Journal of Oil Palm Research
DOI: https://doi.org/10.21894/jopr.2026.0008

THE WATER FOOTPRINT OF OIL PALM PLANTATION IN THE KAMPAR CATCHMENT, RIAU, INDONESIA

PRIMA WAHYU TITISARI[1]*; ELFIS[1]; INDRY CHAHYANA[2] and TIKA PERMATASARI[3]

ABSTRACT

Oil palm plantations have faced heightened scrutiny over their water consumption and environmental consequences; yet, quantitative evaluations of their water footprint (WF) in relation to watershed-level water availability are still limited. This study assesses the green, blue and grey WFs of oil palm plantation in the Kampar Watershed, Riau, Indonesia, while integrating regional water balance analysis with the FJ Mock technique and evapotranspiration (ET) modelling utilising the Penman-Monteith equation. The total WF in Kampar Regency was 327.37 m³/t (green: 170.49 m³/t; grey: 129.10 m³/t; blue: 27.78 m³/t), whereas Pelalawan Regency recorded 272.88 m³/t (green: 159.82 m³/t; grey: 84.67 m³/t; blue: 28.39 m³/t). Although the Kampar River has adequate water resources, the growth of plantations raises sustainability issues. Grey water footprint scores (WFS) denote moderate environmental performance in both regions. Sensitivity study indicates that fluctuations in rainfall and yield can markedly affect WF estimates, particularly the grey component. This comprehensive strategy emphasises the necessity for improved fertiliser and water management techniques to guarantee sustainable oil palm cultivation in water-abundant yet environmentally delicate tropical catchments.

Keywords: bioresource management, Kampar Watershed, sustainable agriculture, water footprint, water management.

Received: 10 February 2024; **Accepted:** 13 October 2025; **Published online:** 28 January 2026.

INTRODUCTION

Indonesia is the leading global producer of palm oil (Dermoredjo et al., 2025; Setiajiati et al., 2024). According to the Central Statistics Agency (BPS), it is expected to produce 45.58 million tonnes of palm oil in 2022, which is a 1.02% increase from the previous year's production of 45.12 million tonnes (Gandhi & Fumie, 2023). Riau is a major hub for palm oil production in Indonesia, with an estimated production of 8.97 million tonnes in 2022. This represents 19.68% of the total national palm oil production, which amounts to 45.58 million tonnes (Apresian et al., 2020; Numata et al., 2022).

Measuring the water footprint (WF) is critical for assessing environmental sustainability. To ensure the sustainability of oil palm plantations, it is imperative to assess the WF at each plantation site. The spread of oil palm cultivation in Indonesia has led to a significant transformation of land use on a large scale, influenced by social, economic and ecological factors. This transformation involves converting forests to intensive agricultural systems, which can have a significant impact on the hydrological cycle (Merten et al., 2016; Noerrizki et al., 2019).

Oil palm plants are highly susceptible to dry conditions, particularly in areas with an annual moisture deficit of 400 mm (Afandi et al., 2022). The water requirements for oil palm are similar to those of sugarcane, ranging from 1,000-1,500 mm annually (Riajaya & Kadarwati, 2022; Yusara et al., 2019). Bananas also require an

---

[1] Department of Agrotechnology, Faculty of Agriculture,
Universitas Islam Riau, Jalan Kaharuddin Nasution No. 113,
Pekanbaru, Riau 28284, Indonesia.

[2] Biomanagement, School of Life Sciences and Technology,
Institut Teknologi Bandung, Jl. Ganesha No. 10,
Bandung, Jawa Barat 40132, Indonesia.

[3] Department of Biology, Faculty of Biology,
Universitas Gadjah Mada, Bulaksumur, Depok,
Special Region of Yogyakarta 55281, Indonesia.

* *Corresponding author e-mail: pw.titisari@agr.uir.ac.id*

annual water supply ranging from 700–1,700 mm (Dos Santos et al., 2019; Santosh & Tiwari, 2019). However, the water needs of oil palm and banana are relatively lower when compared to staple crops like rice, corn, maize and soybean, which require an annual water consumption of 1,200–2,850 mm. Compared to other plantation crops, oil palm needs more water, around 4.10–4.65 mm/day, which accumulates to approximately 1,500–1,700 mm annually (Khanh & Ngoc, 2022; Materu et al., 2018; Titisari, 2024a, 2024b, 2025; Watson-Hernández et al., 2022).

Existing literature on oil palm plantations has primarily focused on assessing water quality (Ahmad et al., 2021; Merten et al., 2016; Safitri et al., 2018b, 2022a). Limited social science studies on water quantity fails to comprehensively understand factors contributing to the reported water availability decrease (Suharyanti et al., 2020). Natural science studies on oil palm's water impact are scarce and often narrow in scope. Heidari et al. (2020) found a 9.00% reduction in average annual river flow on converted land, and their study suggested investigating the impact of decreasing groundwater levels based on seasons. Jaya et al. (2018) found that erosion and surface runoff in five-year-old oil palm plantation areas were higher than in forest areas, which has implications for soil nutrient loss and water pollution. Sumarga et al. (2016) predicted that in the next 100 years, around 67.00% of peatlands planted with oil palm will experience regular flooding. However, this study only focused on peat soil types, therefore exploring areas with different soil characteristics is necessary. Oil palm plantations exhibit inferior nutrient and water conservation capabilities compared to other tree plantings (Comte et al., 2015; Dislich et al., 2017; Manoli et al., 2018; Santi et al., 2021). Akram et al. (2022) and Gómez et al. (2023) find a 30.00%–40.00% reduction in water influx from oil palm plantations to river systems, raising concerns about water quality degradation (Murphy et al., 2021; Syahza, 2019). Evaluating water-related issues in oil palm plantations is complex due to interactions among soil conditions, climate variables and agricultural methods (Safitri et al., 2022; Sukarman et al., 2022).

The WF method evaluates how much water is used to grow crops. The WF method is a comprehensive approach for evaluating direct and indirect water consumption in different sectors, including the industrial, agricultural and domestic sectors. In agriculture, the WF is an essential metric for assessing water usage and its environmental impact. The WF is divided into three components: Green, blue and grey WFs. The green WF refers to the volume of rainwater stored in the soil and used by plants through evapotranspiration (ET). The blue WF refers to the volume of surface and groundwater used for irrigation. The grey WF measures the volume of water required to dilute pollutants to meet specific standards (Madrid-López, 2023; Mialyk et al., 2024; Yi et al., 2024).

Recently, different approaches for the assessment of water consumption in production processes have been introduced. Most WF studies have been conducted in agricultural sectors using the Penman-Monteith combined with the FJ Mock method to assess water availability. Mekonnen and Hoekstra (2011) studied the water requirements of different crops using this method. FJ Mock calculations are based on monthly rainfall data, ET, soil moisture and groundwater. FJ Mock method has a principle which states that the rain that falls on the catchment area will partly disappear due to ET, some will become direct runoff, and some will enter the ground. FJ Mock method shows a relatively simple calculation method for various components based on the results of study on watersheds throughout Indonesia (Ministry of Public Works Directorate General of Natural Resources, 2013). The WF is the total amount of freshwater used to produce agricultural products. Many studies have been conducted on the WF of oil palm, including those by Ichwan et al. (2019) which predicted the water requirements of oil palm only based on the net radiation evaporation method. Mohammad Sabli et al. (2017) and Subramaniam and Hashim (2018), assessed oil palm WF with a life cycle assessment (LCA) approach. However, the difficulty is that there is little or no reliable data on water usage in life cycle databases; furthermore, there is no agreed life cycle impact assessment method for estimating impacts related to freshwater use (Jeswani & Azapagic, 2011). Safitri et al. (2018a, 2022) analysed the WF of oil palm cultivation over a specific period and root water uptake. Santosa et al. (2018) focus on analysing the WF to produce fresh fruit bunches (FFB) and crude palm oil (CPO) by reference to Hoekstra et al. (2011). These studies were based on field calculations. Mekonnen and Gerbens-Leenes (2020) critically evaluate the WF of agricultural production and assess the sustainability of the blue WF. Afandi et al. (2022) studied several soil and moisture conservation techniques that can increase oil palm yield.

The Kampar Watershed, located in Riau Province, Indonesia, is a swiftly developing oil palm frontier distinguished by peatland and mineral soils. In the last 20 years, the region has undergone significant alterations in land cover, chiefly due to the transformation of forests and secondary vegetation into oil palm plantations (Erniwati et al., 2017; Numata et al., 2022). This transformation is propelled by advantageous climatic conditions, navigable terrain and robust market demand, establishing Kampar as one of the most dynamic palm oil-producing regions in Southeast Asia (Apresian et al., 2020; Meiwanda et al., 2022). Nonetheless, the ecological fragility of its peat regions and escalating demands on water resources prompt critical enquiries regarding the long-term viability of continued expansion.

Notwithstanding the growing focus on sustainable water utilisation in agriculture, the majority of current study regarding the WF of oil palm in Indonesia has been confined to plot-level or crop-level assessments. These studies frequently assess water consumption or greywater pollution loads without considering the hydrological capacity of the region (Gómez et al., 2023; Safitri et al., 2022). A significant knowledge gap persists in correlating spatially explicit water availability, obtained from catchment-scale hydrological models, with the water demands and environmental impacts of plantation expansion.

The objective of this study was to combine the FJ Mock method, which simulates water availability at the watershed level, with Penman-Monteith based calculations of WF (including green, blue and grey components) to address this gap. This integrated method facilitates the spatial assessment of the alignment between oil palm expansion and the water surplus or deficit conditions in particular regions of the Kampar catchment. The study provides new insights into regional water planning, sustainable land-use allocation and oil palm governance under climate variability by contextualising plantation water demand within the region's hydrological carrying capacity.

MATERIALS AND METHODS

Site Location

The study was conducted in eight villages within the Kampar Catchment, Riau Province, central Sumatra, Indonesia (Figure 1). The catchment extends across Kampar and Pelalawan Regencies and represents a continuous upstream–downstream hydrological gradient influencing water availability for oil palm plantations. In Kampar Regency, the study sites included the subdistricts of XIII Koto Kampar (0°16′14.7″ N, 100°41′38.0″ E), Kampar (0°17′49.5″ N, 101°06′46.8″ E), Kampar Kiri Hulu (0°06′09.6″ S, 100°50′53.0″ E), and Kampar Kiri Hilir (0°06′59.4″ N, 101°29′19.9″ E). In Pelalawan Regency, four subdistricts were investigated: Langgam (0°14′57.3″ N, 101°43′03.0″ E), Pelalawan (0°32′31.0″ N, 102°03′07.2″ E), Teluk Meranti (0°30′31.7″ N, 102°38′59.1″ E), and Kuala Kampar (0°34′44.3″ N, 103°12′29.3″ E). The study area is dominated by lowland tropical oil palm plantations, including both mineral soils and peatlands, where plantation water use, evapotranspiration, and groundwater management are key determinants of the catchment-scale water footprint.

Data Collection

The study utilised primary and secondary data on runoff from the Kampar Watershed. Primary data were collected from eight water estimation posts, with four affiliated with the Sumatra III River Regional Office in Riau Province (Gunung Bungsu, Gema/Kuntu, Gunung Sahilan and Lipat Kain Village), two in Kampar Regency (District XIII Koto Kampar and Kampung Pinang, Panti Raja District) and two in Pelalawan Regency (Lubuk Ogung Langgam and Pangkalan Kerinci). The locations were acquired from the Public Works and Spatial Planning Agency (PUPR) of the respective regencies. Secondary data representing internet search results which include production outcomes, agricultural land area and fertiliser application information from the Riau Province Agricultural Service, as well as precipitation data and climatological parameters (mean temperature, air humidity, wind velocity and sunlight duration) from Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) Pekanbaru. *Figure 2* depicts the study framework, comprising three primary stages. The initial phase involves data gathering, comprising primary data (river discharge from monitoring stations, land data, productivity and fertiliser application) and secondary data (climatic conditions, precipitation, temperature, humidity, radiation and agricultural production statistics from the relevant office). The second stage is an examination of water availability utilising the FJ Mock technique, which considers monthly water balances, encompassing evapotranspiration, runoff, infiltration, groundwater storage and river discharge. The third stage involves calculating the WF using the Penman-Monteith technique and CROPWAT 8.0, which categorises the WF into three components: Green, blue and grey. The WF results are subsequently compared with the water availability from the FJ Mock to evaluate the equilibrium between oil palm crop requirements and the hydrological capacity of the Kampar Watershed.

This paradigm illustrates the integration of the watershed water balance at the watershed scale with crop water requirements at the crop scale. This flow illustrates that the study outcome comprises not only WF values but also the water footprint score (WFS), serving as an indicator of water and fertiliser management efficacy in oil palm plantations.

Water Availability Analysis

Water availability was determined using the FJ Mock method. The CROPWAT 8.0 program was used to evaluate ET using the Penman-Monteith technique with data from 2014 to 2022. ET was calculated using the FJ Mock method and water requirements are estimated using the SNI 6728.1:2015 Standard method (Badan Standarisasi Nasional, 2015).

Research procedure for calculating Water availability for the Kampar Watershed Based on the FJ Mock Method includes the calculation of potential evapotranspiration (*PET*) using the Penman-Monteith method with CROPWAT 8.0, followed by the calculation of actual evapotranspiration (ET_a) (mm/month) as shown in Equation (1) and (2).

$$\Delta ET = \left(\frac{m}{20}\right) \times (18 - n) \times PET \qquad (1)$$

$$ET_a = PET - \Delta ET \qquad (2)$$

where, ET_a is the difference between *PET* and *ΔET* (mm/month); *m* is the exposed surface and *n* is the number of rainy days. The calculations of water surplus (W_s) (mm/month) is determined using Equation (3):

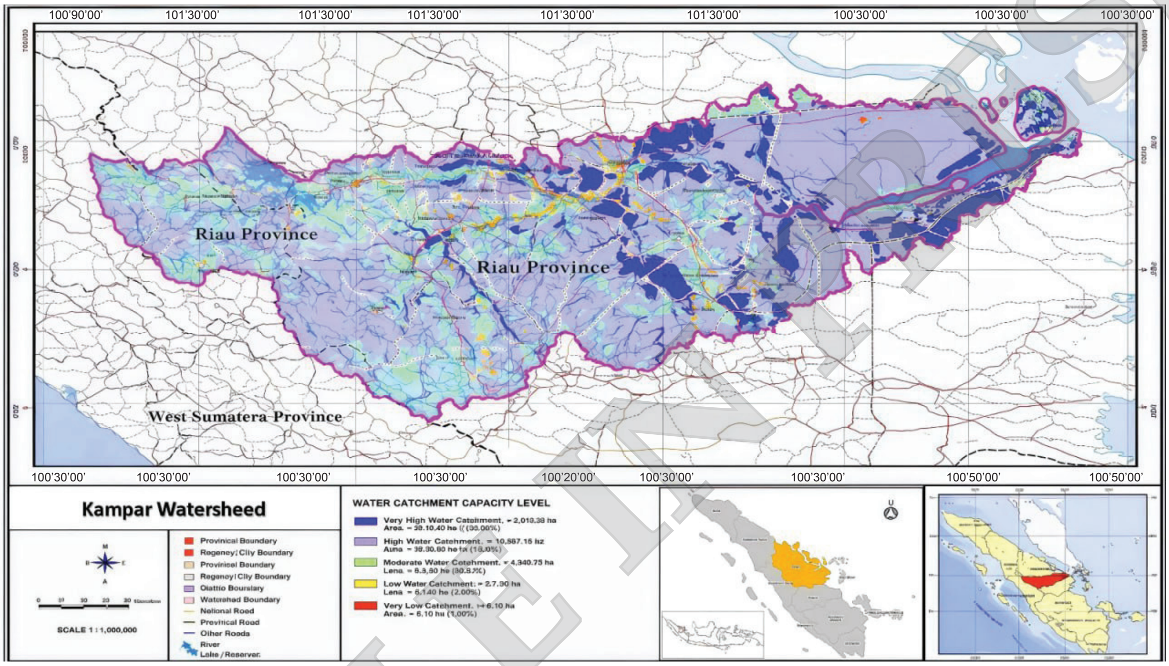


Figure 1. Study location map.

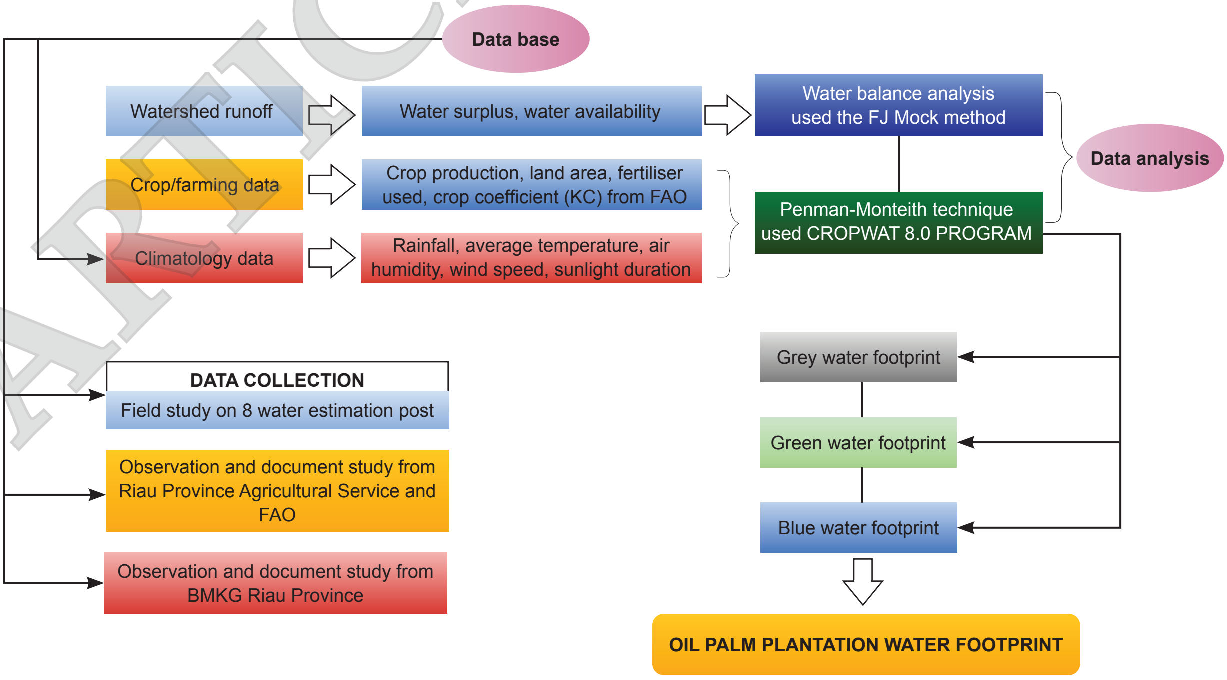


Figure 2. The framework of the study.

$$W_S = (P - ET_a) + SS \tag{3}$$

where, W_S is the difference between the rainfall (P) (mm/month) and ET_a with the addition of soil storage (SS) (mm/ month) (0 if $P - ET_a > 0$, and $P - ET_a$ if $P - ET_a < 0$).

The infiltration of base flow (BF) (mm/month), direct runoff (DRO) (mm/month) and storm runoff (SRO) (mm/month) based on FJ Mock method is calculated using Equation (4):

$$i = W_S \times i_f \tag{4}$$

where, i is the infiltration (mm/month), calculated by multiplying the W_S to infiltration coefficient (i_f). Meanwhile, the groundwater storage (GWS) is calculated using Equation (5):

$$GWS = \{0.5 \times (1 + K) \times i\} + \{K \times GSom\} \tag{5}$$

where, GWS is the groundwater storage (mm/ month); K is the groundwater recession constant and $GSom$ is the groundwater storage of the previous month.

After the GWS value was obtained, continue by calculating the BF (mm/month) using Equation (6):

$$BF = i - \Delta GWS \tag{6}$$

where, ΔGWS is the changes in groundwater storage.

The direct runoff (DRO) (mm/month) based on FJ Mock method calculated by Equation (7):

$$DRO = W_S - i \tag{7}$$

The SRO (mm/month) was a water that overflowed into rivers when heavy rain occurred, and being calculated based on FJ Mock method according to the provisions [Equation (8) and (9)];

$$\text{if } P < SMC, \text{ then } SRO = 0 \tag{8}$$

$$\text{if } P > SMC, \text{ then } SRO = P \times PF \tag{9}$$

where, SMC is the soil moisture capacity (mm) and PF is the SRO percentage factor. The total runoff (TRO) (mm/month) was calculated by Equation (10):

$$TRO = BF + DRO + SRO \tag{10}$$

where, TRO is the total runoff (mm/month) which is the cumulation of BF, DRO and SRO for the month.

The calculation of debit (Q) using Equation (11):

$$Q = TRO \times CA \tag{11}$$

where, Q is the debit (m^3/s) by multiplying to the TRO catchment area (CA) (km^2) and the irrigation water requirements (QIR) (m^3/yr) were calculated using Equation (12):

$$QIR = L \times It \times a \tag{12}$$

where, L is the agriculture land area (ha); It is the planting intensity (number of seasons/yr x 3,600 s/hr x 24 hr/day x number of days/season) and a is the standard for irrigation use (referring to SE PUPR Number 07 of 2018; the water requirement for then rice plants is 1 L/s/ha and the secondary crops is 0.8 L/s/ha).

Finally, the Kampar Watershed water balance was calculated by determining the difference between the water availability and requirements [Equation (13)].

$$\Delta Q = Q_{avaiability} - Q_{requirement} \tag{13}$$

where ΔQ is the difference between the water availability ($Q_{avaiability}$) (m^3/yr) and water requirements ($Q_{requirement}$) (m^3/yr).

Water Footprint (WF) Analysis

The WF analysis manual book explains three types of water footprints; green, blue, and grey. Green and blue WF are formed by ET, crop coefficient (K_C) and production, and P respectively. The grey WF is calculated based on the water used to dilute pollutants from fertiliser and production processes. The WF calculation model used is described as Equation (14):

$$WF_{total} = WF_{blue} + WF_{green} + WF_{grey} \tag{14}$$

Calculation of the blue water footprint (WF_{blue}). The blue water footprint (WF_{blue}) components of crop in a geographic area are determined using Equation (15):

$$WF_{proc,blue} = \frac{CWU_{blue}}{Y} \tag{15}$$

where, $WF_{proc,blue}$ is the blue process WF (m^3/t); CWU_{blue} is the blue crop water use; and Y is the yield (t/ha). To calculate CWU_{blue} used, the blue evapotranspiration (ET_{blue}) is calculated based on crop water requirements (CWR), determined by CROPWAT 8.0 program. In optimal growth conditions, it is assumed that CWR are met adequately, resulting in equality between real crop evapotranspiration (ET_C) and CWR, which is denoted by ET_C equal to CWR.

ET_C calculations are carried out based on irrigation requirement (IR). The underlying premise of this methodology assumes that losses resulting from irrigation practices will persist and eventually flow back into the watershed. The estimated ET_{blue} value is obtained from Equation (16) and (17):

$$ET_{blue} = IR \quad (16)$$

$$IR = ET_C - P_{eff} \quad (17)$$

where, IR is the difference of ET_C and effective rainfall (P_{eff}). Calculation of P_{eff} is carried out using the USDA Soil Conservation Service method on CROPWAT 8.0 software. If P_{eff} exceeds ET_C, the ET_{blue} value is set to zero. ET_C estimation was carried out using 10 day time steps throughout the growing season, using Equation (18):

$$ET_C = K_C \times ET_0 \quad (18)$$

where, ET_C is the multiplication of K_C and reference evapotranspiration (ET_0). K_C integrates crop characteristics and soil evaporation impact. ET_0 measured in mm/month, was calculated using the Penman-Monteith method in CROPWAT 8.0 software, incorporating climatological data.

***Calculation of the green water footprint* (WF_{green}).** The green water footprint (WF_{green}) is determined by the green crop water use (CWU_{green}) and the resulting Y (t/ha), as expressed in Equation (19):

$$WF_{proc,green} = \frac{CWU_{green}}{Y} \quad (19)$$

where, $WF_{proc,green}$, the green process WF (m^3/t) is obtained by dividing the CWU_{green} by the Y (t/ha). Quantifying CWU_{green} involves assessing ET_c and P_{eff} in m^3/ha using the CROPWAT 8.0 program. Meteorological data, including average, maximum, and minimum monthly temperatures, relative humidity, wind speed, and sunshine duration, is used in ET_c modelling. P_{eff} represents the soil-retained fraction of precipitation usable by plants. The CROPWAT 8.0 model employs the USDA Soil Conservation Service method to calculate P_{eff}.

***Calculation of grey water footprint* (WF_{grey}).** The grey water footprint (WF_{grey}) measures freshwater needed to assimilate pollution while accounting for natural background concentrations and water quality standards (Hoekstra et al., 2011) [Equation (20)].

$$WF_{proc,grey} = LC_{max} \times C_{nat} \quad (20)$$

where, $WF_{proc,grey}$ is the grey process water footprint (m^3/t); L is the leaching (amount of pollutant or fertiliser introduced into the water system [kg/yr]); C_{max} is the maximum pollutant concentration; and C_{nat} is the concentration of pollutants that naturally exist in water bodies.

The data processing methodology employed in this investigation involved the utilisation of Excel and CROPWAT programs, as previously documented in the study conducted by Hoekstra et al. (2009) and Altobelli et al. (2015, 2019).

Water Footprint Score (WFS) Performance Analysis

The water footprint score (WFS) evaluates crop water efficiency through water management and fertilisation, comparing actual water footprint to the annual reference level (WF'). The WF_{green}/WF_{blue} ratio determines the ideal irrigation method, reflecting plant water consumption. This study assesses irrigation management by analysing rainwater utilisation levels and comparing actual green and blue WF to annual reference values. According to this approach, the value of WFS consists of two part which are: $WFS_{green/blue}$, which reflects water management performance (the ratio of green to blue WF) [Equation (21)]; and WFS_{grey}, which reflects the fertilisation performance (WF_{grey}) [Equation (22)].

$$WFS_{green/blue} = 100\% \times WF_{green} WF_{blue} \times WF'_{green} WF'_{blue} \quad (21)$$

$$WFS_{grey} = 100\% \times WF'_{grey} WF_{grey} \quad (22)$$

The WFS data is subsequently categorised into three distinct groups to assess the effectiveness of the WFS, as depicted in *Table 1*.

TABLE 1. WATER FOOTPRINT SCORE (WFS) PERFORMANCE CATEGORIES

WFS	Performance
0–29	Poor
30–69	Medium
70–100	Excellent

Source: Fotia and Tsirogiannis (2023).

RESULTS AND DISCUSSION

Oil Palm Plant Production in Kampar and Pelalawan Regency

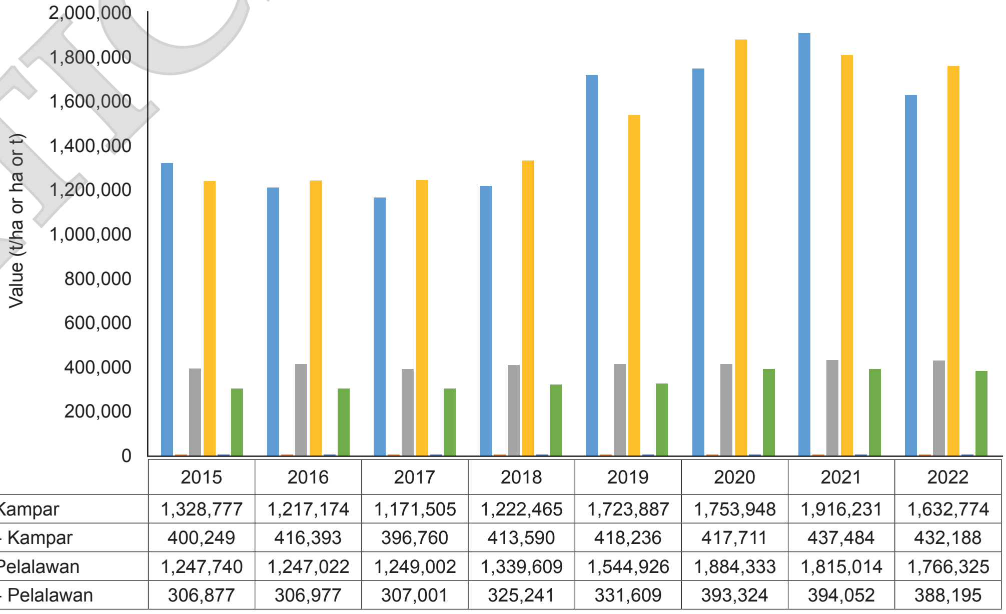
The subsequent data represent the production, productivity and land area of oil palm plantations in Kampar and Pelalawan Regency. *Figure 3* illustrates a gradual expansion of oil palm plantations in Kampar and Pelalawan Regency, particularly in Pelalawan where a notable increase occurred between 2019 and 2020. This expansion has led to a rise in overall output levels and productivity. Data show that quite significant increases in land area and production occurred in 2020 (Pelalawan Regency) and 2021 (Kampar Regency). As depicted in *Figure 3*, the significant increase indicates the driving forces of the region's economics/market demand and government policies. The increase in production and productivity reflects the strategic prioritisation of oil palm as a primary agricultural commodity (Wenzel et al., 2024). Study conducted by Syahza (2019) and Safriyana et al. (2021), Kampar Regency in Riau Province is involved in palm oil production and has seen a consistent annual expansion in land area dedicated to oil palm plantations. The possibility of expanding oil palm plants in Kampar Regency remains viable. The increase in oil palm plantations in Kampar Regency is due to the conversion of land from rubber plantations, secondary forests and shrubs, resulting in deforestation (Apresian et al., 2020; Erniwati et al., 2017; Numata et al., 2022). The trends in *Figure 3* help us understand the potential environmental and socioeconomic consequences of quickly increasing farming activities (Utami et al., 2017). It is anticipated that there will be a moderate increase in oil palm production in the next five years (Guntoro et al., 2022; Meiwanda et al., 2022).

The productivity of oil palm plantations is influenced by various factors including plantation size, fertilisers and pesticide application, labour efficiency, climate variables (ET, duration of light exposure, wind speed and P), and stakeholders' involvement (Nainggolan et al., 2021; Yanita & Suandi, 2021; Zulkefli et al., 2020).

Water Use and Available Water for Oil Palm Plantation in Kampar and Pelalawan Regencies

Figure 4 presents an analysis of the discharge of the Kampar Watershed in Kampar and Pelalawan Regency. The Kampar River has a surplus of water, making it sufficient for oil palm plantations. However, the annual increase in water usage due to the expanding plantation areas raises concerns about long-term sustainability. The observed pattern of rising water demands for oil palm cultivation aligns with the study by Ichwan et al. (2019) which indicates that water requirements for oil palm tend to escalate as they mature but decline during periods of heavy rainfall. According to Sharma et al. (2018) and Murphy et al. (2021), the escalating spread of oil palm plantations, along with the concurrent decline in biodiversity, will inevitably lead to a rise in water demands. This study's findings suggest that without strategic water management practices, the sustainability of oil palm cultivation in these regions could be at risk, potentially leading to conflicts over water resources or environmental degradation.

Several areas in Kampar and Pelalawan Regency have great potential for oil palm plantations, based on the findings from the water balance study. These areas include Tapung Hulu, Tapung Hilir, Tapung, Kampar Kiri Hulu, Gunung Sahilan, Kampar Kiri and Kampar Kiri Hilir in



	2015	2016	2017	2018	2019	2020	2021	2022
🟦 Production (t) - Kampar	1,328,777	1,217,174	1,171,505	1,222,465	1,723,887	1,753,948	1,916,231	1,632,774
⬜ Cultivation (ha) - Kampar	400,249	416,393	396,760	413,590	418,236	417,711	437,484	432,188
🟨 Production (t) - Pelalawan	1,247,740	1,247,022	1,249,002	1,339,609	1,544,926	1,884,333	1,815,014	1,766,325
🟩 Cultivation (ha) - Pelalawan	306,877	306,977	307,001	325,241	331,609	393,324	394,052	388,195

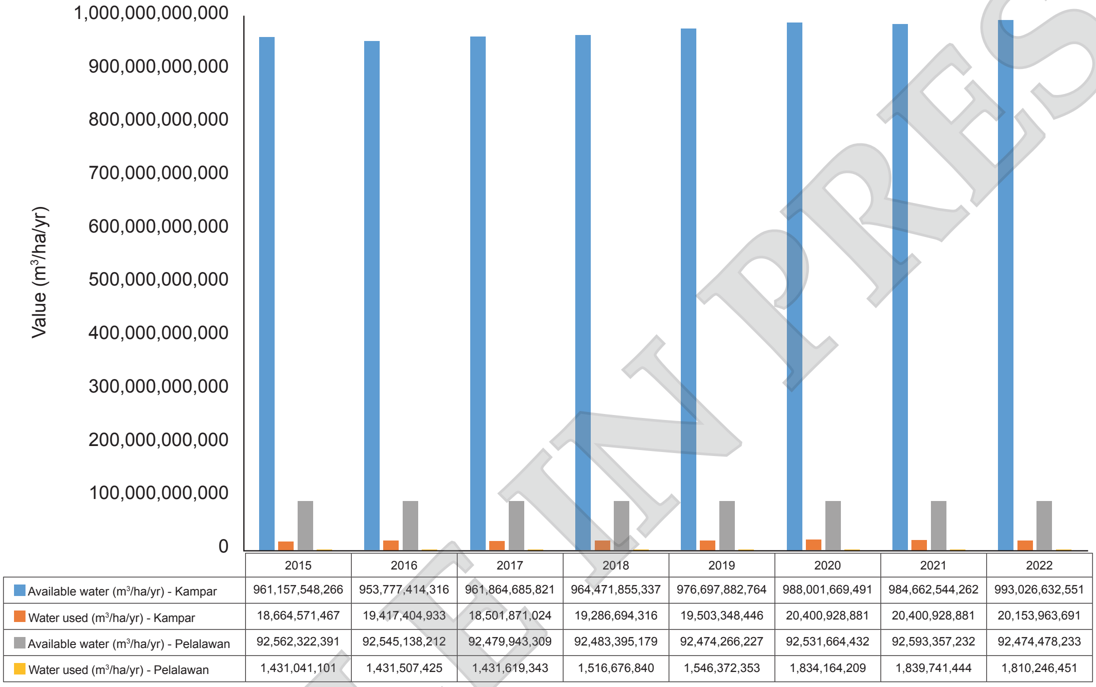
Figure 3. *Production (t) and cultivated area (ha) of oil palm in Kampar and Pelalawan Regencies in Kampar watershed.*

Kampar Regency, as well as Meranti, Pelalawan, Bunut, Langgam, Ukui, Pangkalan Lesung, Bandar Petalangan and Kerumutan districts in Pelalawan Regency (*Figure 5* and *6*).

Water Footprint of Oil Palm Plantation in Kampar and Pelalawan Regencies at Kampar Watershed

The WF of oil palm encompasses three components: Green, blue and grey WFs. The study found that Kampar Regency has a higher total WF at 327.37 m³/t, consisting of green (170.49), grey (129.10) and blue (27.78) water components. Meanwhile, Pelalawan Regency's total WF is 272.88 m³/t, with green (159.82), grey (84.67) and blue (28.39). *Figure 7* shows the WF values for each district.

According to the data presented in *Figure 7*, the WF of oil palm cultivation in Kampar and Pelalawan Regency is primarily composed of a green WF. Oil palms have a very high green WF value, which is subsequently followed by the



	2015	2016	2017	2018	2019	2020	2021	2022
🟦 Available water (m³/ha/yr) - Kampar	961,157,548,266	953,777,414,316	961,864,685,821	964,471,855,337	976,697,882,764	988,001,669,491	984,662,544,262	993,026,632,551
🟧 Water used (m³/ha/yr) - Kampar	18,664,571,467	19,417,404,933	18,501,871,024	19,286,694,316	19,503,348,446	20,400,928,881	20,400,928,881	20,153,963,691
⬜ Available water (m³/ha/yr) - Pelalawan	92,562,322,391	92,545,138,212	92,479,943,309	92,483,395,179	92,474,266,227	92,531,664,432	92,593,357,232	92,474,478,233
🟨 Water used (m³/ha/yr) - Pelalawan	1,431,041,101	1,431,507,425	1,431,619,343	1,516,676,840	1,546,372,353	1,834,164,209	1,839,741,444	1,810,246,451

Figure 4. Water used (m³/ha/yr) and available water (m³/ha/yr) for oil palm cultivation in Kampar and Pelalawan Regency at Kampar Watershed.

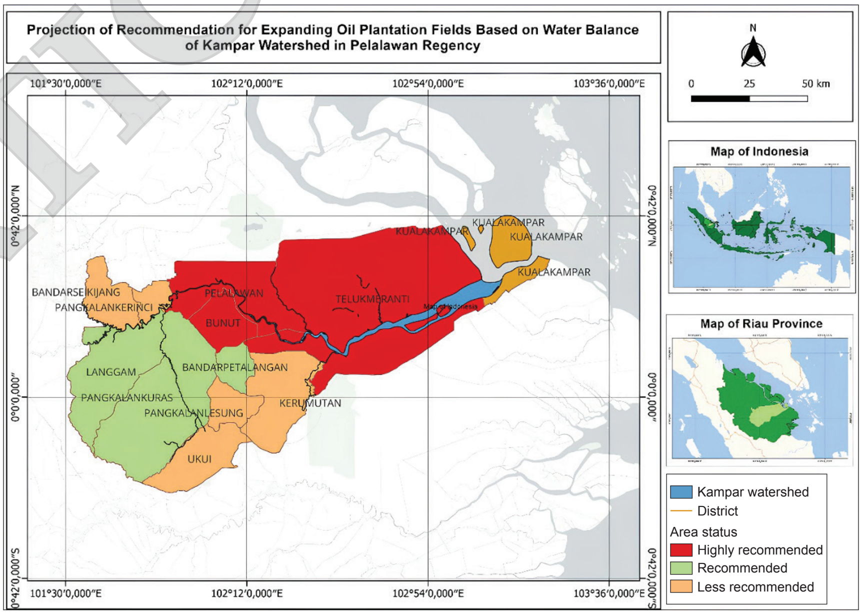


Figure 5. Potential areas to be developed for oil palm plantations in Pelalawan Regency.

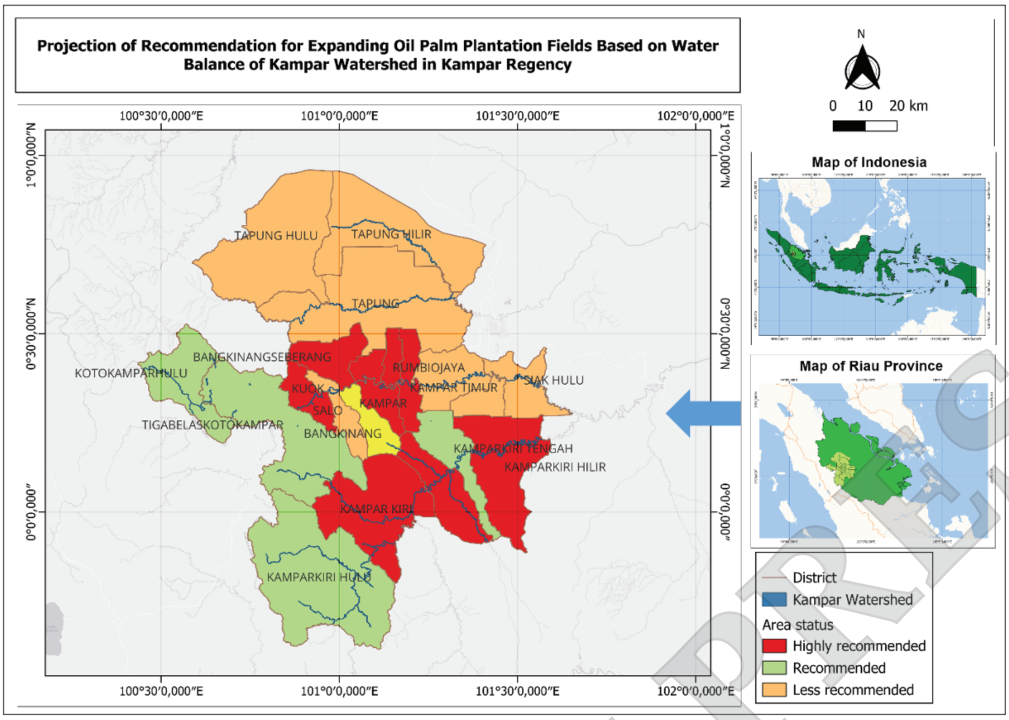
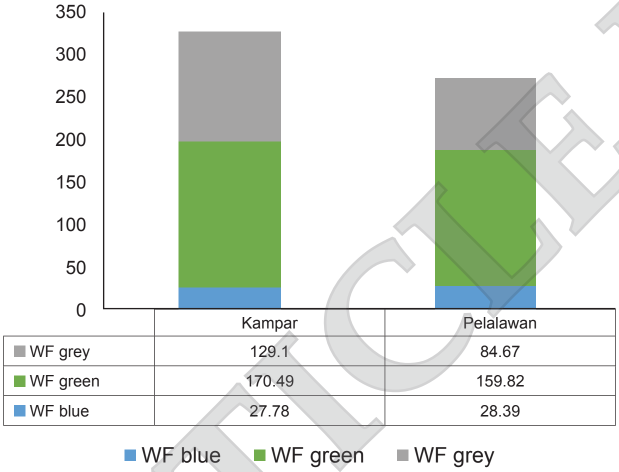


Figure 6. Potential areas to be developed for oil palm plantations in Kampar Regency.



	Kampar	Pelalawan
WF grey	129.1	84.67
WF green	170.49	159.82
WF blue	27.78	28.39

Figure 7. The water footprint (WF) (m^3/t) of oil palm plantation in Kampar and Pelalawan Regency at Kampar Watershed.

grey WF. Consistent with the study conducted by Safitri et al. (2018a), it was shown that the presence of green water, which is derived from rainfall in the upper root zone of oil palm, significantly contributes to the absorption of water by oil palm roots in comparison to blue water sourced from groundwater in the lower layer of the root zone. Other study supports these findings, showing reduced oil palm groundwater usage (Kospa et al., 2017; Santosa et al., 2018). Several factors, including the high grey WF produced, can influence the reduction of groundwater in this case. According to Daundi et al. (2022), palm oil liquid waste can potentially reduce the quality of groundwater and surface water. Based on data from the Minister of Environment and Forestry Kampar District, the Kampar Watershed has an alluvial plain landform but is not a swampy area and has a groundwater depth of 50 cm. Furthermore, the groundwater level from October 2019 to May 2020 ranged from 22.7 to 52.0 cm (Lutfi et al., 2021). In the study conducted by Safitri et al. (2018b), documented values of 876.7 m^3/t for green, 89.55 m^3/t for grey and 35.9 m^3/t for blue WFs. In addition, Mekonnen and Hoekstra (2011) analysed the WF of oil palm. Their findings revealed a green WF of 1,057 m^3/t, grey WF of 40 m^3/t and blue WF of 0 m^3/t. In a study conducted by Suttayakul et al. (2016), it is known that the presence of green water traces is higher than the grey and blue WF.

Water footprint (WF) measurements in palm oil production vary due to factors such as plant productivity, climate conditions, land type and use of fertilisers. The value can be influenced by analysis methods, as reported in studies by Mungkalasiri et al. (2015), Lovarelli et al. (2016) and Marston et al. (2018). Kampar and Pelalawan Regency share similar climates and land types. This study explores the impact of productivity characteristics and fertiliser use on the oil palm WF in these regions. The analysis focuses on green WF, considering crop productivity and rainfall. Data reveal higher oil palm production in Pelalawan than in Kampar. Increased farm production correlates with a reduced WF (Gheewala et al., 2014; Tuninetti et al., 2020).

The grey WF for oil palm cultivation in the Kampar Watershed is 213.77 m^3/t, the second most significant component. Studies by Dong et al. (2021) and Cruz-Pérez et al. (2023) indicate that oil palm cultivation in the Kampar Watershed has a high WF due to poor water management practices and excessive fertiliser use. To mitigate this, wise fertiliser management can be improved to reduce the WF of crops (Huang et al., 2015; Wang et al., 2023).

The overall WF of oil palm farming in Kampar (327.37 m^3/t) and Pelalawan (272.88 m^3/t) is moderate in comparison to worldwide standards. The values are below the 400.00–500.00 m^3/t range reported for Thailand by Suttayakul et al. (2016) and Safitri et al. (2018a) in Central Kalimantan, Indonesia. Mekonnen and Hoekstra (2011) calculated a considerably elevated green WF of 1,057.00 m^3/t for oil palm worldwide, with no blue WF reported, suggesting divergent climatic assumptions and possibly wider geographical ranges.

The WF assessments in Malaysia, Indonesia's primary regional rival, are often elevated. Kospa et al. (2017) documented total WFs of up to 476.10 m^3/t in South Sumatra, Indonesia, while Mohammad Sabli et al. (2017) observed comparable or elevated values in Malaysian plantations employing life cycle methodologies. These variables indicate disparities in approach, yield, fertiliser use and precipitation patterns.

This study's reduced blue water component indicates little irrigation dependence, demonstrating enhanced alignment with SDG 6 (Clean Water and Sanitation), even in water-rich areas. The medium grey WF ratings indicate nitrogen leaching and fertiliser inefficiency, which are issues related to SDG 12 (Responsible Consumption and Production), particularly in terms of pollution and the sustainable use of agricultural inputs. Minimising grey WF through precise nitrogen management and augmenting yields per hectare are essential for diminishing environmental impacts and raising water productivity. This study contributes to the international discourse on sustainable palm oil production by contextualising Indonesian oil palm water usage within global standards and highlighting the necessity for locally adaptive water management strategies.

Water Footprint Score (WFS) and Performance of Oil Palm Plantation in Kampar and Pelalawan Regencies at Kampar Watershed

Table 2 shows that oil palms in Kampar and Pelalawan Regencies have moderate grey WFSs in the Kampar Watershed area. Water usage for fertilisation is important due to increasing expansion of oil palm plantations annually. Grey WFS values for Kampar and Pelalawan Regencies are 129.10 and 84.67 respectively. Fertilisers and pesticides used in oil palm plantations can contaminate nearby river systems through runoff, adversely affecting aquatic ecosystems (Comte et al., 2015; Gómez et al., 2023; Jaya et al., 2018). Oil palm plantations can enhance water management through optimised rainfall consumption, utilising canals fed by Kampar River runoff. Efficient water management supports optimal water use and preserves soil moisture. Fertilisation relies on systematic methods of assessing plant nutrient needs based on soil and water conditions (Kospa et al., 2017; Subramaniam & Hashim, 2018). These findings underscore the importance of adopting more sustainable fertilisation practices and optimising water management. This is to mitigate the environmental impact of oil palm cultivation, thereby improving the overall performance of these plantations in the Kampar Watershed area.

TABLE 2. GREY WATER FOOTPRINT SCORE (WFS)OF OIL PALM PLANTATION IN KAMPAR AND PELALAWAN REGENCIES

Location	Grey WFS	Performance
Kampar Regency	129.10	Medium
Pelalawan Regency	84.67	Medium

The root water uptake of crops is contingent upon factors such as crop age and soil type. Oil palm has a 13 year lifespan and consumes the most water when cultivated on spodosol. This crop's average daily rate of water consumption was recorded at 3.07–3.73 mm/day (Safitri et al., 2018a). Assessing the WF of oil palm cultivation, including green and blue water use, and root water uptake allocation, is a reliable measure of environmental sustainability (Hariyanti et al., 2022; Husin et al., 2023; Indriyadi, 2022).

Uncertainty and Sensitivity Analysis

The values of the WF are significantly influenced by critical biophysical variables, including precipitation, agricultural productivity and fertiliser application. A sensitivity study was performed to assess the robustness of the computed WF components, utilising a ±10% variation in two key input parameters: Effective rainfall and oil palm production. This methodology yields a spectrum of credible WF values for green, blue and grey components, reflecting standard field variability, in accordance with the techniques employed by (Huang et al., 2015; Wang et al., 2023). In Kampar

Regency, a ±10% variation in oil palm output (baseline: 19.3 t/ha) led to the green WF fluctuating between 155.90 and 188.32 m^3/t, demonstrating an inverse correlation between yield and WF for each tonnes. Correspondingly, grey WF ranged from 116.45 to 143.22 m^3/t, whereas blue WF fluctuated between 25.00 and 30.80 m^3/t. In Pelalawan Regency, with a baseline output of 21.7 t/ha, the green WF varied from 145.29 to 176.46 m^3/t, the grey WF ranged from 76.20 to 93.57 m^3/t and the blue WF oscillated between 25.55 and 31.23 m^3/t.

The data indicated that the green and grey WF components are especially susceptible to fluctuations in production and variations in fertiliser application rates. As yield serves as the denominator in WF computations, even small decreases in productivity significantly amplify per-unit WF estimations. Simultaneously, variations in rainfall affected the effective precipitation component utilised in calculating green and blue WF, albeit their influence was rather minor. These findings highlight the necessity of integrating uncertainty boundaries into WF estimates, particularly in tropical agricultural systems characterised by climate variability and erratic management approaches. Subsequent studies ought to incorporate Monte Carlo simulations or probabilistic modelling to enhance these uncertainty intervals.

CONCLUSION

Precision farming is crucial for sustainable palm oil production. This study highlights the intricate water dynamics of oil palm cultivation. It emphasises the need for sustainable water management practices in the industry to ensure environmental conservation and the continued viability of palm oil production in Indonesia and beyond. In Kampar Regency, the WF consists of 170.49 m^3/t of green water, 129.10 m^3/t of grey water and 27.78 m^3/t of blue water, totalling 327.37 m^3/t. In Pelalawan Regency, the corresponding values are 159.82, 84.67 and 28.39 m^3/t, respectively, totalling 272.88 m^3/t. The grey WF falls within the medium category in both districts. However, based on the water use and availability, Kampar Watershed has a surplus of water, making it sufficient for oil palm plantations. However, the annual increase in water usage due to the expanding plantation areas raises concerns about long-term sustainability. Several areas in Kampar and Pelalawan Regencies have great potential for oil palm plantations, based on the findings from the water balance study. These areas include Tapung Hulu, Tapung Hilir, Tapung, Kampar Kiri Hulu, Gunung Sahilan, Kampar Kiri and Kampar Kiri Hilir in Kampar Regency, as well as Meranti, Pelalawan, Bunut, Langgam, Ukui, Pangkalan Lesung, Bandar Petalangan and Kerumutan districts in Pelalawan Regency. By implementing Good Agricultural Practices (GAP), oil palm plantations can effectively conserve water and soil. These practices encompass the use of cover crops, the creation of terracing systems and mound systems, as well as the application of mulch. Additionally, through biomass cultivation, soil fertility can be improved and water conservation can be achieved. A benchmarking system should be utilised to measure water usage and scarcity.

ACKNOWLEDGEMENT

We express our profound gratitude to the Directorate General of Higher Education, Ministry of Education and Culture, Republic of Indonesia (DRTPM), Universitas Islam Riau, and all individuals and organisations who have contributed to the completion of this research project.

REFERENCES

Afandi, A. M., Zulkifli, H., Nur Zuhaili H. A. Z. A., Norliyana, Z. Z., Hisham, H., Saharul, A. M., Dzulhelmi, M. N., & Vu Thanh, T. A. (2022). Oil palm water requirement and the need for irrigation in dry Malaysian areas. *Journal of Oil Palm Research*, *35*(3), 391–405. https://doi.org/https://doi.org/10.21894/jopr.2022.0052

Ahmad, S. W., Purwanto, M. Y. J., Sapei, A., & Widiatmaka, N. (2021). Dynamic models of water conservation in sustainable palm oil plantations. *Journal of Physics: Conference Series*, *1899*(1), 012011. https://doi.org/10.1088/1742-6596/1899/1/012011

Akram, H., Levia, D. F., Herrick, J. E., Lydiasari, H., & Schütze, N. (2022). Water requirements for oil palm grown on marginal lands: A simulation approach. *Agricultural Water Management*, *260*, 107292. https://doi.org/10.1016/j.agwat.2021.107292

Altobelli, F., Giudice, T. D., & Marta, A. D. (2019). Adopting irrigation advisory services for water footprint estimation to improving biodiversity conservation: A European survey. *Italian Review of Agricultural Economics*, *74*(3), 23–28. https://doi.org/https://doi.org/10.13128/rea-11209

Altobelli, F., Lupia, F., Falanga Bolognesi, S., De Michele, C., D'Urso, G., Vuolo, F., & Dalla Marta, A. (2015) Crop water footprint: A methodological approach for its estimation based on irrigation advisory services data.

Water footprint application for water resources management in agriculture. *Italian Journal of Agrometeorology, Special Issue*, 110–116.

Apresian, S. R., Tyson, A., Varkkey, H., Choiruzzad, S. A. B., & Indraswari, R. (2020). Palm oil development in Riau, Indonesia: Balancing economic growth and environmental protection. *Nusantara: An International Journal of Humanities and Social Sciences*, *2*(1), 1–29. https://doi.org/10.6936/NIJHSS.202006_2(1).0001

Badan Standarisasi Nasional. (2015). *SNI 6728.1:2015 Penyusunan neraca spasial sumber daya alam – Bagian 1: Sumber daya air* [Composition of natural resource spatial balance – Part 1: Water resources]. Badan Standarisasi Nasional.

Comte, I., Colin, F., Grünberger, O., Whalen, J. K., Harto Widodo, R., & Caliman, J.-P. (2015). Watershed-scale assessment of oil palm cultivation impact on water quality and nutrient fluxes: A case study in Sumatra (Indonesia). *Environmental Science and Pollution Research*, *22*(10), 7676–7695. https://doi.org/10.1007/s11356-015-4359-0

Cruz-Pérez, N., Santamarta, J. C., & Álvarez-Acosta, C. (2023). Water footprint of representative agricultural crops on volcanic islands: The case of the Canary Islands. *Renewable Agriculture and Food Systems*, *38*, e36. https://doi.org/10.1017/S1742170523000303

Daundi, K., Langsa, M. H., & Sirampun, A. D. (2022). Pengaruh pemanfaatan limbah cair pabrik kelapa sawit terhadap kualitas air pada lahan kelapa sawit PT. PMP di Kabupaten Maybrat [The effect of using palm oil mill effluent on water quality in palm oil land PT. PMP in Maybrat District]. *Jurnal Natural*, *17*(2), 85–96. https://doi.org/10.30862/jn.v17i2.148

Dermoredjo, S. K., Darmawan, D. H. A., Sumedi, Mutaqin, Dani, F. Z. D. P., Yusuf, E. S., Pasaribu, S. M., Sayaka, B., Wardana, I. P., Adnyana, I. M. O., Estiningtyas, W., & Antriyandarti, E. (2025). The global sway of Indonesian palm oil: An export analysis. *Journal of Agriculture and Food Research*, 22, 102064. https://doi.org/10.1016/j.jafr.2025.102064

Dislich, C., Keyel, A. C., Salecker, J., Kisel, Y., Meyer, K. M., Auliya, M., Barnes, A. D., Corre, M. D., Darras, K., Faust, H., Hess, B., Klasen, S., Knohl, A., Kreft, H., Meijide, A., Nurdiansyah, F., Otten, F., Pe'er, G., Steinebach, S., … Wiegand, K. (2017). A review of the ecosystem functions in oil palm plantations, using forests as a reference system. *Biological Reviews*, *92*(3), 1539–1569. https://doi.org/10.1111/brv.12295

Dong, H., Zhang, L., Geng, Y., Li, P., & Yu, C. (2021). New insights from grey water footprint assessment: An industrial park level. *Journal of Cleaner Production*, *285*, 124915. https://doi.org/10.1016/j.jclepro.2020.124915

Dos Santos, M. R. , Donato, S. L. R., Magalhães, D. B., & Cotrim, M. P. (2019). Precocity, yield and water-use efficiency of banana plants under planting densities and irrigation depths, in semiarid region. *Pesquisa Agropecuária Tropical*, *49*, 1–10. https://doi.org/10.1590/1983-40632019v4953036

Erniwati, E., Zuhud, E. A. M., Anas, I., Sunkar, A., & Santosa, Y. (2017). Independent smallholder oil palm expansion and its impact on deforestation: Case study in Kampar District, Riau Province, Indonesia. *Jurnal Manajemen Hutan Tropika (Journal of Tropical Forest Management)*, *23*(3), 119–127. https://doi.org/10.7226/jtfm.23.3.119

Fotia, K., & Tsirogiannis, I. (2023). Water footprint score: A practical method for wider communication and assessment of water footprint performance. *ECWS-7 2023*, 71. https://doi.org/10.3390/ECWS-7-14311

Gandhi, P., & Fumie, T. (2023). Differences in organization structure and the supply chain of private with state-owned palm oil mills in North Sumatra, Indonesia. *E3S Web of Conferences*, *454*, 02025. https://doi.org/10.1051/e3sconf/202345402025

Gheewala, S., Silalertruksa, T., Nilsalab, P., Mungkung, R., Perret, S., & Chaiyawannakarn, N. (2014). Water footprint and impact of water consumption for food, feed, fuel crops production in Thailand. *Water*, *6*(6), 1698–1718. https://doi.org/10.3390/w6061698

Gómez, A. M., Parra, A., Pavelsky, T. M., Wise, E., Villegas, J. C., & Meijide, A. (2023a). Ecohydrological impacts of oil palm expansion: A systematic review. *Environmental Research Letters*, *18*(3), 033005. https://doi.org/10.1088/1748-9326/acbc38

Guntoro, Lisnawita, Zamzami, & Setiawan, D. (2022). Prediction of palm oil production in Riau Province using the single exponential smoothing method. *IOP Conference Series: Earth and Environmental Science*, *1041*(1), 012055. https://doi.org/10.1088/1755-1315/1041/1/012055

Hariyanti, F., Syahza, A., Zulkarnain, & Nofrizal. (2022). Sustainability of the palm oil industry: An empirical study of the development of sustainable oil palm in Bengkalis Regency, Indonesia. *International Journal of Sustainable Development and Planning*, *17*(1), 109–118. https://doi.org/10.18280/ijsdp.170110

Heidari, A., Mayer, A., Watkins, D., & Castillo, M. M. (2020). Hydrologic impacts and trade-offs associated with developing oil palm for bioenergy in Tabasco, Mexico. *Journal of Hydrology: Regional Studies*, *31*, 100722. https://doi.org/10.1016/j.ejrh.2020.100722

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2009). *Water footprint manual*. Water Footprint Network.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The water footprint assessment manual*. Routledge. https://doi.org/https://doi.org/10.4324/9781849775526

Huang, J., Xu, C., Ridoutt, B., & Chen, F. (2015). Reducing agricultural water footprints at the farm scale: A case study in the Beijing Region. *Water*, *7*(12), 7066–7077. https://doi.org/10.3390/w7126674

Husin, S., Wijaya, C., Ghafur, A. H. S., & Machmud, T. M. Z. (2023). Sustainable palm oil industry: A literature study with bibliometric analysis. *Indonesian Interdisciplinary Journal of Sharia Economics (IIJSE)*, *6*(3), 2269–2293. https://doi.org/10.31538/iijse.v6i3.3871

Ichwan, N., Fajra, A. M., Marbun, S. M., & Sumono. (2019). Crop coefficient and water requirement for oil palm (*Elaeis guineensis* Jacq.) on the nursery based on radiation evaporation method. *IOP Conference Series: Earth and Environmental Science*, *260*(1), 012041. https://doi.org/10.1088/1755-1315/260/1/012041

Indriyadi, W. (2022). Palm oil plantation in Indonesia: A question of sustainability. *Salus Cultura: Jurnal Pembangunan Manusia Dan Kebudayaan*, *2*(1), 1–10. https://doi.org/10.55480/saluscultura.v2i1.40

Jaya, A., Birawa, C., Adji, F. F., Anwar, M., & Banuwa, I. S. (2018). Erosion and surface runoff on forest and oil palm plantation in Jalemu Watershed, Gunung Mas Regency, Central Kalimantan Province. *Journal of Tropical Soils*, *23*(3), 151–159. https://doi.org/10.5400/jts.2018.v23i3.151

Jeswani, H. K., & Azapagic, A. (2011). Water footprint: Methodologies and a case study for assessing the impacts of water use. *Journal of Cleaner Production*, *19*(12), 1288–1299. https://doi.org/10.1016/j.jclepro.2011.04.003

Khanh, P. T., & Ngoc, T. T. H. (2022). Estimation of crop water demand for rice by the FAO Penman Monteith evapotranspiration model. *Sarhad Journal of Agriculture*, *38*(5), 158–165. https://doi.org/10.17582/journal.sja/2022.38.5.158.165

Kospa, H. S. D., Lulofs, K. R. D., & Asdak, C. (2017). Estimating water footprint of palm oil production in PTP Mitra Ogan Baturaja, South Sumatera. *International Journal on Advanced Science, Engineering and Information Technology*, *7*(6), 2115. https://doi.org/10.18517/ijaseit.7.6.2451

Lovarelli, D., Bacenetti, J., & Fiala, M. (2016). Water footprint of crop productions: A review. *Science of the Total Environment*, *548–549*, 236–251. https://doi.org/10.1016/j.scitotenv.2016.01.022

Madrid-López, C. (2023). Water footprint. In *Elgar encyclopedia of ecological economics* (pp. 517–521). Edward Elgar Publishing. https://doi.org/10.4337/9781802200416.ch90

Manoli, G., Meijide, A., Huth, N., Knohl, A., Kosugi, Y., Burlando, P., Ghazoul, J., & Fatichi, S. (2018). Ecohydrological changes after tropical forest conversion to oil palm. *Environmental Research Letters*, *13*(6), 064035. https://doi.org/10.1088/1748-9326/aac54e

Marston, L., Ao, Y., Konar, M., Mekonnen, M. M., & Hoekstra, A. Y. (2018). High-resolution water footprints of production of the United States. *Water Resources Research*, *54*(3), 2288–2316. https://doi.org/10.1002/2017WR021923

Materu, S., Shukla, S., Sishodia, R., Tarimo, A., & Tumbo, S. (2018). Water use and rice productivity for irrigation management alternatives in Tanzania. *Water*, *10*(8), 1018. https://doi.org/10.3390/w10081018

Meiwanda, G., Syahza, A., & Isnaniah, I. (2022). The existence of oil palm plantations and challenges for the Riau Provincial Government. *Ilomata International Journal of Social Science*, *3*(4), 399–408. https://doi.org/10.52728/ijss.v3i4.611

Mekonnen, M. M., & Gerbens-Leenes, W. (2020). The water footprint of global food production. *Water (Switzerland)*, *12*(10), 2696. https://doi.org/10.3390/w12102696

Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*, *15*(5), 1577–1600. https://doi.org/10.5194/hess-15-1577-2011

Merten, J., Röll, A., Guillaume, T., Meijide, A., Tarigan, S., Agusta, H., Dislich, C., Dittrich, C., Faust, H., Gunawan, D., Hein, J., Hendrayanto, Knohl, A., Kuzyakov, Y., Wiegand, K., & Hölscher, D. (2016). Water scarcity and oil palm expansion: Social views and environmental processes. *Ecology and Society*, *21*(2), 5. https://doi.org/10.5751/ES-08214-210205

Mialyk, O., Schyns, J. F., Booij, M. J., Su, H., Hogeboom, R. J., & Berger, M. (2024). Water footprints and crop water use of 175 individual crops for 1990-2019 simulated with a global crop model. *Scientific Data*, *11*(1), 206. https://doi.org/10.1038/s41597-024-03051-3

Ministry of Public Works Directorate General of Natural Resources. (2013). *Irrigation Planning Standards*.

Mohammad Sabli, N. S., Zainon Noor, Z., Kanniah, K. A., Kamaruddin, S. N., & Mohamed Rusli, N. (2017). Developing a methodology for water footprint of palm oil based on a methodological review. *Journal of Cleaner Production*, *146*, 173–180. https://doi.org/10.1016/j.jclepro.2016.06.149

Mungkalasiri, J., Wisansuwannakorn, R., & Paengjuntuek, W. (2015). Water footprint evaluation of oil palm fresh fruit bunches in Pathumthani and Chonburi (Thailand). *International Journal of Environmental Science and Development*, *6*(6), 455–459. https://doi.org/10.7763/IJESD.2015.V6.636

Murphy, D. J., Goggin, K., & Paterson, R. R. M. (2021). Oil palm in the 2020s and beyond: Challenges and solutions. *CABI Agriculture and Bioscience*, *2*(1), 39. https://doi.org/10.1186/s43170-021-00058-3

Nainggolan, S., Yanita, M., & Leonardo, M. (2021). Factors that affect the productivity of palm oil plantations self-help patterns in Jambi Province. *Randwick International of Social Science Journal*, *2*(4), 404–410. https://doi.org/10.47175/rissj.v2i4.321

Noerrizki, A. M., Putri, T. K., & Ernah, E. (2019). Utilization of palm oil waste as bioenergy. *Sustinere: Journal of Environment and Sustainability*, *3*(1), 48–66. https://doi.org/10.22515/sustinere.jes.v3i1.77

Numata, I., Elmore, A. J., Cochrane, M. A., Wang, C., Zhao, J., & Zhang, X. (2022). Deforestation, plantation-related land cover dynamics and oil palm age-structure change during 1990-2020 in Riau Province, Indonesia. *Environmental Research Letters*, *17*(9), 094024. https://doi.org/10.1088/1748-9326/ac8a61

Riajaya, P. D., & Kadarwati, F. T. (2022). Water use efficiency of sugarcane clones under rainfed condition. *IOP Conference Series: Earth and Environmental Science*, *974*(1), 012029. https://doi.org/10.1088/1755-1315/974/1/012029

Safitri, L., Hermantoro, H., Purboseno, S., Kautsar, V., Saptomo, S., & Kurniawan, A. (2018a). Water footprint and crop water usage of oil palm (*Elaeis guineensis*) in Central Kalimantan: Environmental sustainability indicators for different crop age and soil conditions. *Water*, *11*(1), 35. https://doi.org/10.3390/w11010035

Safitri, L., Kautsar, V., Purboseno, S., Wulandari, R. K., & Ardiyanto, A. (2018b). Water footprint analysis of oil palm (case study of the Pundu Region, Central Borneo). *International Journal of Oil Palm*, *1*(3), 95–102.

Safitri, L., Hermantoro, H., Kautsar, V., Suparyanto, T., Hidayat, A. A., & Pardamean, B. (2022). Sustainability of the water footprint of various soil types on oil palm plantations. *IOP Conference Series: Earth and Environmental Science*, *998*(1), 012004. https://doi.org/10.1088/1755-1315/998/1/012004

Safriyana, S., Marimin, M., Anggraeni, E., & Sailah, I. (2021). Spatial-based model for oil palm plantation suitability rating and its smallholder farmers' competitiveness: A case study at Kampar Regency, Riau Province, Indonesia. *Journal of Science and Technology Policy Management*, *12*(2), 283–308. https://doi.org/10.1108/JSTPM-03-2020-0066

Santi, L. P., Ardiyanto, A., Kurniawan, A., Prabowo, L. A., & Sebastian, I. (2021). Improvement of water and nutrient efficiencies oil palm through bio-silicic acid application. *E-Journal Menara Perkebunan*, *89*(1), 26–36. https://doi.org/10.22302/iribb.jur.mp.v89i1.409

Santosa, E., Stefano, I. M., Tarigan, A. G. G., Wachjar, A., Zaman, S., & Agusta, A. H. (2018). Tree-based water footprint assessment on established oil palm plantation in North Sumatera, Indonesia. *Jurnal Agronomi Indonesia (Indonesian Journal of Agronomy)*, *46*(1), 111. https://doi.org/10.24831/jai.v46i1.13665

Santosh, D. T., & Tiwari, K. N. (2019). Estimation of water requirement of banana crop under drip irrigation with and without plastic mulch using dual crop coefficient approach. *IOP Conference Series: Earth and Environmental Science*, *344*(1), 012024. https://doi.org/10.1088/1755-1315/344/1/012024

Setiajiati, F., Nurrochmat, D. R., Van Assen, B. W., & Purwawangsa, H. (2024). Current status of Indonesia’s palm oil products and their competitiveness in the global market. *IOP Conference Series Earth and Environmental Science*, *1379*(1), 012022. https://doi.org/10.1088/1755-1315/1379/1/012022

Sharma, S. K., Baral, H., Laumonier, Y., Okarda, B., Komarudin, H., Purnomo, H., & Pacheco, P. (2018). *An analysis of multiple ecosystem services under future oil palm expansion scenarios in Central and West Kalimantan, Indonesia*. (CIFOR Occasional Paper No. 187).Center for International Forestry Research (CIFOR). https://doi.org/10.17528/cifor/006953

Subramaniam, V., & Hashim, Z. (2018). Charting the water footprint for Malaysian crude palm oil. *Journal of Cleaner Production*, *178*, 675–687. https://doi.org/10.1016/j.jclepro.2018.01.061

Suharyanti, N. A., Mizuno, K., & Sodri, A. (2020). The effect of water deficit on inflorescence period at palm oil productivity on peatland. *E3S Web of Conferences*, *211*, 05005. https://doi.org/10.1051/e3sconf/202021105005

Sukarman, S., Saidy, A. R., Rusmayadi, G., Adriani, D. E., Primananda, S., Suwardi, S., Wirianata, H., & Fitriana, C. D. A. (2022). Effect of water deficit of ultisols, entisols, spodosols, and histosols on oil palm productivity in Central Kalimantan. *SAINS TANAH - Journal of Soil Science and Agroclimatology*, *19*(2), 180. https://doi.org/10.20961/stjssa.v19i2.65455

Sumarga, E., Hein, L., Hooijer, A., & Vernimmen, R. (2016). Hydrological and economic effects of oil palm cultivation in Indonesian peatlands. *Ecology and Society*, *21*(2), art52. https://doi.org/10.5751/ES-08490-210252

Suttayakul, P., H-Kittikun, A., Suksaroj, C., Mungkalasiri, J., Wisansuwannakorn, R., & Musikavong, C. (2016). Water footprints of products of oil palm plantations and palm oil mills in Thailand. *Science of the Total Environment*, *542*, 521–529. https://doi.org/10.1016/j.scitotenv.2015.10.060

Syahza, A. (2019). The potential of environmental impact as a result of the development of palm oil plantation. *Management of Environmental Quality: An International Journal*, *30*(5), 1072–1094. https://doi.org/10.1108/MEQ-11-2018-0190

Titisari, P. W., Elfis, E., Zen, I. S., Chahyana, I., Permatasari, T., Maryanti, A., & Dalilla, F. (2024a). The role of Kampar Watershed in achieving sufficient rice production and sustaining agriculture. *Water Supply*, *24*(2), 480–496. https://doi.org/10.2166/ws.2024.016

Titisari, P. W., Elfis, Maryanti, A., Chahyana, I., Permatasari, T., & Dalilla, F. (2024b). Grey water footprint of crop in Riau Province. *IOP Conference Series: Earth and Environmental Science*, *1297*(1), 012024. https://doi.org/10.1088/1755-1315/1297/1/012024

Titisari, P. W., Elfis, Chahyana, I., Permatasari, T., Dalilla, F., & Herza, D. P. S. B. (2025). Maize waterfootprint of Kampar Watershed to bolster sustainable agriculture in Indonesia. *IOP Conference Series: Earth and Environmental Science*, *1476* (1), 012021. https://doi.org/10.1088/1755-1315/1476/1/012021

Tuninetti, M., Ridolfi, L., & Laio, F. (2020). Ever-increasing agricultural land and water productivity: A global multi-crop analysis. *Environmental Research Letters*, *15*(9), 0940a2. https://doi.org/10.1088/1748-9326/abacf8

Utami, R., Kumala Putri, E. I., & Ekayani, M. (2017). Economy and environmental impact of oil palm palm plantation expansion (case study: Panyabungan Village, Merlung Sub-District, West Tanjung Jabung Barat District, Jambi). *Jurnal Ilmu Pertanian Indonesia*, *22*(2), 115–126. https://doi.org/10.18343/jipi.22.2.115

Wang, Q., Huang, K., Liu, H., & Yu, Y. (2023). Factors affecting crop production water footprint: A review and meta-analysis. *Sustainable Production and Consumption*, *36*, 207–216. https://doi.org/10.1016/j.spc.2023.01.008

Wasilul Lutfi, M., Baskoro, D. P. T., Anwar, S., & Pulunggono, H. B. (2021). Relation subsidence and water level of peatland cultivated with oil palm in Riau, Indonesia. *IOP Conference Series: Earth and Environmental Science*, *756*(1), 012028. https://doi.org/10.1088/1755-1315/756/1/012028

Watson-Hernández, F., Serrano-Núñez, V., Gómez-Calderón, N., & Pereira da Silva, R. (2022). Quantification and evaluation of water requirements of oil palm cultivation for different climate change scenarios in the central pacific of Costa Rica using APSIM. *Agronomy*, *13*(1), 19. https://doi.org/10.3390/agronomy13010019

Wenzel, A., Westphal, C., Ballauff, J., Berkelmann, D., Brambach, F., Buchori, D., Camarretta, N., Corre, M. D., Daniel, R., Darras, K., Erasmi, S., Formaglio, G., Hölscher, D., Iddris, N. A.-A., Irawan, B., Knohl, A., Kotowska, M. M., Krashevska, V., Kreft, H., … Grass, I. (2024). Balancing economic and ecological functions in smallholder and industrial oil palm plantations. *Proceedings of the National Academy of Sciences*, *121*(17), e2307220121. https://doi.org/10.1073/pnas.2307220121

Yanita, M., & Suandi. (2021). What factors determine the production of independent smallholder oil palm? *Indonesian Journal of Agricultural Research*, *4*(1), 39–46. https://doi.org/10.32734/injar.v4i1.5379

Yi, J., Gerbens-Leenes, P. W., & Aldaya, M. M. (2024). Crop grey water footprints in China: The impact of pesticides on water pollution. *Science of the Total Environment*, *935*, 173464. https://doi.org/10.1016/j.scitotenv.2024.173464

Yusara, A., Handoko, H., & Budianto, B. (2019). Water demand analysis of sugarcane based on crop simulation model (case study: Kediri Regency, East Java). *Agromet*, *33*(1), 30–40. https://doi.org/10.29244/j.agromet.33.1.30-40

Zulkefli, F., Syahlan, S., Bakar, M. A., Khalid, M. F., & Rakibe, I. (2020). Factors influencing labour productivity in oil palm estate. *International Journal of Academic Research in Business and Social Sciences*, *10*(4), 119–131. https://doi.org/10.6007/IJARBSS/v10-i4/7114