SAINS TANAH – Journal of Soil Science and Agroclimatology, 22(1), 2025, 220-230

SAINS TANAH – Journal of Soil Science and Agroclimatology

Journal homepage: http://jurnal.uns.ac.id/tanah

Estimation of water use efficiency (WUE) for efficient irrigation level of oil palm during the main nursery phase

Iput Pradiko[1]*, Rana Farrasati[1,2], Nuzul Hijri Darlan[1], Sumaryanto[1], Dhaffa Agung Thirafi[3]

[1] Department of Soil Science and Agronomy, Indonesian Oil Palm Research Institute (IOPRI), Medan, 20158, Indonesia
[2] Graduate Program of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE 68583-0915, USA
[3] Undergraduate Program of Agronomy, Faculty of Agriculture, Universitas Gadjah Mada, Yogyakarta, 55281, Indonesia

ARTICLE INFO

Keywords:
Biomass
Environmental
Evapotranspiration
Vegetative
Watering

Article history
Submitted: 2024-09-12
Revised: 2025-05-15
Accepted: 2025-05-28
Available online: 2025-06-28
Published regularly: June 2025

* *Corresponding Author*
Email address:
iputpradiko@gmail.com

ABSTRACT

The water requirement of oil palm depends on the growth phase (e.g., higher demand during vegetative expansion), environmental conditions (e.g., increased under high vapour pressure deficit), and agricultural practices (e.g., reduced demand through effective water management). Therefore, the water used for oil palm nurseries should be used efficiently to preserve environmental sustainability. The main objective of this research was to determine the water use efficiency (WUE) of oil palm during the main nursery phase. The study evaluated several irrigation strategies inside and outside the greenhouse, including fixed daily watering (two liters per seedling), irrigation based on actual evapotranspiration (ETa), rainfall-dependent watering, and no irrigation. In the outdoor treatments, one group of seedlings was irrigated according to ETa, but watering was withheld when daily rainfall exceeded five mm, while another group received two liters per day only when rainfall was below five mm. These two treatments showed the highest daily evapotranspiration rates, greater vegetative growth, and higher biomass accumulation compared to the other treatments. Notably, the ETa-based treatment was recorded as having the highest water use efficiency (WUE). This study concludes that water loss during evapotranspiration is the main determining factor for irrigation volume. Therefore, irrigation in oil palm nurseries should be based on ETa to improve efficiency and lower costs. These findings offer practical guidance for farmers or plantation management to support more sustainable and cost-effective irrigation practices.

How to Cite: Pradiko, I., Farrasati, R., Darlan, N.H., Sumaryanto, Thirafi, D.A. (2025). Estimation of water use efficiency (WUE) for efficient irrigation level of oil palm during the main nursery phase. Sains Tanah Journal of Soil Science and Agroclimatology, 22(1), 220-230. https://doi.org/10.20961/stjssa.v22i1.93336

1. INTRODUCTION

Rainfall plays a critical role in oil palm growth and development as it serves as the main source of water for physiological processes and fruit development. Water supply shortages can lead to yield reductions of up to 26% (Delgado et al., 2024). The oil palm grows optimally with rainfall of about 2000-2500 mm year^{-1} and without dry months (Corley & Tinker, 2015). The dry month criteria for oil palm are when the monthly rainfall is less than 60 mm month^{-1}. The drought stress on oil palm occurs when one or more of the following conditions occur: rainfall < 1250 mm year^{-1}, water deficit > 200 mm year^{-1}, dry months > 3 months year^{-1}, and the most extended non-raining day series (dry spell) > 20 days (Darlan et al., 2016). On the other hand, heavy rainfall of more than 3000 mm year^{-1} is also not optimal for oil palm plantations (Sujadi et al., 2020). Essentially, oil palm requires a minimum amount of rainfall equal to the water needed.

Plant water requirements are calculated based on the amount of water loss from plants through evapotranspiration (ETc), assuming that the plants are healthy, planted in an area with optimal soil moisture and fertility conditions, and have produced optimal yield (Ahmed et al., 2021). In oil palm, water requirements for mature plants range from 3.5 to 5.5 mm day^{-1} in the rainy season and 0.6-2.9 mm day^{-1} in the dry season (Carr, 2011; Murphy et al., 2021). Another study by Harahap and Darmosarkoro (1999) and Evizal et al. (2021) reported that an oil palm aged 6-7 years requires 4-4.65 mm of water day^{-1}. In immature plants, the average water requirement is 3.3 mm day^{-1} and around 1.85-2 mm day^{-1} of

STJSSA, p-ISSN 1412-3606 e-ISSN 2356-1424
http://dx.doi.org/10.20961/stjssa.v22i1.93336

water for the main nursery (MN) phase or the equivalent of 1-3 liters of water day^{-1} (Sigalingging et al., 2018).

Plant water requirements will vary greatly depending on the growth phase, environmental conditions, and the agronomic practices applied (Afandi et al., 2023; Trinugroho et al., 2024). Water availability will likely not be a limiting factor in areas with sufficient and relatively even rainfall throughout the year. Meanwhile, in areas with fluctuating rainfall with monsoonal rainfall types, water availability can be a limiting factor for oil palm growth and production (Darlan et al., 2016; Pradiko et al., 2016). With climate change, it is estimated that rainfall conditions in the tropics will fluctuate more (Christensen et al., 2013; Sianipar, 2021). Rainfall fluctuations will pose significant water management challenges in oil palm plantations. Prolonged dry periods may lead to water deficits stress, and yield reduction (Choukri et al., 2023; Darlan et al., 2016; Sukmawan et al., 2022), while excessive rainfall can result in waterlogging stress (Rivera-Mendes et al., 2016), nutrient leaching, and yield reduction. Therefore, efficient water use and adaptive management strategies, such as rainfall harvesting, soil moisture conservation, and proper irrigation timing, are essential to sustain yield and mitigate the risks associated with rainfall fluctuation.

In order to optimize water usage, it is crucial to understand water use efficiency (WUE) levels in certain crops. WUE is defined as the amount of water required to produce one unit of productivity or dry biomass (Hebbar et al., 2020). WUE identification can be used to find out which oil palm material is efficient in utilizing water (Noor & Harun, 2007; Pangaribuan & Akoeb, 2022). A positive correlation has been reported between the amount of available water absorbed by the oil palm and the yield produced (Noor & Harun, 2007). A higher WUE indicates that oil palm can produce more biomass or yield with the same or less water. Conversely, WUE decreases under drought stress or during periods of high vapor pressure deficit (VPD), when oil palm lose more water through transpiration than they can utilize for biomass production (Monzon et al., 2022). In such conditions, oil palm produce less dry matter and may experience reduced bunch number or weight, thereby lowering overall yield. Given the dynamic rainfall patterns and potential future water shortages, improving oil palm WUE is essential for maintaining yield stability. Higher WUE can be achieved through proper agronomic practices, genotype selection, and effective water management.

However, information on water use efficiency (WUE) for oil palm is still minimal and has yet to be applied in the management of oil palm cultivation in Indonesia. One stage closely related to the application of WUE is the oil palm nursery stage. To date, irrigation has been the main water source for oil palm nursery. In Indonesia, irrigation in oil palm main nursery is carried out at a constant level, providing two liters of water per seedling per day, if there is no rainfall (Agele et al., 2022; Muhamad et al., 2014). Moreover, Sukmawan et al. (2022) mentioned that irrigation for oil palm seedlings is between 1.5 and 2.1 liters per day. Although a range of irrigation volumes is provided, there is no explanation of the seedling age or the environmental conditions. This static approach contrasts with the scientific understanding that plant water needs vary with the growth phase, weather conditions, and soil moisture availability. Neglecting these variations may lead to over- or under-irrigation, affecting seedling growth.

This study aims to evaluate the WUE of oil palm seedlings in the main nursery (MN) stage by quantifying the relationship between daily actual evapotranspiration (ETa) and biomass accumulation under controlled irrigation conditions. Specifically, the research involves monitoring ETa using weighing technique and measuring seedling dry biomass over a defined growth period. WUE is determined based on the ETa and the biomass produced by the oil palm seedlings. The findings of this study are expected to assist oil palm nursery management by identifying the optimal watering volume required to achieve maximum vegetative growth with optimal water input. By understanding how much water the seedlings actually use in relation to their biomass production, oil palm planters can make data-driven irrigation decisions that reduce water waste, lower operational expenditure, and enhance seedling performance.

2. MATERIAL AND METHODS

2.1. Study site

The study was located in the oil palm seedlings area of Soil Physics Laboratory, Indonesian Oil Palm Research Institute (IOPRI), Medan, North Sumatra, Indonesia from 17th January 2020 to 16th April 2020. The research location has an equatorial rainfall pattern with average rainfall from 2013-2018 of about 2164 mm/year. The rainfall peak occurred in May and September. The average air temperature ranges from 27°C to 28°C. The maximum temperature was up to 38°C, and the minimum temperature was around 22°C.

Table 1. Irrigation treatments employed in the study

Treatments Code	Locations	Irrigation Treatments
KN+	Greenhouse	Watered with 2 liters per day
KTN	Outside greenhouse	Watered with 2 liters per day if rainfall was less than 5 mm
N1	Greenhouse	Watered according to daily water loss (evapotranspiration-based)
TN1	Outside greenhouse	Watered based on daily water loss; not watered if rainfall > 5 mm
N2	Greenhouse	Watered according to rainfall
TN2	Outside greenhouse	Relied solely on rainfall as the water source
KN-	Greenhouse	Not watered during the study

The average humidity was 80%, with low humidity conditions, particularly in the middle of the year (June-August). Average solar radiation fluctuated from 13.69 to 20.07 MJ m^{-2}. The average monthly wind speed was generally relatively high at the beginning of the year (January to March).

2.2. Experimental design

The research was conducted on the six months old oil palm seedlings grown in plastic pots with a diameter of 40 cm and a height of 32 cm. The bottom of the pot is lined with a plastic container to prevent oil palm seedlings' roots from growing over the soil under the pots. This study was conducted using a randomized block design with seven treatments, which are explained in Table 1. Watering 2 liters per day is the conventional irrigation level practiced during the oil palm main nursery (MN) phase in Malaysia and Indonesia. Each treatment consisted of three oil palm seedlings, for a total of 21 palms.

2.3. Parameters

The experimental parameters were daily actual evapotranspiration (ETa) and oil palm vegetative growth (height, trunk diameter, and the number of fronds) which were observed once a week. In the beginning, watering was carried out slowly and evenly into the pot until the soil was saturated. The pot weights (including seedlings and soil) from all treatments were then weighed using a digital scale in grams (Ws). Next, the pot was weighed daily (Wa), and the difference between Ws-Wa was the actual daily evapotranspiration (ETa). Daily actual ET values were estimated in liters. Then this value was converted to kg m^{-2} to determine the value of water use efficiency (WUE).

The measurement of the dry biomass was carried out at the end of the research. The seedling's biomass increment was estimated using the allometric method. This method estimated the dry biomass increment based on vegetative variables, which was previously conducted by Aholoukpè et al. (2013). Initially, each palm's height and trunk diameter were used as independent variables in the model to estimate the dry biomass of each palm's parts. After that, the best model with the highest coefficient of determination was selected. Based on the analysis results, equations used to estimate the upper part biomass from seedlings inside and outside of the greenhouse have a coefficient determination (R^2) of about 81.43% and 85.45%, respectively.

Moreover, estimating the roots biomass is more challenging. The highest coefficient determination to estimate roots and shoots biomass was only 39.11%. The equations used are Equation 1, 2, and 3.

$$y\ shoots_1 = -56.273 + 2.9214t - 24.078d \quad [1]$$

$$y\ shoots_2 = -489.73 + 5.50047t + 26.6828d \quad [2]$$

$$y\ roots = 0.3611\ yshoot + 14.607 \quad [3]$$

where y $shoots_1$ was shoot biomass from seedlings in the greenhouse, y $shoots_2$ was shoot biomass from seedlings outside the greenhouse, t was seedlings' height, d was trunk diameter, y roots was a root biomass, y shoots was a shoot biomass (from seedlings inside and outside greenhouse).

WUE analysis was performed by plotting the daily accumulated evapotranspiration (kg m^{-2}) as the x-axis with the dry biomass accumulation (g m^{-2}) as the y-axis for each treatment. Furthermore, a linear equation was generated. From each of these linear models, the gradient value would be obtained. The gradient value represented the WUE (g kg^{-1}). This method of determining WUE has been widely used in several studies, including research conducted by Hatfield and Dold (2019). WUE represented the addition of 1 gram of biomass with the addition of 1 kg of water. Therefore, the more efficient the plant utilizes water, the higher the WUE.

2.4. Data analysis

Data analysis and interpretation were performed using R-software version 4.0.4, R-studio version 1.4.1106, and Google Colab. The effect of irrigation on the growth rate, daily evapotranspiration, and WUE were descriptively analyzed. Meanwhile, the ANOVA test with a significant level of 5% was carried out to determine whether treatment affected the dry biomass of MN seedlings.

3. RESULTS

3.1. Vegetative growth

The results of irrigation treatments on the seedling's vegetative performance are shown in Figure 1, and the visual condition is depicted in Figure 2. Figure 1 illustrates six graphs showing the effects of various irrigation treatments on different growth parameters of 7 to 9-month-old oil palm seedlings. Each graph displays changes in a specific variable over the weeks of observation for each irrigation treatment. Figure 1A shows the increase in plant height over time. Treatments involving regular watering demonstrated significant height growth, whereas KN- (no watering) showed stunted growth. Furthermore, treatments with consistent irrigation, such as KN+ and N1, displayed steady height increments, while the KN- treatment had lower and more erratic increments. Consistent irrigation treatments (KN+, N1, TN1) showed a steady increase in frond numbers, while the KN- treatment had lower and more erratic increments.

Consistent irrigation treatments (KN+, N1, TN1) showed a steady increase in frond numbers, while KN- (without watering) experienced a decline. Figure 1C displays the weekly increase in frond numbers. Seedlings with regular watering experienced more consistent frond additions, while those without water showed more fluctuation. Moreover, regularly watered seedlings (KN+, N1) showed more stable trunk diameter growth than KN-, with almost no diameter change (Fig. 1E). Figure 1F presents the weekly increase in trunk diameter. Treatments with consistent watering (KN+, N1) showed higher increments, while the KN- seedlings showed minimal growth.

Overall, Figure 1 demonstrates that oil palm seedlings receiving regular irrigation, both inside and outside the greenhouse, exhibited better growth in height, frond number, and trunk diameter than seedlings that were not watered (KN-). The seedlings without irrigation survived for approximately two weeks. After that, the seedlings began to die. This highlights the importance of adequate irrigation for optimal growth, especially during the early developmental stages of oil palm seedlings.

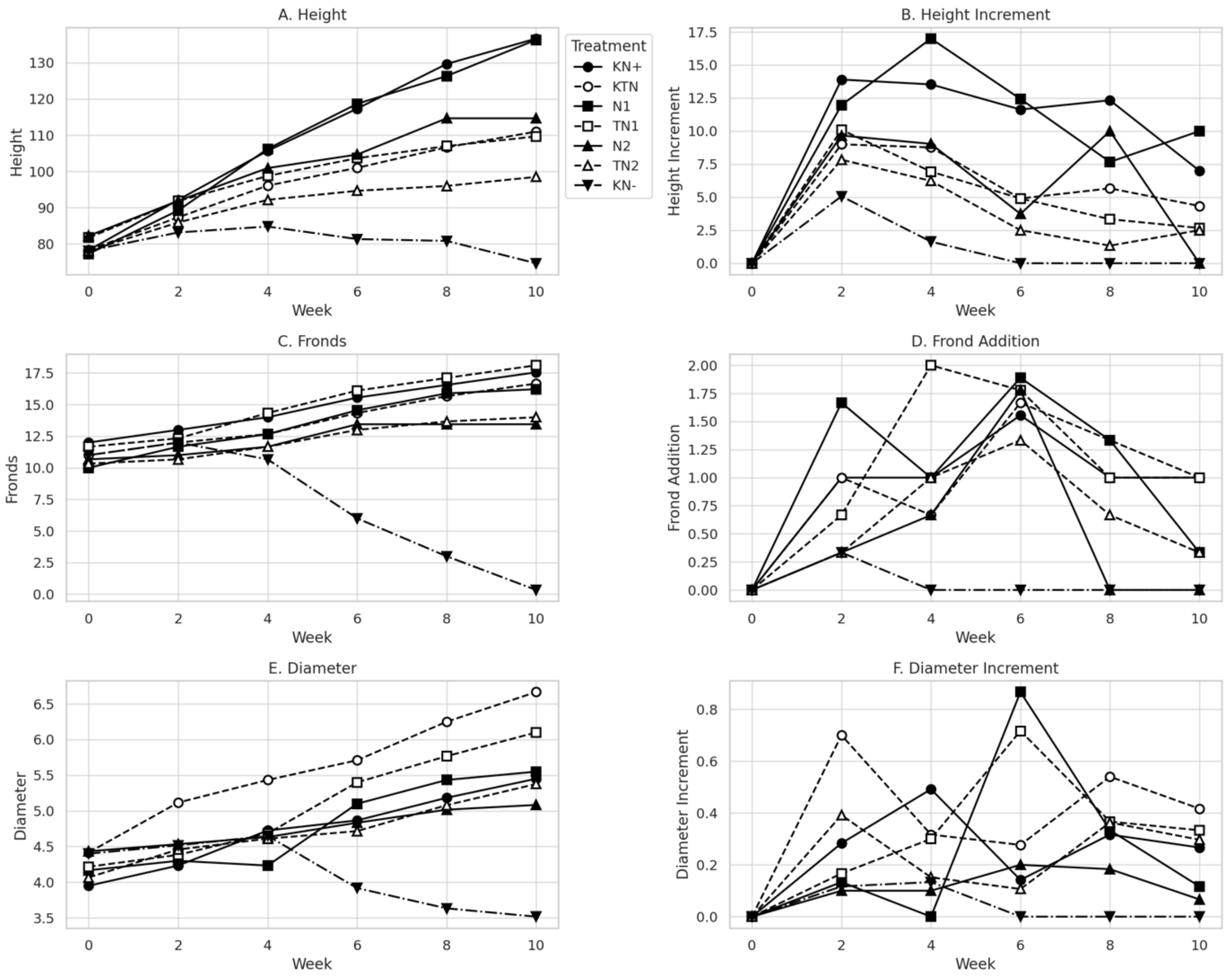


Figure 1. Oil palm height in cm (A), height increment in cm (B), number of fronds (C), fronds number add (D), trunk diameter in cm (E), and diameter increment in cm (F) of oil palm age 7-9 months with irrigation treatments. Symbols shown in the legend represent different irrigation treatments. KN+ is oil palm seedlings grown in a greenhouse watered with 2 liters day^{-1}; KN- is seedlings grown in a greenhouse and not watered during the study; N1 is seedlings grown in the greenhouse and watered according to water loss; N2 is seedlings grown in the greenhouse and watered according to rainfall; TN1 is seedlings grown outside the greenhouse and watered according to the water loss and not watered when it rained >5 mm; TN2 is seedlings grown outside the greenhouse, only use rainfall as the source of water; and KTN is watered 2 liters day^{-1} when the rainfall is <5 mm.

Figure 2 visually compares oil palm seedlings subjected to various irrigation treatments. The seedlings exhibit noticeable differences in growth and health based on the watering regimes they were subjected to during the experiment. Seedlings with consistent irrigation (N1, KN+, TN1, KTN) exhibit healthier growth and larger frond numbers, while those with insufficient water, especially KN-, show poor development. This visual reinforces the critical role of water management in promoting the healthy growth of oil palm seedlings.

3.2. Daily evapotranspiration

The boxplot (Fig. 3) visualizes oil palm seedlings' daily water consumption (ETa, in liters per day) under different irrigation treatments. Each treatment is represented along the x-axis, and the water use (ETa) is displayed on the y-axis, ranging from 0 to 2 liters day^{-1}. The boxplots show the distribution of water use across several measurements for each treatment, while the red numbers and dots indicate the mean value for each treatment. The N1 treatment shows a mean ETa of 0.89 liters day^{-1}, indicating that the seedlings watered based on water loss use a moderate amount of water. The distribution of data points is relatively tight, showing consistent water use with a few outliers at both high and low extremes.

The seedlings in N2 treatment, watered according to rainfall, have a mean ETa of 0.37 liters day^{-1}, showing significantly lower water use compared to N1. The data distribution is also narrower, suggesting more consistent but lower water availability. With a mean ETa of 0.91 liters day^{-1}, seedlings in KN+ treatment (watered with 2 liters day^{-1} in the greenhouse) demonstrate high water use, comparable to N1. The distribution is slightly wider, indicating some variation in water use, but the treatment provides enough water for healthy growth. Otherwise, the seedlings without any watering in the greenhouse (KN-) have a very low mean ETa of 0.36 liters day^{-1}, reflecting minimal water consumption. This indicates extreme water stress and limited water availability, leading to the poor condition of these seedlings.

Figure 2. Vegetative performance of oil palm seedlings aged 7-9 months with different irrigation treatments. KN+ is oil palm seedlings grown in a greenhouse watered with 2 liters day^{-1}; KN- is seedlings grown in a greenhouse and not watered during the study; N1 is seedlings grown in the greenhouse and watered according to water loss; N2 is seedlings grown in the greenhouse and watered according to rainfall; TN1 is seedlings grown outside the greenhouse and watered according to the water loss and not watered when it rained >5 mm; TN2 is seedlings grown outside the greenhouse, only use rainfall as the source of water; and KTN is watered 2 liters day^{-1} when the rainfall is <5 mm. III represents replication number three.

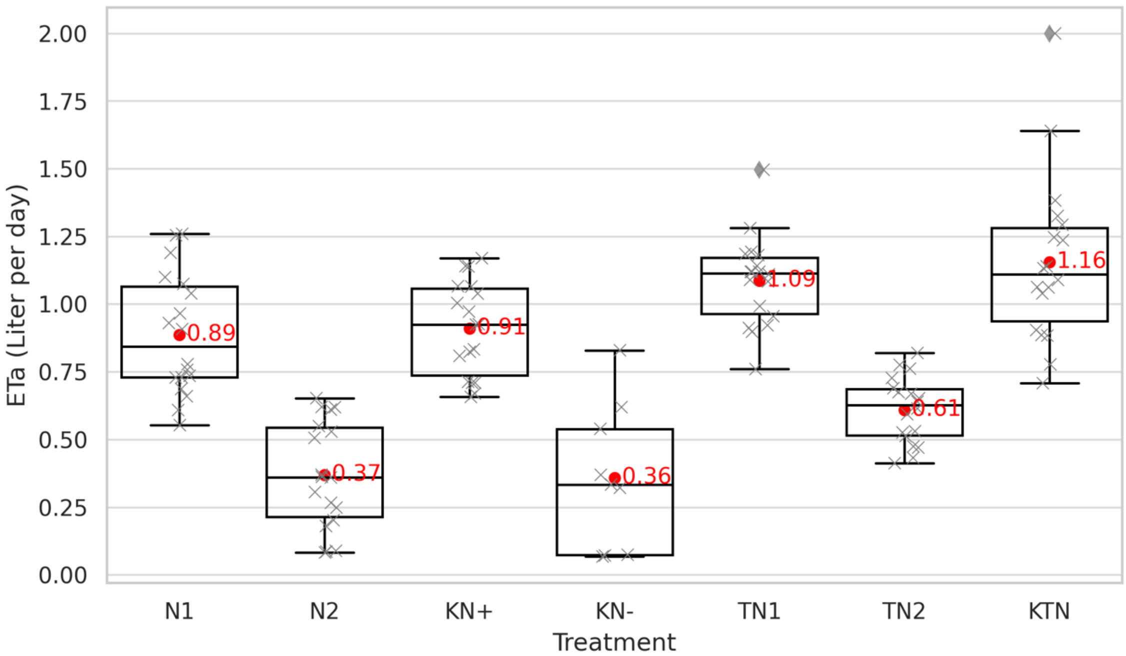
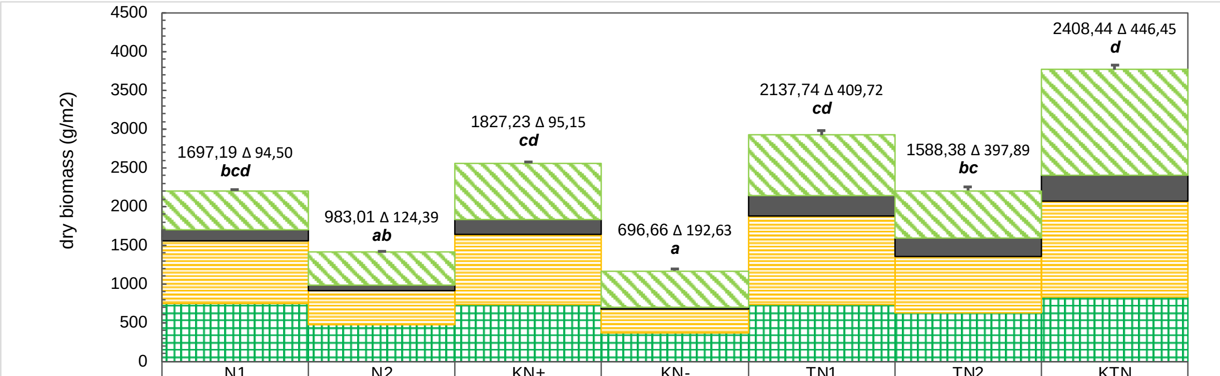


Figure 3. Daily evapotranspiration (liter per day) of oil palm seedlings with irrigation treatments. KN+ is oil palm seedlings grown in a greenhouse watered with 2 liters day^{-1}; KN- is seedlings grown in a greenhouse and not watered during the study; N1 is seedlings grown in the greenhouse and watered according to water loss; N2 is seedlings grown in the greenhouse and watered according to rainfall; TN1 is seedlings grown outside the greenhouse and watered according to the water loss and not watered when it rained >5 mm; TN2 is seedlings grown outside the greenhouse, only use rainfall as the source of water; and KTN is watered 2 liters day^{-1} when the rainfall is <5 mm.

Seedlings grown outside the greenhouse (TN1), watered based on water loss and not watered during rain (>5 mm), show a mean ETa of 1.09 liters day^{-1}. This is one of the highest water usages, indicating effective irrigation in this condition, with a relatively wide distribution of data points. Seedlings that rely solely on rainfall outside the greenhouse (TN2) show a mean ETa of 0.61 liters day^{-1}, which is lower than TN1. Moreover, the seedlings watered with 2 liters day^{-1} when rainfall is less than 5 mm (KTN) have the highest mean ETa of 1.16 liters day^{-1}, reflecting the most water use among all treatments.



	N1	N2	KN+	KN-	TN1	TN2	KTN
root	508.49	427.28	733.81	472.13	788.48	616.77	1362.00
bole	132.70	70.33	188.69	16.72	252.39	232.48	332.01
petiole	816.08	437.63	903.40	313.69	1150.21	721.60	1243.10
leaves	748.41	475.05	735.14	366.24	735.14	634.29	833.33

Figure 4. Dry biomass (g m^{-2}) of oil palm seedlings aged 9 months with different irrigation treatments. The fronds part was divided into petiole and leaves. The number on bar chart represents mean value. Means with different letters within the treatments are significantly different (least significant difference test at α = 0.05). KN+ is oil palm seedlings grown in a greenhouse watered with 2 liters day^{-1}; KN- is seedlings grown in a greenhouse and not watered during the study; N1 is seedlings grown in the greenhouse and watered according to water loss; N2 is seedlings grown in the greenhouse and watered according to rainfall; TN1 is seedlings grown outside the greenhouse and watered according to the water loss and not watered when it rained >5 mm; TN2 is seedlings grown outside the greenhouse, only use rainfall as the source of water; and KTN is watered 2 liters day^{-1} when the rainfall is <5 mm.

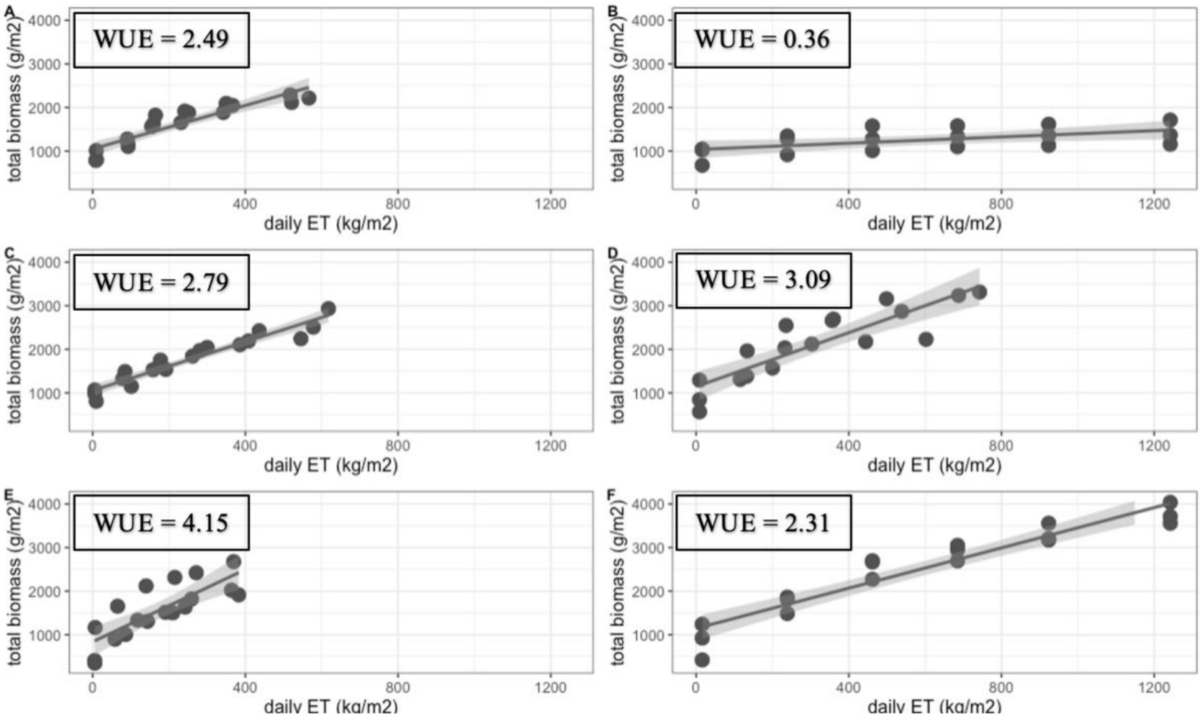


Figure 5. Water use efficiency of oil palm seedlings under N1 (A), N2 (B), KN+ (C), TN1 (D), TN2 (E), and KTN (F). KN+ is oil palm seedlings grown in a greenhouse watered with 2 liters day^{-1}; N1 is seedlings grown in the greenhouse and watered according to water loss; N2 is seedlings grown in the greenhouse and watered according to rainfall; TN1 is seedlings grown outside the greenhouse and watered according to the water loss and not watered when it rained >5 mm; TN2 is seedlings grown outside the greenhouse, only use rainfall as the source of water; and KTN is watered 2 liters day^{-1} when the rainfall is <5 mm. The KN- treatment, where seedlings were not watered in the greenhouse, was excluded from the WUE analysis. This is because the seedlings died after two weeks due to extreme water stress and lack of irrigation.

The boxplot highlights that irrigation treatments significantly impact the water consumption of oil palm seedlings. Treatments with consistent irrigation (KN+, TN1, KTN) show higher water use, which correlates with better growth, while treatments with minimal or no irrigation (KN-, N2) show much lower water use, reflecting water stress conditions. These results reinforce the importance of sufficient and well-managed irrigation for optimal seedling development.

3.3. Biomass production

The bar chart (Fig. 4) illustrates oil palm seedlings' dry biomass (g m^{-2}) distribution across different irrigation treatments. The stacked bars represent the total dry biomass, showing the contribution of various parts, such as roots, bole (trunk), petiole (leaf stalk), and leaves. The values are presented for each treatment, with total dry biomass indicated at the top of each bar and broken down into the four parts below the chart. Additionally, the letters (a, b, c, d) represent statistical groupings, with treatments sharing the same letter being statistically similar in terms of biomass.

Of all treatments, the irrigation treatments showed significantly different results on biomass production for ten weeks of study. Figure 4 shows how different irrigation treatments affect the dry biomass accumulation in various parts of the oil palm seedlings. Treatments with consistent and adequate watering (KTN, TN1) result in the highest total biomass, with roots and petioles being the largest contributors to the overall biomass. KTN produced the highest biomass with total biomass (roots and shoots) of about 3770.34 g m^{-2}, followed by TN1 with 2926.22 g m^{-2}. Meanwhile, the lowest biomass was produced by KN- treatments of about 1168.78 g m^{-2}, which is 31% lower compared to TN1. Oil palm seedlings subjected to no irrigation (KN-) accumulate significantly lower biomass, particularly in the bole and leaves, indicating poor growth due to water stress. Statistical groupings reveal significant differences in growth, with KTN and TN1 yielding the best results.

3.4. Water Use Efficiency (WUE)

Figure 5 represents the relationship between daily evapotranspiration (ET, in kg m^{-2}) and total dry biomass (g m^{-2}) for different oil palm seedling irrigation treatments. The water use efficiency (WUE), a measure of the biomass produced per unit of water used (g m^{-2} per kg m^{-2} of water), is highlighted in each plot. WUE is critical for understanding how efficiently plants convert water into biomass under varying irrigation conditions.

Figure 5A shows a positive correlation between daily ET and total biomass, indicating that seedlings in N1 treatment respond well to water usage. The WUE of 2.49 suggests that the seedlings are relatively efficient at converting water into biomass when watered based on water loss. The higher WUE compared to other treatments implies moderate water use combined with decent biomass production. Otherwise, Figure 5B shows a weak correlation between daily ET and biomass, with a low WUE of 0.36. It suggests that seedlings in this treatment (which rely on rainfall) use water inefficiently, likely due to inconsistent water availability. The very low WUE means that despite some water usage, biomass accumulation is minimal, reflecting suboptimal conditions for growth.

Figure 5C shows seedlings watered with 2 liters per day in the greenhouse (KN+), exhibiting a WUE of 2.79. The positive correlation between daily ET and biomass suggests that seedlings convert the water into biomass fairly efficiently in this controlled environment. Regular irrigation helps ensure the seedlings have a consistent water supply, leading to better growth outcomes.

Seedlings in TN1 treatment, grown outside the greenhouse and watered based on water loss but not irrigated when rainfall exceeds 5 mm, demonstrate a WUE of 3.09. This relatively high WUE indicates that the seedlings use irrigation and rainfall efficiently. The correlation between ET and biomass shows that this irrigation strategy promotes optimal water use, allowing the seedlings to grow efficiently with available water.

The seedlings under TN2, which rely solely on rainfall as their water source, exhibit the highest WUE of 4.15. This strong positive correlation between daily ET and biomass indicates that despite using only rainfall, the seedlings are highly efficient in converting available water into biomass. The high WUE suggests that seedlings under this treatment adapt well to the natural water supply, making the most out of limited water resources. Under conditions of short-term drought stress, plants will try to increase WUE by lowering the stomatal aperture and transpiration rate (Franks et al., 2015).

Lastly, in the KTN treatment (KTN), seedlings were watered with 2 liters per day when rainfall was less than 5 mm and the WUE was 2.31. This value reflects moderate efficiency in water usage, with a steady positive correlation between daily ET and biomass. The seedlings have access to supplemental irrigation and rainfall, resulting in consistent biomass production, though slightly less efficient in water-to-biomass conversion than TN2.

The WUE values and scatter plots demonstrate the influence of different irrigation strategies on water use efficiency (WUE) in oil palm seedlings. Treatments like TN1 and TN2, which balance irrigation with natural rainfall, show higher WUE, reflecting efficient water use for biomass production. TN2, which relies solely on rainfall, achieved the highest WUE of 4.15, indicating that the seedlings efficiently convert natural water resources into biomass. However, despite the high WUE, TN2 produced less biomass than TN1, suggesting that depending solely on rainfall, although efficient, was not sufficient for optimal growth. In contrast, TN1, which combined rainfall with supplemental irrigation, produced higher biomass while maintaining good water use efficiency (WUE = 3.09). This made TN1 a superior strategy for maximizing both growth and water efficiency, as it provided a balanced and consistent water supply that led to better overall plant development compared to TN2.

Furthermore, treatments like KN+ and KTN, which used a fixed irrigation rate of 2 liters per day, were shown to be less efficient. Despite providing enough water for healthy growth, their WUE values (2.79 for KN+ and 2.31 for KTN) were significantly lower compared to TN1 and TN2. This indicated that applying 2 liters of water per day was not an efficient irrigation practice, as it results in excessive water use without corresponding gains in biomass production, leading to suboptimal water utilization.

The exclusion of the KN- treatment from the WUE analysis, due to seedling death after two weeks of water deprivation underscores the critical role of adequate irrigation, especially during early growth stages. Overall, the results highlight TN1 as the most effective strategy, balancing high WUE and superior biomass production, while fixed irrigation with 2 liters per day was inefficient. For sustainable agricultural practices, efficient water management is essential, particularly in regions with limited water resources, and TN1 provides the best model for optimizing both growth and water use.

4. DISCUSSION

This study revealed that oil palm seedlings receiving irrigation volumes adjusted according to daily actual evapotranspiration (ETa) achieved vegetative growth and biomass production comparable to or better than seedlings given a fixed irrigation volume of 2 liters per day. Treatments combining irrigation with rainfall monitoring (e.g., TN1) resulted in the highest biomass accumulation and demonstrated the best water use efficiency (WUE). Conversely, conventional or fixed-rate irrigation led to lower efficiency. Moreover, no irrigation treatments resulted in severe growth limitations or seedling mortality. These findings underscore the importance of tailoring water supply to actual seedling water needs to enhance growth and reduce water waste during the main nursery phase. The results of this study are consistent with the findings of Sukmawan and Riniarti (2020), who reported that water deficiency in oil palm can lead to stunted growth and plant mortality if prolonged. Furthermore, watering oil palm seedlings every two or three days combined with mulching could produce no less than the performance by watering every day. Other similar research by Ikhajiagbe et al. (2022) and Pangaribuan et al. (2024) asserted that drought stress on oil palm seedlings could cause a reduction in leave water content, shoot and root dry weight, seedling height, root length, and root volume. Najihah et al. (2019) stated that insufficient irrigation caused a decrease in vegetative growth after the sixth week.

Moreover, the daily evapotranspiration trends in this study were in line with a previous study by Brum et al. (2021), which stated that the performance of oil palm plantations, especially the productivity, would increase in the dry season if given adequate irrigation. Additionally, the lower daily ET rate of seedlings inside the greenhouse compared to the outside showed that climatic factors also contribute as a critical element in determining the actual daily ET rate of oil palm seedlings. This condition was per research conducted by Agele et al. (2022) and Pradiko et al. (2022), which insisted that the water demand for oil palm plantations was strongly influenced by climatic conditions, especially solar radiation and vapor pressure deficits. Earlier technical guidelines for irrigation of oil palm seedlings stated that the need for irrigation water for oil palm seedlings was 2 liters per day (Sukmawan et al., 2019) or 1.5-2.1 liters per day (Sukmawan et al., 2022). Some literature even stated that the volume of water for watering oil palm seedlings was 2.25 liters per day (Silalahi & Charloq, 2021). However, in this study, the data reported that the irrigation or water supply level should be done precisely and cannot be generally followed the 2 liters per day. Instead, irrigation volume was suggested to be adjusted with the plant growth phase and environmental conditions such as the evapotranspiration rates of the seedlings.

Similar trends in biomass production indicated that water availability influences the growth and physiological process within oil palm seedlings. Sufficient water availability would support the physiological process of oil palm. For instance, drought stress decreased stomatal conductance and photosynthetic rate (Mehdi Jazayeri et al., 2015). In the case of oil palm plantations aged six years, the water deficit first causes depreciation in gas exchange. Furthermore, there was a decline in the rate of photosynthesis and transpiration (Bayona-Rodriguez & Romero, 2019). Based on previous research implicated that the formation of biomass was not optimal due to the limiting factors of the environment.

In this study, the results of WUE rates emphasized that the effective and efficient irrigation volume occurred when the water applied has been adjusted to the water loss by daily actual evapotranspiration. The irrigation volume of 2 liters per day was not proper and was more likely seen as an act of wasteful water. Thus, it was necessary to increase the WUE, which was achieved by developing drought-tolerant oil palm materials and maintaining soil moisture (Ahmed et al., 2021). In addition, irrigation intervals could also be adjusted. Likewise, crop irrigation can be applied by considering the plant water status (Tran et al., 2015).

This research is expected to provide additional information for implementing more optimal irrigation for oil palm seedlings. By applying irrigation tailored to actual evapotranspiration (ETa), planters can improve water use efficiency and potentially reduce operational costs associated with over-irrigation. According to Chalvantharan et al. (2023), the estimated annual irrigation cost to compensate for water shortage in oil palm plantations in Malaysia is USD 160.95 per hectare, assuming a fixed water requirement of 150 mm per month. This cost reflects generalized estimates that may not account for temporal variations in seedling water demand or local microclimates. Water use by oil palm varies significantly depending on environmental conditions and growth stages. Therefore, using a fixed monthly water volume often leads to either excessive water use (which increases pumping and labor costs) or insufficient irrigation (which can suppress growth and reduce yield potential). By contrast, performing detailed irrigation planning based on ETa values allows for dynamic adjustments in water application, matching actual plant needs daily. For example, if ETa measurements show that the water loss is only 90 mm instead of the assumed 150 mm, the planter can reduce irrigation volume by 40%, thereby cutting irrigation costs proportionally. This calculation involves monitoring ETa (e.g., through weighing methods has been done in this study, lysimeters, or climate-based models), estimating daily water loss, and calibrating irrigation schedules accordingly. Over time, this approach ensures better seedling performance. It contributes to significant cost savings in water procurement, energy use, and labor, which is particularly valuable in regions facing rising input costs or limited water availability.

In relation to this study, the treatment with the highest WUE value requires at least 1.09 liters of water per day. Assuming the water tariff in Indonesia is 0.5 USD m^{-3}, the cost of purchasing water to irrigate 200 seedlings, the minimum number of seedlings required for 1 hectare, is 3.27 USD per month. This is more economical than watering 2 liters per seedling daily, which costs 6 USD per month, nearly double the ETa-based approach. These estimates only reflect water procurement costs and do not yet account for labor costs, which can vary significantly between provinces due to regional minimum wage differences. Furthermore, additional operational expenses such as fuel for water pumps, pump maintenance, and irrigation infrastructure further increase the cost under fixed irrigation scenarios. For large-scale plantation companies, where the number of seedlings can reach hundreds of thousands or more, the cumulative savings from ETa-based irrigation can become highly significant. By avoiding over-irrigation and optimizing resource allocation, companies can achieve substantial cost reductions while promoting more sustainable and efficient nursery management practices.

5. CONCLUSION

Irrigation for oil palm seedlings during the main nursery (MN) phase should be carried out effectively and efficiently by aligning water application with actual oil palm seedling water needs. This study demonstrated that adjusting irrigation volume based on actual evapotranspiration (ETa), particularly in the TN1 treatment, where seedlings were located outside greenhouse then watered based on daily water loss and not watered if rainfall was more than 5 mm, resulted in higher water use efficiency (WUE) and biomass accumulation greater than conventional fixed-rate irrigation of 2 liters per day. ETa-based irrigation using approximately 1.09 liters per seedling per day not only supported optimal vegetative growth but also significantly reduced water use by up to 45%, highlighting the inefficiency of fixed irrigation schedules. A practical method, such as the daily weighing of seedling pots or polybags, can estimate water loss by implementing ETa-based irrigation, guiding precise irrigation volumes. This approach can help minimize excess water use, lower irrigation costs, and maintain seedling performance, making it feasible for both smallholders and large-scale nurseries. Moreover, the results underline the importance of moving from conventional irrigation practices toward climate-responsive and plant-based irrigation planning for sustainable oil palm cultivation.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

References

Afandi, A. M., Zulkifli, H., Nur Zuhaili, H. A. Z. A., Norliyana, Z. Z., Hisham, H., Saharul, A. M., . . . Vu Thanh, T. A. (2023). 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/10.21894/jopr.2022.0052

Agele, S., Charles, F. E., Obi, A. E., & Agbona, A. I. (2022). Oil Palm-Based Cropping Systems of the Humid Tropics: Addressing Production Sustainability, Resource Efficiency, Food Security and Livelihood Challenges. In H. Kamyab (Ed.), *Elaeis guineensis*. IntechOpen. https://doi.org/10.5772/intechopen.98257

Ahmed, A., Mohd, Y. B. I., & Abdullah, A. M. (2021). Oil palm in the face of climate change: A review of recommendations. *IOP Conference Series: Earth and Environmental Science*, *646*(1), 012065. https://doi.org/10.1088/1755-1315/646/1/012065

Aholoukpè, H., Dubos, B., Flori, A., Deleporte, P., Amadji, G., Chotte, J. L., & Blavet, D. (2013). Estimating aboveground biomass of oil palm: Allometric equations for estimating frond biomass. *Forest Ecology and Management*, *292*, 122-129. https://doi.org/10.1016/j.foreco.2012.11.027

Bayona-Rodriguez, C. J., & Romero, H. M. (2019). Physiological and agronomic behavior of commercial cultivars of oil palm ('*Elaeis guineensis*') and OxG hybrids ('*Elaeis oleifera*'x'*Elaeis guineensis*') at rainy and dry seasons. *Australian Journal of Crop Science*, *13*(3), 424-432. https://doi.org/10.21475/ajcs.19.13.03.p1354

Brum, M., Oliveira, R. S., López, J. G., Licata, J., Pypker, T., Chia, G. S., . . . Asbjornsen, H. (2021). Effects of irrigation on oil palm transpiration during ENSO-induced drought in the Brazilian Eastern Amazon. *Agricultural Water Management*, *245*, 106569. https://doi.org/10.1016/j.agwat.2020.106569

Carr, M. K. V. (2011). The water relations and irrigation requirements of oil palm (*Elaeis guineensis*): A review. *Experimental Agriculture*, *47*(4), 629-652. https://doi.org/10.1017/S0014479711000494

Chalvantharan, A., Lim, C. H., & Ng, D. K. S. (2023). Economic Feasibility and Water Footprint Analysis for Smart Irrigation Systems in Palm Oil Industry. *Sustainability*, *15*(10), 8069. https://doi.org/10.3390/su15108069

Choukri, M., Naimi, M., & Chikhaoui, M. (2023). Drought characterization: A systematic literature review. *Sains Tanah Journal of Soil Science and Agroclimatology*, *20*(2), 15. https://doi.org/10.20961/stjssa.v20i2.77206

Christensen, J. H., Kanikicharla, K. K., Aldrian, E., An, S. I., Albuquerque Cavalcanti, I. F., de Castro, M., . . . Zou, L. (2013). Climate phenomena and their relevance for future regional climate change. In *Climate Change 2013 – The Physical Science Basis* (Vol. 9781107057999, pp. 1217-1308). Cambridge University Press. https://doi.org/10.1017/CBO9781107415324.028

Corley, R. H. V., & Tinker, P. B. (2015). *The oil palm* (5th ed.). John Wiley & Sons.

Darlan, N. H., Pradiko, I., & Siregar, H. H. (2016). Dampak el nino 2015 terhadap performa tanaman kelapa sawit di bagian selatan sumatera [Effect of El Nino 2015 on oil palm performance in Central and Southern Sumatera]. *Jurnal tanah dan iklim*, *40*(2), 113-120. https://epublikasi.pertanian.go.id/berkala/jti/article/view/3183

Delgado, T., Ladino, G., & Arias, N. (2024). Evaluation of the Effect of Soil Water Conditions on the Development and Water Requirements of Adult Oil Palm (*Elaeis guineensis* Jacq.) in the Northern Region of Colombia.

Agronomy, *14*(9), 1976. https://doi.org/10.3390/agronomy14091976

Evizal, R., Sari, R. Y., Saputra, H., Setiawan, K., & Prasmatiwi, F. E. (2021). Pengaruh Irigasi pada Pertumbuhan dan Produksi Kelapa Sawit [The Effect of Irrigation on the Growth and Yield of Oil Palm]. *Jurnal Agrotropika*, *20*(1), 58-67. https://doi.org/10.23960/ja.v20i1.4848

Franks, P. J., W. Doheny-Adams, T., Britton-Harper, Z. J., & Gray, J. E. (2015). Increasing water-use efficiency directly through genetic manipulation of stomatal density. *New Phytologist*, *207*(1), 188-195. https://doi.org/10.1111/nph.13347

Harahap, I., & Darmosarkoro, W. (1999). Pendugaan kebutuhan air untuk pertumbuhan kelapa sawit di lapang dan aplikasinya dalam pengembangan sistem irigasi [Estimation of Water Requirements for Oil Palm Growth in the Field and Its Application in Irrigation System Development]. *Jurnal Penelitian Kelapa Sawit*, *7*(2), 87-104. https://pis.iopri.co.id/upload/journalIOPRI/files/230822105956.pdf

Hatfield, J. L., & Dold, C. (2019). Water-Use Efficiency: Advances and Challenges in a Changing Climate [Review]. *Frontiers in Plant Science*, *Volume 10 - 2019*. https://doi.org/10.3389/fpls.2019.00103

Hebbar, K. B., Apshara, E., Chandran, K. P., & Prasad, P. V. V. (2020). Effect of elevated CO2, high temperature, and water deficit on growth, photosynthesis, and whole plant water use efficiency of cocoa (Theobroma cacao L.). *International Journal of Biometeorology*, *64*(1), 47-57. https://doi.org/10.1007/s00484-019-01792-0

Ikhajiagbe, B., Aituae, W., & Ogwu, M. (2022). Morpho-physiological assessment of oil palm (*Elaeis guineensis* Jacq.) seedlings exposed to simulated drought conditions. *Journal of Oil Palm Research (Malaysia)*, *34*(1), 26-34. https://doi.org/10.21894/jopr.2021.0018

Mehdi Jazayeri, S., Rivera, Y. D., Camperos-Reyes, J. E., & Romero, H. M. (2015). Physiological effects of water deficit on two oil palm (*Elaeis guineensis* Jacq.) genotypes. *Agronomía Colombiana*, *33*(2), 164-173. https://www.redalyc.org/articulo.oa?id=180341167006 (IN FILE)

Monzon, J. P., Jabloun, M., Cock, J., Caliman, J.-P., Couëdel, A., Donough, C. R., . . . Grassini, P. (2022). Influence of weather and endogenous cycles on spatiotemporal yield variation in oil palm. *Agricultural and Forest Meteorology*, *314*, 108789. https://doi.org/10.1016/j.agrformet.2021.108789

Muhamad, H., Subramaniam, V., Hashim, Z., Khairuddin, N. S. K., & May, C. Y. (2014). Water footprint: Part 1- production of oil palm seedlings in Peninsular Malaysia. *Journal of Oil Palm Research*, *26*(4), 273-281. https://jopr.mpob.gov.my/water-footprint-part-1-production-of-oil-palm-seedlings-in-peninsular-malaysia/

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

Najihah, T. S., Ibrahim, M. H., Razak, A. F. A., Nulit, R., & Wahab, P. E. M. (2019). Effects of water stress on the growth, physiology and biochemical properties of oil palm seedlings. *AIMS Agriculture and Food*, *4*(4), 854-868. https://doi.org/10.3934/agrfood.2019.4.854

Noor, M. R. M., & Harun, M. H. (2007). Technique for determining Water Use Efficiency (WUE) in oil palm. MPOB Information Series. http://tot.mpob.gov.my/tt-no-354-technique-for-determining-water-use-efficiency-wue-in-oil-palm/

Pangaribuan, I. F., & Akoeb, E. N. (2022). Analysis of morphological responses of drought stress oil palm in nursery phase. *IOP Conference Series: Earth and Environmental Science*, *977*(1), 012013. https://doi.org/10.1088/1755-1315/977/1/012013

Pangaribuan, I. F., Rahmawati, N., Akoeb, E. N., Yenni, Y., Sujadi, & Pangaribuan, Y. (2024). Reactions of Drought-Affected Oil Palm Variety Seedlings during the Nursery Phase: Bud and Root Responses. *IOP Conference Series: Earth and Environmental Science*, *1308*(1), 012034. https://doi.org/10.1088/1755-1315/1308/1/012034

Pradiko, I., Ginting, E. N., Darlan, N. H., Winarna, & Siregar, H. H. (2016). Hubungan pola curah hujan dan performa tanaman kelapa sawit di Pulau Sumatra dan Kalimantan selama El Nino 2015 [The Relationship Between Rainfall Patterns and Oil Palm Performance in Sumatra and Kalimantan During the 2015 El Niño]. *Jurnal Penelitian Kelapa Sawit*, *24*(2), 87-96. https://core.ac.uk/reader/231264600

Pradiko, I., Rahutomo, S., Farrasati, R., Ginting, E. N., Hidayat, F., & Syarovy, M. (2022). Transpiration of oil palm (*Elaeis guineensis* Jacq.) based on sap flow measurement: the relation to soil and climate variables. *Journal of Oil Palm Research*, *35*(1), 168-184. https://doi.org/10.21894/jopr.2022.0035

Rivera-Mendes, Y. D., Cuenca, J. C., & Romero, H. M. (2016). Physiological responses of oil palm (*Elaeis guineensis* Jacq.) seedlings under different water soil conditions. *Agronomía Colombiana*, *34*(2), 163-171.

Sianipar, E. M. (2021). Pengaruh Perubahan Iklim Terhadap Ekofisiologi Tanaman Kelapa Sawit (Elaeis guineensis Jacq.) [The Impact of Climate Change on the Ecophysiology of Oil Palm (*Elaeis guineensis* Jacq.)]. *Majalah Ilmiah Methoda*, *11*(1), 75-80. https://doi.org/10.46880/methoda.Vol11No1.pp75-80

Sigalingging, R., Sumono, & Rahmansyah, N. (2018). Evapotranspiration and crop coefficient of oil palm (*Elaeis guineensis* Jacq.) on the main nursery in a greenhouse. *IOP Conference Series: Earth and Environmental Science*, *122*(1), 012099. https://doi.org/10.1088/1755-1315/122/1/012099

Silalahi, J. E. L., & Charloq, F. (2021). The Effect of Watering Frequency on Several Types of Oil Palm (Elais guineensis Jacq.) Great Bunches Superior Seeds 'Yangambi'in Main Nursery Ages of 4 to 7 Months.

JURNAL AGROTEKNOLOGI, *9*(1). https://talenta.usu.ac.id/joa/article/view/6530

Sujadi, S., Pradiko, I., Rahutomo, S., & Farrasati, R. (2020). Prediksi Kemampuan Adaptasi Delapan Varietas Kelapa Sawit pada Cekaman Abiotik Akibat Perubahan Iklim Global [Prediction of the Adaptive Capacity of Eight Oil Palm Varieties Under Abiotic Stress Caused by Global Climate Change]. *Jurnal tanah dan iklim*, *44*(2), 129-139. https://epublikasi.pertanian.go.id/berkala/jti/article/view/3262

Sukmawan, Y., & Riniarti, D. (2020). Respons Pertumbuhan Bibit Kelapa Sawit Akibat Pengaturan Bobot Mulsa Tandan Kosong dan Frekuensi Penyiraman [Growth Response of Oil Palm Seedlings to Empty Fruit Bunch Mulching and Watering Frequency Adjustment]. *Jurnal Penelitian Kelapa Sawit*, *28*(3), 159-168. https://doi.org/10.22302/iopri.jur.jpks.v28i3.121

Sukmawan, Y., Riniarti, D., & Pranandi, G. (2022). The Effect of Irrigation Time and Slow-Release Fertilizer on Oil Palm Seedlings Under Controlled Drip Irrigation System. *IOP Conference Series: Earth and Environmental Science*, *1012*(1), 012025. https://doi.org/10.1088/1755-1315/1012/1/012025

Sukmawan, Y., Riniarti, D., Utoyo, B., & Rifai, A. (2019). Efisiensi air pada pembibitan utama kelapa sawit melalui aplikasi mulsa organik dan pengaturan volume penyiraman [Water Use Efficiency in Main Nursery of Oil Palm Through Organic Mulch Application and Irrigation Volume Management]. *Jurnal Pertanian Presisi (Journal of Precision Agriculture)*, *3*(2), 141-154. https://doi.org/10.35760/jpp.2019.v3i2.2331

Tran, N., Bam, P., Black, K., Graham, T., Ping, Z., Dixon, M., . . . Downey, A. (2015). Improving irrigation scheduling protocols for nursery trees by relating cumulative water potential to concurrent vapour pressure deficitâ©. https://doi.org/10.17660/ActaHortic.2015.1085.22

Trinugroho, M. W., Arif, S. S., Susanto, S., & Nugroho, B. D. A. (2024). Assessing irrigation water demand and pumping operations for rice farming in the Bengawan Solo River, Indonesia. *Sains Tanah Journal of Soil Science and Agroclimatology*, *21*(1), 13. https://doi.org/10.20961/stjssa.v21i1.79343