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OIL PALM WATER REQUIREMENT AND THE NEED FOR IRRIGATION IN DRY MALAYSIAN AREAS

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ABSTRACT

Water is essential for the growth and productivity of oil palm and hence adequate rainfall contributes to the oil palm water requirement. Sufficient rainfall becomes crucial in attaining good growth and yield. Over the past 23 years, the yield response from irrigated palms in Serting Hilir, Malaysia was reported to be 12 t ha^{-1} yr^{-1} or 56% higher than the non-irrigated palms. The drip irrigation system is selected to irrigate areas with limited water sources but with sufficient nutrient inputs. However, in areas with unlimited water, the furrow irrigation system is favoured. Feasibility analysis on irrigation implementation economics was done for the oil palm plantation. The analysis showed that irrigation is able to increase the yield by 5-6 t ha^{-1} yr^{-1} which is economically acceptable. To irrigate an oil palm plantation, a large source of water is required. Nevertheless, conserving water that penetrates the soil is the most practical approach to resolve issues of limited water supply, unsuitable terrains and logistics. The present paper reviews and discusses various techniques for soil and moisture conservation that are viable to increase oil palm yields.

Keywords: dry area, irrigation, moisture conservation, oil palm, yield response.

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INTRODUCTION

Malaysia's climate is similar to that of West Africa, thus it provides a suitable condition for oil palm to grow. Oil palm in Malaysia originates from West Africa and the Tennamaram Estate in Selangor was the first commercial oil palm plantation. *Tenera*, a hybrid of *Dura* and *Pisifera* varieties is an oil palm variety that has been commercially grown in Malaysia (Corley and Tinker, 2003).

Theoretically, the highest oil yield was estimated to be about 18.50 t ha^{-1} yr^{-1} and the average oil yield worldwide stands at around 3.00 t ha^{-1} yr^{-1} (Woittiez *et al*., 2017). Meanwhile, in Malaysia, it was approximately about 3.64 t ha^{-1} yr^{-1} (Malaysian Palm Oil Board Statistics, 2019). Yield prediction through simulation models were applied to determine the oil palm yield. Recent oil palm growth models include PALMSIM (Hoffmann *et al*., 2014), OPRODSIMv1 (Henson, 2009), APSIM-Oil Palm (Huth *et al*., 2014), CLM-Palm (Fan *et al*., 2015), CLIMEX-Oil Palm (Paterson *et al*., 2015) and PySawit (Teh and Cheah, 2018). The most recent PySawit attempts to model oil palm photosynthesis, as well as the microclimate environment within and beneath the canopies and was developed for oil palm planted at a wide range of densities, from about 120-300 palms ha^{-1}, whereas APSIM-Oil Palm, CLM-Palm, and PALMSIM were only validated over a narrow planting density with a range of 127-156 palms ha^{-1}. PySawit predicted the growth and yield parameters of oil palm with good accuracy for total dry matter (TDM), leaf area index (LAI) and trunk height parameters. The yield declines caused by two *El Nino* occurrences (which resulted in dry periods) were

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demonstrated in the model simulations. However, discrepancies between yield predictions and observations increased with increasing planting density probably due to very dense canopies which were not well understood and insufficiently characterised by the model. The yields may be limited by factors such as insufficient rainfall, shallow soil depth, inclination and poor drainage. These factors can reduce nutrient availability and productivity of oil palm. Amongst these yield-limiting factors, rainfall plays the most important role because oil palm water requirements depend entirely on rainfall. The suitability of oil palm cultivation areas is also related to rainfall. Vital climatic factors that affect oil palm growth, yield and performance are rainfall amount, and distribution (Paramanathan, 2003). Oil palms require a large amount of rainfall. A monthly rainfall of at least 100 mm that is well distributed throughout the year is preferred (Paramanathan, 2013). Therefore, this signifies those areas with a prolonged dry season are less suitable for growing oil palm as the crop is a rain-fed crop (Kallarackal *et al*., 2004). Even though the average rainfall in Malaysia is high at over 2000 mm yr^{-1}, certain areas receive an uneven rainfall distribution. The rainfall distribution is reported to be more uniformly distributed in the east coast of Peninsular Malaysia as compared to other regions. A higher spatial rainfall variation is observed in the west coast regions of Peninsular Malaysia (Wong *et al*., 2009).

Water-induced stress in oil palm strongly suppresses yields (Carr, 2011; Corley, 1996; Palat *et al*., 2008; Woittiez *et al*., 2017). This is because the oil palm leaves do not wilt even though the opening of new leaves is shown. Besides, deficits in available soil water and air vapour pressure will greatly influence stomatal opening, and thus affect the photosynthesis rate (Caliman, 1992; Henson and Chang, 1989; Smith, 1989). Insufficient water supply has been a short-term problem in certain areas throughout the year, or in years when extreme weather conditions occur (Arifin *et al*., 2002; Chan *et al*., 1985; Corley and Hong, 1982; Henson and Chang, 1989; Kallarackal *et al*., 2004; Turner, 1976). For example, in Kedah water deficits could occur for about three consecutive months each year (Roslan and Haniff, 2004b). The drought conditions may negatively affect oil palm yield and difficult for the oil palm to grow and achieve its optimum potential because oil palm requires sufficient water supply for its growth.

Irrigation was exploited as an option to supplement the rainfall shortages experienced by oil palm fields. Studies on different methods of irrigation for oil palm were compared and the effectiveness of drip irrigation in overcoming water deficit was demonstrated (Rao *et al*., 2018; Tittinutchanon *et al*., 2000). In areas where water is not a limiting factor, a furrow irrigation system is applied. Nevertheless, since oil palm irrigation needs an abundant water supply, the installation of an irrigation system is only economically feasible when the yield is increased (Lee and Izwanizam, 2013). The water shortage for irrigation can be resolved by preserving rainfall water that penetrates the soil through mulching and covering crops.

This review discusses water requirements for oil palm, the effects of rainfall and water shortage in oil palm plantations. The need for irrigation implementation and soil moisture conservation for dry areas in Malaysia is also reviewed. Information about other palm oil-producing countries with similar situations as Malaysia is also included.

Environmental and Climate Conditions for Oil Palm Plantation

Certain climate conditions and soil suitability are required to ensure high yield production for oil palm in Malaysia and they are highlighted as follows: (1) Annual rainfall of at least 2000 mm to 2500 mm evenly distributed throughout the year (Hartley, 1988b); (2) Mean minimum and maximum air temperatures of 22ºC-24ºC and 29ºC-33ºC, respectively (Norman *et al*., 2014); (3) Relative humidity >45% for optimal transpiration (Roslan and Haniff, 2004a); (4) Average 5 hr of daily bright sunlight during the whole year, with up to 16-17 MJm^{-2} d^{-1} of daily solar energy for about 7 hr day^{-1} in some months (Lim *et al*., 2011; Norman *et al*., 2014); (5) Lowland areas (land less than 300 m or 1000 feet above sea level) (Paramanathan, 2015; PORIM, 1993); and (6) Loose soil texture or well-aggregated soils without hard layer will allow roots proliferation (Lim *et al*., 2011). Though the above criteria are best suited for optimum production, oil palm is also successfully grown in less favourable conditions, for example in Thailand and parts of West Africa and South America, whereby the dry seasons occur regularly.

Soil texture plays an important role in oil palm water deficit. Sand-textured soils (less than 10% clay content) have high porosity and are prone to moisture stress and nutritional deficiencies (Paramanathan, 2013). As a result, the oil palm yield potential on these soils is less than 19 t ha^{-1} yr^{-1} FFB, compared to 30-35 t ha^{-1} on clayey soils (Nordiana *et al*., 2008; 2013).

Corley and Tinker (2003) and Hartley (1988a) have summarized the main criteria to grow oil palms are temperature, sunshine and rainfall. Most oil palm planting systems are rain-fed, thus rainfall has become an important determining factor of oil palm yield. However, Corley and Tinker (2003) reviewed the role of water in oil palm productivity and reported that there was no relation between total rainfall and yield. A good oil palm yield is ensured when the requirement for a total yearly rainfall of at least 1500-3000 mm is achieved. The rainfall should be distributed uniformly throughout the year with a minimum of 100 mm every month and no definite dry season (Nur Nadia and Syuhadatul Fatimah, 2016; Paramananthan, 2003). With sufficient relative humidity (75%-85%), oil palm can tolerate temperatures that are below or equal to 38ºC (Paramananthan, 2003).

At least 20% of rainfall is deflected by the apex, bunches, and frond bases of oil palm, while the remaining rain that penetrates soil is taken up by roots via the transpiration process (Chang and Rao, 1983). Furthermore, the effective rainfall (ER) is determined by the gross rainfall minus [run-off + deep percolation + interception by the vegetation] (Kee *et al*., 2000). The ER is referred to as a percentage of available rainfall to plants and crops. In Malaysia, the monthly ER varies from 11%-84% of gross rainfall. The number of months with soil water deficit varies from 2-12 months with an average of nine months (Claude *et al*., 2013).

In Peninsular and East Malaysia, the production of crude palm oil expresses variations in average oil palm yield. This is partly due to the amount of rainfall (12%-24%) although the seasonality in oil palm yields is possibly slightly independent of the rainfall (Chow, 1992). Oil palm can adapt to a higher amount of rainfall, but prolonged water logging will negatively affect the soil respiration, and flooding will result in the death of palms. Heavy rainfall during pollination can cause poor pollination and consequently reduce bunch fruit set, leading to a decline in the mean fruit bunch weight and bunch oil content (Haniff and Roslan, 2002) while excessive rainfall will increase the moisture in fruitlets, which results in a lower oil extraction rate (Nur Nadia and Syuhadatul Fatimah, 2016). However, continuous low rainfall (<100 mm) for more than two months significantly reduces the palm yield (Haniff *et al*., 2010). In 1998, there were significant reductions of 18.7%, 28.6%, and 14.6% in fresh fruit bunches (FFB) yield as compared to that in 1997 due to the *El Niño* phenomenon in Sabah, Sarawak and Peninsular Malaysia, respectively (Nur Nadia and Syuhadatul Fatimah, 2016).

Paramananthan (2013) estimated and summarised the potential of Malaysian oil palm yields for different rainfall regions. The yields were acquired based on standard agronomic management and the palms were grown on levelled undulating soil terrain (0%-22%). The average FFB yields for wet, moderate, and dry regions were 26, 24, and 18 t ha^{-1} yr^{-1}, respectively. The yields were higher in wet and moderate wet regions as compared to dry regions by about 32% and 27%, respectively.

Water Footprint of Oil Palm

Worldwide, the agricultural sector has the largest water usage, which currently recorded about 85% of freshwater consumption worldwide (Hoekstra and Chapagain, 2007; Shiklomanov, 2000). Crop types and climate influence the water requirement for the crop that can be supplied either by rainfall or irrigation. As in any agriculture-based produce, the general perception that concerns oil palm production is the direct water usage of oil palm.

A technique for communicating and managing water consumption patterns that affect the environment is water footprint (WF) determination. Hoekstra (2003) introduced the WF concept, which was further elaborated by Hoekstra and Chapagain (2008) to quantify the human allocation of freshwater resources. The WF analysis is aimed at achieving a variety of goals from business identification, processes or products based on water consumption level and promotion of sustainable water resources usage (Hoekstra *et al*., 2011). According to Hoekstra and Chapagain (2008), WF is the volume of freshwater used for FFB production. The WF for oil palm plantation is determined by the summation of daily crop evapotranspiration (mm day^{-1}) over the growing period of oil palm.

Based on Hoekstra and Chapagain (2008), the WF includes three components namely green WF, blue WF and grey WF. Green WF is the rainwater that evaporates during crop growth, while blue WF indicates the volume of the surface and groundwater that evaporates during crop growth. Meanwhile, the grey WF is the amount of water required to mitigate pollutants that are released into the natural water system to meet specific water quality standards (Mekonnen and Hoekstra, 2010).

Bluewater usage (m^3 ha^{-1}) is measured by the daily total volume of irrigation-water evapotranspiration. The blue crop water used in oil palm production is often considered zero. The summation of daily evapotranspiration values (mm day^{-1}) over growing period length measures green crop water usage (m^3 ha^{-1}). This is calculated using Hoekstra and Chapagain (2008) method. The green WF and blue WF of oil palm (m^3 t^{-1}) are determined by the total volume of green and blue water usage (m^3 yr^{-1}), which is then divided by the quantity of FFB yield (t ha^{-1} yr^{-1}). In addition, the grey WF of FFB production shows the volume of freshwater pollution, whereby is calculated by measuring the volume of water required to assimilate nutrients that reach the ground or surface water. Nutrients leaching from agricultural fields are the main cause of non-point source pollution of surface and subsurface water bodies. Calculation of the grey WF component (m^3 t^{-1}) involves multiplying the leached fraction of fertiliser/pesticide or runs off by its application rate (L ha^{-1}). The value obtained is divided by the difference in concentration between maximum acceptable nitrogen concentration (kg ha^{-1}) and natural nitrogen concentration in the receiving water body (kg ha^{-1}) and by the actual crop yield (t ha^{-1} yr^{-1}). Zulkifli *et al*. (2014) reported the first WF of FFB production in Malaysia based on the inventory data obtained from 281 plantations for mineral soils, which covered an area of approximately 440 000 ha. The WF for FFB production were 21 920 m^3 ha^{-1} comprising 4.8 blue, 1054.0 green, and 107.0 grey m^3 t^{-1} FFB, thus, the main source of water used was green water.

As we have insufficient water resources although there is a high demand for water for biofuel feedstock and food production, there is a need for better water management to prevent conflict over water. Furthermore, oil palm's WF is different according to different countries based on the crop yields, climate and agricultural practices amongst countries, which is with or without irrigation. Previously, only WF of oil palm cultivation in Thailand (Piyanon and Shabbir, 2013) and Indonesia (FAOSTAT, 2011) were reported *(Table 1)* as they have implemented irrigation systems due to insufficient rainfall. Generally, in Malaysia, there is an adequate amount of rainfall to support oil palm growth, thus the sustainable use of water resources does not encounter pressing issues.

TABLE 1. THE WATER FOOTPRINT OF OIL PALM CULTIVATION FOR TOP PRODUCERS

Country	FFB yield ($t\ ha^{-1}\ yr^{-1}$)	Green +Blue ($m^3\ t^{-1}$)
Indonesia	17.9*	802*
Thailand	5.5-16.0**	965–2 353**
Malaysia	20.7***	1 059***

Note: Greywater was excluded in * and **.

Sources: *FAOSTAT (2011); **Piyanon and Shabbir (2013) and ***Zulkifli *et al*. (2014).

Plant and Soil Water Deficit

Water deficit in the soil is defined as soil relative dryness measurement that reflects the water quantity that is removed from the soil within the rooting zone of the crop. It refers to the actual amount of water required to refill the root zone, thus it will balance out the soil moisture level. Different methods can be applied to measure water deficit in soil. One method is by using pan evaporation or Penman's estimate of evaporation. The estimated value is multiplied by the crop factor that is derived directly from crop evapotranspiration measurement. The crop factor is used to estimate how much water a plant can extract. Kumar (1997) indicated that the crop factor of oil palm is 0.7. The product of pan evaporation and crop factor determines the potential evapotranspiration (PE). For example, if the pan evaporation is 5.0 mm day^{-1}, then PE would be 3.5 mm day^{-1} (Roslan and Haniff, 2004b). The percentage of water that remains in the soil for several days and then undergoes saturation determines the field capacity, which is expressed in terms of weight or volume. The palm may encounter water stress whenever there are water deficit events in the soil. Factors that may vary the critical water deficit value and affect yield are soil type, soil depth, rooting density and palm age.

In Malaysia, monthly rainfall of less than 100 mm is considered a dry month (Claude *et al*., 2013). The most crucial moisture stress in oil palms is for 24, 18, and 5 months before fruit bunch maturation (Roslan *et al*., 2013). Ling (1979) reported that the oil palm evapotranspiration value in central Peninsular Malaysia might reach 160 mm $month^{-1}$. Dufrene (1989) found that the maximum evapotranspiration rate was 4-5 mm day^{-1} or 120-150 mm $month^{-1}$. Therefore, moisture loss replacement at 5 mm day^{-1}, or an equivalent of 350 L $palm^{-1}$ of irrigation water should be applied for a planting density of 143 palms ha^{-1}. When relative humidity (RH) reaches 30%-34%, a few oil palm growth limitations may occur. Meanwhile, RH below 30% could induce severe growth limitations (Kumar, 1997). Although palms are sufficiently watered, there are 10% losses in yield as they close their stomata during midday during the peak sun hours (Corley, 1973). Atmospheric stress from low RH and higher temperatures could develop a high vapour pressure deficit (VPD) even with sufficient irrigation. This may affect carbon assimilation. Henson (1991) proved that oil palm stomata are closed during high VPD, even though there is no limit on soil moisture. Kallarackal (1996) reported that oil palm stomatal closure was detected when VPD > 1.0 KPa and stomatal conductance was severely reduced when VPD ≥ 1.9 KPa.

Oil Palm Responses to Water Deficit

Symptoms of water stress in oil palms include unopened leaves accumulation, premature desiccation of pinnae edges, broken green leaves, bunch desiccation which causes abortion, crown collapse, and palm death, especially in newly planted palms (Paramananthan, 2003). Water stress is also associated with high juvenile incidence, fused pinnae and retarded seedlings growth that are thrown away at the end of nursery culling. Water stress reduces photosynthesis and inhibits oil palm growth (Corley, 1976; Ochs and Daniel, 1976; Roslan and Haniff, 2004b). Water deficit in the plant will cause an immediate physiological response such as stomatal closure and consequent reduction in transpiration and photosynthesis by the canopy. In Malaysia, these oil palm conditions have previously been documented (Corley, 1973; Henson, 1991; Henson and Chang, 1989). The rise in canopy temperature (Henson, 1991; Henson *et al*., 2005) is a direct effect of reduced transpiration rates, which resulted from the stomatal closure.

It is noteworthy that any physiological stress will shift the sex ratio, whereby the number of female inflorescences per total inflorescences is in favour of male flowers, and as consequence productivity is reduced (Rao *et al*., 2018). The flower sex determination occurs 24 months before fruit ripening (Haniff *et al*., 2010). If the palms experience water stress during this peak period, a higher proportion of the inflorescences will turn into male flowers (*i.e.* reduction in sex ratio). Oil palms are regarded to be under severe drought if their soil water potential is less than -1.5 MPa (Méndez *et al*., 2012). This influences the physiological processes involved in growth, development and production. In response to low soil water potential, there is a positive relationship between stomatal conductance and transpiration (Jazayeri *et al*., 2015). In most plants, during water stress the stomata will close and leaves start to wilt. This results in minimal photosynthetic activity at a low carbohydrate status, thus it supports the formation of male inflorescences as less nutrition is required to develop. Since fewer female inflorescences develop, only a small number of fruit bunches are produced. On the other hand, more female inflorescences will be produced when the carbohydrate status is recovered. The time of inflorescence abortion is 18 months before fruit maturity, while the time for pollination is five months before fruit maturity.

The common effects of drought stress as previously described by Darlan *et al.* (2010) are an increase in abortion, failed or rotten bunches, fluctuation and low productivity, and long inflorescences time from eight to nine months. Due to the long developmental period of bunch production during drought periods, the yield will be negatively affected. However, the impact on yield will only become apparent later after more than a year. Water deficit also reduces growth and yield, causing vegetative disorder. Cheng-Xu *et al.* (2011) stated that water stress decreased relative chlorophyll a/b and oil palm yield. The decrease is via inflorescence abortion increment and a decrease in sex ratio (Henson *et al*., 2005; Roslan and Haniff, 2004b; Turner, 1976).

Previous irrigation-based research on water requirement of 4-5 mm day^{-1} showed slight success in ameliorating the yield caused by inadequate water and nutrients (Chan, 1979; Chan *et al*., 1985; Corley and Hong, 1981; Kee and Chew, 1991). Studies on the yield reduction estimation at various annual moisture deficits were conducted (Gawankar *et al*., 2003; Gerritsma and Wessel, 1997; Turner, 1976). The effects of severe droughts on oil palms were also identified where numerous closed spears, broken green leaves, desiccated leaves, toppled spears and the death of palms was observed (Dislich *et al.*, 2017). Moreover, water deficit will negatively affect the oil content of fruit bunches because of less oil to the mesocarp ratio. In more severe cases, many fruits tend to be dried up and reduce the extraction rates by 30%-40% for several weeks (Kumar, 1997).

Less availability in soil moisture could also limit nutrient uptake since palms take up nutrients from the soil solution. With a monsoonal climate, the rate of nitrogen application in irrigated oil palm areas may be reduced by half as compared to non-irrigated areas (Kee and Chew, 1991). This is achieved by better nutrient uptake under adequate soil water supply during the year, whereby optimal palm nutritional status is ensured. The palm growth rates may be reduced by either water shortage, drought or poor drainage (Gawankar *et al*., 2003; Roslan *et al*., 2011). However, the effect of drought can be reduced by irrigation. In La Mé, Ivory Coast, irrigation trials revealed that the irrigated plots produced higher yields mainly due to the higher sex ratio and the number of bunches produced per palm (Fairhurst and Härdter, 2003; Hartley, 1988b). On that account, irrigation is required to achieve the maximum response towards the application of mineral fertilisers that tend to improve growth and increase oil palm yield.

Soil Water Management by using Irrigation

The irrigation system. Irrigation is implemented to avoid the restricted growth of plants due to the rainfall shortages, whereby the application rate is dependent on the amount and distribution of water. Moreover, the best method to determine irrigation timing is by measuring the plant water status based on stomatal behaviour and application rate by soil water deficit (Chan, 1979). The Univanich Oil Palm Research Centre (OPRS) in Thailand, successfully conducted irrigation trials since 1993 at Chean Vanich Estate (80º 32” 06.0’ N, 980º 54” 27.4’ E) in South Thailand. Based on OPRS trials, a more reliable irrigation system is considered if the four-drip line at every row with dripper rates of 150 L hr^{-1} and 250 L hr^{-1} is adopted for immature and mature palms, respectively. Moreover, to ensure good water distribution the furrow system requires additional maintenance to avoid blockages. In areas where infield mechanisation is practised, bridges over the furrows would increase the capital cost.

The micro sprayer irrigation systems have a high capital cost and need regular maintenance to keep them functioning effectively (Tittinutchanon *et* *al*., 2000). The following are some technical issues on oil palm irrigation in Thailand (Afandi *et al*., 2013):

- Root damage may be caused by trenches for the dripper line dug near the palm, which could also cause depression in yields after installation.
- Irrigation near the palm is not necessary since mature palms can find water as far as 36 m.
- Setting up mobile dripper lines from the mainline, can irrigate seedlings at 150 L palm^{-1} day^{-1}.
- The use of dripper lines that are coiled around the palm of a single mobile dripper line would have no significant difference. However, using a dripper line coiled around the palm is more costly.

A drip irrigation system can reduce soil water deficit. Although there are available water sources, optimum benefits could only be achieved by applying a suitable irrigation infrastructure, an appropriate amount of water and frequency of application. The drip system supplies water in small quantities directly to the rooting zone. Therefore, it permits the request for water supply adjustment at any time and concurrently limits the loss through percolation. Most drip systems require water only at a low pressure of 1.0-1.5 kg cm^{-2} as compared to 3.5 kg cm^{-2} in standard irrigations (Kumar, 1997). However, this system has a drawback, whereby it requires frequent maintenance of the drippers, especially when the operation has stopped. By using surface drip irrigation, the upper 150 mm soil layer is much more hydrated as compared to subsurface drip irrigation (Srinivas, 1996).

The success of drip irrigation systems in oil palm depends on the irrigation designs to derive a higher irrigation efficiency (IE) rate, installation, operation, and maintenance. IE is defined as the proportion of consumed water or consumptive use that is beneficially used by a crop (Burt *et al*., 1997). More efficient irrigation systems have increased this proportion [Equation (1)], which allows less water to be applied for a given yield.

$$\text{Irrigation efficiency} = \frac{\text{Effective water}}{\text{Consumptive use of water}} \qquad (1)$$

In the drip system, a small volume of water can achieve an IE of up to 85%-95%, as compared to only 75%-80% IE with a flood and furrow system. The drip irrigation system is selected when water saving is of prime concern, as compared to surface irrigation systems.

In Malaysia, FELDA Agricultural Services Sdn. Bhd. (FASSB) had carried out field irrigation trials by using flatbed and drip systems (FASSB, 2000). The implementation of a drip irrigation system in cotton cultivation increased the yield by 28%-35%, particularly when fertilisation was adopted (Hanna *et al*., 2014). In southern Thailand, irrigation at 4-5 mm day^{-1} shows a positive impact on bunch number per palm (Tittinutchanon *et al*., 2000). Increased production in the total number and weight of FFBs was also recorded by Rao *et al*. (2018), which was due to high female inflorescences when drip irrigation was used as compared to micro-jet irrigation in an 18-year-old oil palm plantation in Andhra Pradesh, India. The drip irrigation systems reduced soil evaporation in narrow rows but did not cause a significant difference with furrow irrigation when soil water was non-limiting (Howell *et al*., 1987). Hodgson *et al*. (1990) had proven higher water efficiency when using drip irrigation systems. Furrow irrigation systems could achieve higher performance if transmission losses are reduced between the pump and irrigated field. This is possible by reducing run-off losses, recirculating run-off water, and reducing waterlogging.

Economics of irrigation. Lee and Izwanizam (2013) reported that the initial capital cost for flatbed irrigation systems was estimated to be about RM4688 ha^{-1}. Combined with the financial cost at an annual interest rate of 6% per year, the total cost was approximated at RM7500 ha^{-1} or RM750 ha^{-1} year^{-1} amortised over a 10 year period. The capital and operating costs of the drip irrigation system at 300 L palm^{-1} in Thailand were about 1300 USD and 70 USD ha^{-1} yr^{-1}, respectively, and it was only over half of the amount for 150 L palm^{-1} (Tittinutchanon *et al*., 2000). The estimated initial cost to set up drip irrigation systems on undulating terrain was about RM18 000 ha^{-1} (Afandi *et al*., 2013). A furrow irrigation system is cheaper than a drip irrigation system. It has to be noted that for any irrigation projects under oil palm to be viable and profitable, the FFB yield should increase by at least 4 t ha^{-1} yr^{-1}, assuming that the FFB price is RM400 t^{-1}. In Malaysia, an increased yield of at least 5-6 t ha^{-1} yr^{-1} would be more economically justifiable for irrigation implementation (Lee and Izwanizam, 2013).

The irrigation rate and water balance. Norizan *et al*. (2021) discovered that the FAO Cropwat model is an excellent method for assessing crop water requirements (CWR) for Malaysian oil palm demands. To calculate the amount of water to be utilised for irrigation, this model requires effective rainfall, soil type, soil water-holding capacity, meteorological and crop data. An accurate estimate of the water amount applied to a field is critical to any irrigation management approach. A minimal amount of water can cause unnecessary water stress, which will reduce yield. Too much water promotes waterlogging and leaching, which can again result in yield loss. The appropriate water amount can be estimated using information collated from the evaporation pan (E-pan) and meteorological data. E-pan data of 4.0 mm day^{-1} implies that the evapotranspiration is equivalent to 4.0 L m^2 day^{-1}. At a planting density of 148 palms ha^{-1} each palm can occupy an area of 67.6 m^2 (10 000 m^2/148). However, each palm occupies only a fraction of the occupied area. Therefore, with an estimated canopy radius of 3.0 m, it is equivalent to 42% of the estimated occupied area. Each palm requires 113.6 L day^{-1} of water (67.6 m^2 x 0.42 x 4 L m^2 day^{-1}) (Roslan *et al.*, 2011), which represents the estimated amount of water needed to be irrigated according to water requirement. Irrigation timing will depend on the water flow rate, which relies on the water pump efficiency.

The use of the water balance concept for irrigation scheduling is based on soil water content estimation. Daily evapotranspiration and transpiration by leaves show the amount of water that is taken out from the field soil profile. This loss could be replaced either by rainfall or irrigation water (Feddes and van Dam, 2005). When the soil water balance is below the minimum level it indicates that irrigation is required. Water balance under oil palm can be determined by examining the total water needed to generate a balance against the total water input by rainfall and irrigation. For a given volume of soil and plant environment, the water balance Equation (2) (Kee *et al.*, 2000) is as follows:

$$\Delta S = P + I - ET - R - D \qquad (2)$$

where ΔS is the change in soil moisture; P is the precipitation; I is the irrigation; ET is evapotranspiration; R is the surface run-off and D is the drainage.

Yield response. In Malaysia, the variation in FFB yield between dry and wet regions is significant; 10 years after harvesting, the difference in FFB yield between dry and wet regions is between 25.81% and 26.67% (Paramanathan, 2013). Drought reduced palm oil productivity by 10%-30% in Southeast Asia (Paterson and Lima, 2018). Drought raises the temperature as well as affects FFB output; during the drought season, a moisture deficit of 100 mm in a year reduces FFB production by 8%-10% in the year of drought and 3%-4% in succeeding years (Caliman and Southworth, 1998; Fleiss *et al.*, 2017; Suharyanti, *et al.*, 2020). It has been reported that an average temperature of more than 27.83ºC in the eight months preceding harvesting reduces FFB output (Shanmuganathan *et al.*, 2014).

Positive responses to irrigation implementation were reported in Malaysia (Chan, 1979; Chan *et al.*, 1985; Kee and Chew, 1991). Nevertheless, there were cases where irrigation was often uneconomical due to limited water supply, high installation and running costs, poor returns, and relatively low response (Goh, 1995). A study by Foong and Lee (2000) involving a lysimeter was conducted at Sungai Tekam, Pahang, Malaysia, and found the daily potential evapotranspiration of a mature palm would be 5.5-6.5 mm day^{-1}. The potential evapotranspiration for an immature oil palm during dry seasons was about 5.5-6.0 mm day^{-1} while 7.0-8.0 mm day^{-1} was recorded for a mature palm. With optimum water and fertilisers, the lysimeter palm produced an FFB yield of 59 t ha^{-1} yr^{-1} and a total oil yield of 15 t ha^{-1} yr^{-1}. It was observed that irrigation did not affect the seasonal yield fluctuation. Enhanced peak yield and increased yield were observed in some cases. However, this could be due to the trial being well fertilised (*Figure 1*). In most previous studies, irrigation had affected the bunch number rather than the bunch weight (Chan, 1979; Foong and Lee, 2000).

In a distinctly dry environment in Serting, Malaysia, Lee and Izwanizam (2013) reported that for over 23 years, there was an average yield increase of 12 t ha^{-1} yr^{-1} (or 56%) in irrigated palms as compared to the non-irrigated palms. The FFB yield of the irrigated and undulating area (23.96 t ha^{-1} yr^{-1}) is significantly higher than the irrigated terrace area (21.93 t ha^{-1} yr^{-1}). Moreover, there was an increase of 8.5% or 2.03 t ha^{-1} yr^{-1} in the former area (*Figure 2; Figure 3*) (Lee *et al.*, 2008). The increased yield in both areas was dependent on the increase in the bunch number rather than bunch weight.

Corley and Hong (1981) reported an increase of 5% in yield with irrigation on a 12-year-old palm that was planted in the Ulu Tiram and Harimau soil series in Central Johor, Malaysia. The FFB yield increased from 24.7 to 25.8 t ha^{-1} yr^{-1}. In Thailand, a study was conducted in a dry season between December and April, with an average cumulative annual water deficit of 214 mm for over six years (Titinutchanon *et al.*, 2000). In the first trial, two rates of drip irrigation were applied: 150 and 300 L palm^{-1} day^{-1} or 2.1 and 4.3 mm rainfall day^{-1}. As for the second trial, irrigation methods, namely drip, sprinkler, micro-spray and contour furrow were tested at three different rates (120, 240 and 360 L palm^{-1} day^{-1}, or 1.7, 3.4 and 5.1 mm day^{-1}). The irrigation was first applied in the seventh year of field planting, and it was found that at 4-5 mm day^{-1}, the irrigation gave a significant increase in the bunch number per palm but not in the mean of the bunch weight. The dry season had caused higher inflorescence abortion, which resulted in a lower bunch number. However, with irrigation, the bunch number improved.

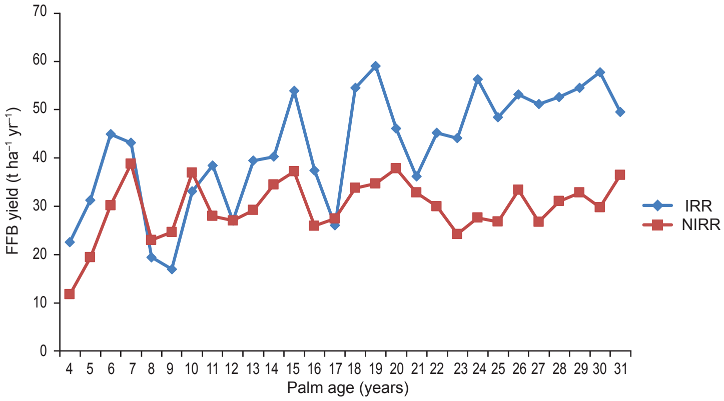

Figure 1. The yearly fluctuation of FFB yields from a single lysimeter study at FELDA's Tun Razak Agricultural Service Centre, Malaysia, where IRR and NIRR denote irrigated and non-irrigated, respectively.

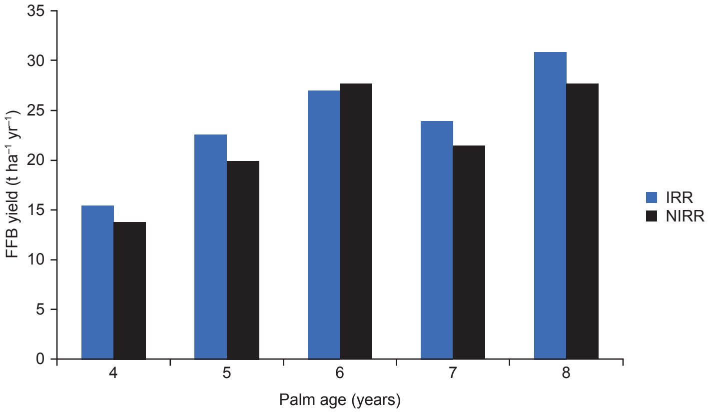

Figure 2. FFB yield from undulating areas with moderate rainfall region in Malaysia with irrigated (IRR) and non-irrigated (NIRR) palms. The mean of extra yield for irrigated palms is about 8%.

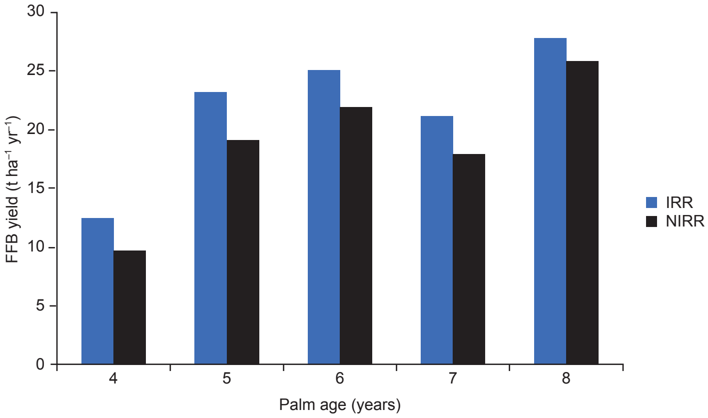

Figure 3. FFB yield from terraced areas with moderate rainfall region in Malaysia with irrigated (IRR) and non-irrigated (NIRR) palms. The mean of extra yield for irrigated palms is about 14%.

Irrigation was only applied when the cumulative water deficit exceeded 30 mm (Roslan and Haniff, 2004b). The FFB yield increase was about 6 t ha^{-1} yr^{-1}. The irrigation showed a significant response, for three out of seven years. Amongst the different irrigation methods, drip and micro-spray irrigation produced higher oil to bunch as compared to those in-furrow and sprinkler irrigation (Roslan and Haniff, 2004b). A review of 15 years of oil palm irrigation implementation in Southern Thailand concluded that the average yield response due to irrigation was about 10 t FFB ha^{-1} yr^{-1} (Tittinutchanon *et al*., 2000).

Another irrigation trial conducted at La Mé, Ivory Coast revealed that the irrigated plots produced higher yields, which was mainly due to the higher sex ratio and the number of bunches produced per palm (Fairhurst and Härdter, 2003; Hartley, 1988b). In Ouidah, West Africa, a study employed by Chaillard *et al*. (1983) on drip irrigation, used polyethylene tubes which were discharged into irrigation rills dug parallel to the rows of palms. In the first part, the yield was recorded at 20.6 t ha^{-1} yr^{-1} with a residual water deficit of 280 mm in the sex differentiation stage. In the second part, a residual water deficit of 360 mm yielded only 13.9 t ha^{-1} yr^{-1}.

Oil palm is a drought-sensitive crop, especially in areas with a moisture deficit of 400 mm yr^{-1}. It was reported that only half of the yields were obtained in zero deficit areas (Stephen *et al*., 2007). In dry areas with distinctly low rainfall for five to seven months each year, the overall mean FFB yield over nine years of irrigated plots showed a significant increase of 24.4 t ha^{-1} yr^{-1} or 25% higher, as compared to non-irrigated plots at only 18.30 t ha^{-1} yr^{-1} (Lee and Izwanizam, 2013). Irrigation during the seasonal dry period might enhance FFB yield by 56% as compared to no irrigation. However, FFB results in moderately moist areas revealed that irrigated areas provided a minor difference of 9% when compared to those without irrigation (Lee and Izwanizam, 2013; Shahkhirat *et al*., 2012). This implies that selecting suitable areas will have a positive impact on irrigation. Without the right selection of site criteria, this irrigation project will fail to meet its objectives or will take a long time to get a high return on investment (ROI) (Norizan *et al*., 2021).

A study by Darmosarkoro (2010) experienced an increase in spear leaf number and frond fracture. Based on water deficit between 200-500 mm yr^{-1}, the number of spear leaves was between 3-5, while the number of fractured fronds was between 1-16. Cheng-Xu *et al*. (2011) reported on water stress studies, which discovered that fertilisation promoted oil palm growth under well-watered conditions, while the growth was negatively affected in underwater stress conditions.

Soil and Water Conservation Practises in Oil Palm Plantation

Irrigation trials showed that a high volume of water was required for oil palm irrigation. Due to the limitation of water availability, unsuitable terrains and logistics, therefore the most practical approach is to preserve the rainfall water that infiltrates into the soil. The various soil and water conservation practices, following forest clearing and replanting, which could reduce water evapotranspiration are summarised below.

Biomass management during replanting. The growth of palms that were planted in residual piles was greater than those planted without biomass, indicating higher fertility in the piles with residues (Khalid *et al*., 1996; 2000a). The mulched areas showed excellent soil structural properties and were rich in organic matter. Crop residue applications can also improve soil moisture-holding capacity. The mulching showed a more definite effect on soil moisture at the initial treatment but gradually decreased with the decomposition of residues. Khalid *et al*. (2000a) recorded significantly higher soil moisture content in the treatment plots with residues during dry periods, such as chipping and pulverisation, as compared to the control plots. The size to which the residues were chopped affects their decomposition rate and directly affected the mulching method that was used to hold the soil moisture. For example, pulverised materials decompose faster than chopped materials, shortening the effect of the mulching on soil moisture.

Terracing and silt pits. Soil erosion is greatly associated with slope steepness, whereby the rate increases with increasing slope gradient. For example, in the second to the fourth year after oil palm planting, the erosion rates on Munchong series soil, with newly established legume ground covers, were 8.8, 24.0, 35.4 and 50.0 t ha^{-1} yr^{-1} on slopes of 2^o, 5^o, 9^o and 15^o, respectively (DID, 1989). This has caused the building of terraces with an adequate back slope and stops bund at regular intervals along the planting and conservation terraces. Soil erosion and run-off can be very severe, even with terraces. Therefore, it is recommended to have silt pits in such areas to reduce the path of water flow, increase water infiltration into the soil, and maximise moisture conservation (Turner and Gillbank, 1974). The construction of silt pits is another typical soil and water conservation strategy in oil palm plantations (Lim, 1989; Soon and Hoong, 2002). The dimensions of silt pits are often 1.2-3.0 m long, 0.6-1.0 m deep and 0.9-1.0 m wide (Lim, 1989; Ramli *et al*., 2016; Soon and Hoong, 2002) built between planting rows and perpendicular to the hill slope direction. Silt pits intend to capture runoff water that contains eroded sediments and nutrients that would otherwise be lost. Following the rainfall event, the collected water and nutrients are redistributed back into the plant root zone around the pits. During land preparation, *Mucuna bracteata* (MB) should be integrated with silt pits or water retention trenches. The length of silt pits varies based on the existing slope and frond placement procedure, but they should be capable of trapping more surface runoff down a slope. When MB and silt pits are used simultaneously, rainwater loss is reduced by 44.83%, illustrating the effectiveness of silt pits in capturing rainwater caused by surface runoff on slopes compared to solely planting legumes. As a result, the combination of MB and silt pits effectively lowers water loss via surface runoff (Afandi *et al*., 2021). Construction of humps and sumps, silt pits in old and new replanting, conservation terraces, planting platforms and *Ganoderma* pits, all of which can be utilised to collect rainwater and benefit the palms later, are some of the options for harvesting rain in rain-shadow environments (Ramli *et al*., 2016).

Establishment of leguminous cover crops and mulching. Legume cover crops need to be established to fully cover the soil as quickly as possible after land preparation. The cover crops could reduce soil erosion and water evapotranspiration and help to improve soil structure and water holding capacity. Besides this, legume cover will also improve soil fertility, soil physical properties and soil microbiological activities (Chan *et al*., 1977). Furthermore, legume cover crops are useful during dry seasons where they improve water infiltration as well as soil temperature reduction (Giller and Fairhurst, 2003). Studies by Khalid *et al*. (2000b) reported the total dry matter of legumes and weeds in the plantation were approximately 5370 and 1930 kg ha^{-1}, respectively. The nutrient contents in the legumes were quite high, recorded at 113 kg N ha^{-1}, 11 kg P ha^{-1}, 106 kg K ha^{-1}, 28 kg Ca ha^{-1}, and 9 kg Mg ha^{-1}. Therefore, the nutrients in legume cover and weeds will become the transient pool that is recycled in the plantation.

Gurmit *et al*. (1989) did an in-depth study of the empty fruit bunch (EFB) advantages of oil palm growth and productivity, including soil properties improvement. The expected organic mulching benefits with EFB included improved soil structure, increased in water holding capacity, improved soil pH and nutrient status, increased in cation exchange capacity, better root growth, increased microbial activities, and reduction in the surface wash, leaching, and soil surface temperature. All these benefits could improve oil palm growth and productivity. EFB was found to minimise erosion and run-off from bare soil around the palm and reduce soil moisture evaporation, especially during the dry months (Lim and Messchalck, 1979). However, the EFB mulching benefits would taper off over time as it decomposes. It is probably ineffective in conserving soil moisture after about 240 days from the time of application. Therefore, re-mulching is necessary after about 200 days to conserve soil moisture effectively (Arif *et al*., 2003).

CONCLUSION

Oil palm growth and yield depends on adequate water supply and evenly distributed rainfall. Uneven rainfall distribution or rainfall shortage could lead to yield fluctuation and thus, decrease the chance to obtain the potential yield. Cultivation of oil palm in regions with prolonged dry seasons or uneven distribution of rainfall could be successful if an adequate source of water is available for irrigation. However, an irrigation system implementation is only economically viable and feasible if the FFB yield increases, which could be achieved through adequate nutrient management and other crop care practices. Drip irrigation was proven to be the most effective method. Combining this method with a fertigation system can be used to maximise the oil palm yield because it can effectively reduce nutrient losses and increase nutrient uptake. This implementation can also help to reduce field supervision and labour shortage in the plantation. Other practices, such as mulching and cover crops, might also be carried out to conserve soil moisture, overcome rainfall shortages and improve soil fertility.

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