et al.,

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2014). Hence, the assessment of WCF is useful to determine the impact of water consumption regarding water deprivation potential. Water deprivation can be calculated by multiplying the blue WCF of crops by the water stress index. Furthermore, the WCF approach following an LCA approach could improve the understanding of water consumption scenarios in crop production. Several WCF studies have been conducted in Southeast Asia following the LCA approach, such as Cheroennet and Suwanmanee (2017), Gheewala et al. (2014) and Silalertruksa et al. (2017). Silalertruksa et al. (2017) determined the impact of greenhouse gases and water use on palm oil cultivation in Thailand. The study combined two methods, including the life cycle greenhouse gas emissions assessment and the water scarcity footprint assessment.

The ISO WF (ISO, 14046) was launched in 2014, and it focuses on water availability and degradation. The LCA and ISO address all input and output in the WF inventory analysis; hence, all environmental effects of water use are also included in the assessment (Pfister et al., 2015; Quinteiro et al., 2015; Núnez et al., 2013; Ridoutt et al., 2010, 2012; Canals et al., 2009). By adopting the WF assessment, relevant input can be applied for the formulation of various types of government policies, such as national or state water policies, river basin policies, local water policies, trade policies, foreign policies, and development cooperation policies (Hoekstra, 2011). ISO 14046 (2014) lists the benefits of WF assessments:

- WF can help in assessing the magnitude of potential environmental impacts related to water.
- Identifying ways to reduce potential water-related impacts of products at various life cycle stages, and of processes and organizations.
- Facilitating water efficiency and optimization of water management at product, process and organizational levels.
- Provide scientifically consistent and reliable information for reporting WF results.

Limitations and uncertainties

During the assessment of the WF, uncertainty is an important factor that must be taken into account, as several variables must be characterized. In most studies, the WF assessment was conducted based on several assumptions and limitations in the data section due to the difficulty in obtaining data from data providers. In addition, it is sometimes impossible to obtain actual data, such as data on water availability, crop water requirements, and crop water use. Another issue is that different irrigation methods, such as surface, sprinkler, and drip irrigation, might contribute to different irrigation efficiencies. Therefore, to limit the uncertainty level of a crop system assessment, the cultivation technique and geographical data should be carefully determined. In the present study, the grey WCF was excluded because the assessment aims to quantify the water quantity instead of the water quality; however, it is important to consider water quality, as shown by several studies conducted in Southeast Asia, because the assessment of green and blue water consumption is more related to water balance than the WF (Loverelli et al., 2016).

In Southeast Asia countries, technology constraints could lead to high water consumption even if water use efficiency and water management are applied. According to Mekonnen and Hoekstra (2015) and Pfister and Bayer (2014), considerations of the available technology and practices (i.e., crop residue management, optimized nutrient

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management, and effective rainfall enhancement) could be useful in WF evaluations. Nevertheless, these aspects do not represent actual farming contexts. Regional conditions and technologies in different countries have significant effects on water management in the agricultural sector. Policies on more sustainable agricultural techniques must be endorsed to help reduce stress on the water use system. In addition, a more environmentally friendly system must be introduced to farmers to improve environmental quality (i.e., reducing fossil fuel dependence, mitigating soil erosion, improving soil quality, optimizing water use), economy (i.e., reducing operating costs) and public health safety (i.e., avoiding hazardous pesticides and fertilizers, producing more nutritious crops, producing food that safe for communities).

Conclusion

Based on this study's results, the green WCF had the highest value compared to the blue WCF for all 15 crops in Peninsular Malaysia for an average of nine years. The results for total WCF indicated that the cultivation of rice requires the highest amount of irrigation in both seasons compared to other crops, i.e., 2265 m^3/ton in the off-season and 2255 m^3/ton in the main season, followed by mangoes and green beans. Cucumbers had the lowest WCF compared to other (175.07 m^3/ton) crops due to higher production (19.66 ton/ha). The value of the WCF depends on the crop yield, and a higher crop yield results in a lower WCF of crops (Gheewala et al., 2014; Bulsink et al., 2010; Chu et al., 2017).

In conclusion, some improvements can still be achieved in WCF calculations and are required to make this indicator more valid in a crop production context. The WCF can be used to compare the water use efficiency of each product, particularly during a water shortage period, so that policies can be developed to determine which plant to promote in consideration of the net profit of a product, market requirements, labour requirements, etc. The findings of this study could be used as a guideline and can provide useful information for both stakeholders and policymakers for better water management practices, particularly in Malaysia.

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