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CLIMATE VARIABILITY AND WATER STRESS EFFECTS ON OIL PALM (*Elaeis guineensis* Jacq.) PRODUCTIVITY IN MALAYSIA

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ABSTRACT

Oil palm is a key pillar of Malaysia's socio-economic development, contributing to the nation's economic stability, and is also a major driver of the global oil industry. However, climate variability has progressively reduced the productivity of oil palm (OP) by subjecting it to water stress through inadequate and irregular rainfall, prolonged dry spells, and elevated temperatures. This article reviews past literature and provides useful insights into the effects of climate elements and the physiological and agronomic effects of water stress on OP. Water stress impairs the physiological and metabolic functions of OP, particularly stomatal conductance, leaf water potential, proline synthesis, sex differentiation, and water use efficiency. These combined effects diminish the biomass and yield of OP. This review also highlights the temporal variability of climate and identifies the role of various soil properties related to water stress. It presents climate projections threatening OP sustainability and presents possible solutions. Additionally, the specific fraction of plant-available water necessary for triggering water stress remains under-researched. The relationship between various physiological and genetic mechanisms that control stomatal response during water stress is unclear. The efficiencies of various irrigation approaches and water conservation measures must also be re-evaluated based on climate predictions.

Keywords: climate change, dry spell, global warming, irrigation, water deficit.

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INTRODUCTION

Oil palm has the highest oil yield, and it is harvested regularly throughout the year (DoCampo *et al*., 2021; Yawson, 2015). Globally, its production expands steadily (Dislich *et al*., 2017; Kawamura *et al*., 2014; Paterson and Lima, 2017) and typically reaches its maximum yield at 9-10 years after field planting, with an average fresh fruit bunch (FFB) yield of 16.6-25.6 t ha^{-1} in Malaysia (Kushairi *et al*., 2019; MPOB, 2022). Although oil palm originated from Africa, Indonesia, Malaysia, China, and India are now the major producers and importers (Carr, 2011), thus dominating the global oil palm industry (Abubakar and Ishak, 2022; Voora *et al*., 2019; World Bank, 2021). Oil palm greatly contributes to Malaysian socioeconomic performance (Norizan *et al*., 2021).

Oil palm production in Malaysia is limited because of water stress resulting from water deficits (Mutert *et al*., 1999; Norizan *et al*., 2021), which is identified as the primary constraint to optimum yields (Woittiez *et al*., 2017). Water for oil palm production comes primarily from precipitation (Miller and Donahue, 1992; Shevade and Loboda,

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2019), which is often insufficient or not distributed uniformly throughout the year, leading to water stress and a decline in yield.

Global warming due to climate change (CC) causes water shortages (Jagtap, 2007; Teh, 2017). Mueller (2009) and Okon *et al*. (2021) reported that CC is a phenomenon that affects different regions of the world in various negative ways, particularly the tropics (Idowu *et al*., 2011; Williams *et al*., 2018). The impact of CC through water stress inducement places more pressure on crop production globally than in any other sector (IPCC, 2014). This suggests that more research is required on the impact of CC on crop production (Koh *et al*., 2011; Okon *et al*., 2021). The adverse effects of CC on crop production are both direct and indirect, as well as short- and long-term (Fitton *et al*., 2019; Obioha, 2008). For instance, CC-induced water stress causes oil palm seedlings to wilt, experience stunted growth, and suffer from impaired root development (Okon *et al*., 2021). Over the past decades, efforts to combat CC have been costly, placing a strain on countries both economically and technically (Abubakar *et al*., 2021; IPCC, 2021).

The effects of CC on the oil palm industry are evident. Intense solar radiation and temperature are twin CC elements that cause oil palm yield reductions (Hoffmann *et al*., 2015) through their effects on critical physiological processes (photosynthesis, respiration, and transpiration) (Cheah *et al*., 2020; Teh and Cheah, 2023). Henson and Harun (2005) linked the impact of CC to seasonal fluctuations in the heat energy balance, which affects the oil palm FFB yields at many sites in Malaysia. Henson and Harun (2005) acknowledged that the effects of CC in some parts of Kedah, Malaysia, were so severe that rainfall during April, May, and June was significantly reduced, with average rainfall amounting to only one-third of the reference evapotranspiration (ETo). For instance, February recorded a mere 0.4 mm ETo. Hoffmann *et al*. (2015) observed a wide range of FFB reduction under various water stress scenarios. MPIC (2018) emphasised the need for accurate and real-time data on oil palm response to water stress and its causal factors for biotechnology and breeding projects aimed at developing climate-resilient oil palm planting materials.

Against this backdrop, this review aims to navigate through previous studies to harmonise various submissions on oil palm behaviour when exposed to water stress under varying climate conditions. The goal of this study was to identify research gaps and suggest possible ways forward. We utilised search engines like Google and Edge, as well as academic databases such as ScienceDirect and Google Scholar, to conduct a comprehensive literature search.

IMPORTANCE OF OIL PALM PRODUCTION

Oil palm is central to the global oil market (DoCampo *et al*., 2021). Although it has the least cultivated area for oil crops (Oil World, 2022), its oil output greatly surpasses (20 times) those of *Glycine max* L. (soybean), *Arachis hypogaea* L. (groundnut), *Brassica napus* L. (canola), and *Helianthus annus* L. (sunflower) (Chang *et al*., 2014; Low, 2019; Moraidi *et al*., 2012; Woittiez *et al*., 2017). Corley and Tinker (2016) and Murphy (2021) stated that worldwide, palm oil accounts for approximately 39% of the total vegetable oil consumed (Murphy, 2021) and is being used for the production of critical additives, reagents, polymers, and organo-minerals (Adileksana *et al*., 2020; Bognár *et al*., 2020; Cheah and Hoi, 1999; Chin *et al*., 2020; Gao *et al*., 2020; Jamshaid *et al*., 2022; Liew *et al*., 2021; Masharuddin *et al*., 2021; Otsuka *et al*., 2006; Uke *et al*., 2021).

Oil palm production is crucial for Malaysian socioeconomic development (MPOC, 2019; Pacheco *et al*., 2017); thus, guides central decisions and policy-making (DOSM, 2020; MPOB, 2022; Singh *et al*., 2021). It also provides gainful employment to a large population (Abdul Rahman, 2018; AsianAgri, 2023; Parveez *et al*., 2023), including 70% of job-seeking foreigners (Hamid *et al*., 2013; Hanafiah *et al*., 2022; Nkongho *et al*., 2014; Parveez *et al*., 2022; Pirker *et al*., 2016; Qaim *et al*., 2020). All these describe oil palm as a multi-utility crop worth sustainable production for enhanced global industrialisation and national growth.

OIL PALM GROWTH, YIELD AND PHYSIOLOGICAL RESPONSE TO WATER STRESS

Yield Gap

USDA (2023) data reveals a significant yield gap in Malaysian oil palm production. On average, the country achieves its expected maximum yield in only one out of twelve months (November). Bakoumé *et al.* (2013), Chalvantharan *et al.* (2023), and USDA (2023) confirmed that optimal yields in Malaysia are achieved in only 4-5 months yr^{-1}. Woittiez *et al.* (2017) reported that actual oil palm yields remain less than 50% of their potential (3.3 *vs*. 8.0 t ha^{-1} yr^{-1}). Rhebergen *et al.* (2018) suggested this gap could be even wider in subsistence production systems. Consequently, addressing this substantial yield gap could significantly impact global oil production. Woittiez *et al.* (2017) estimated that closing this gap could improve world oil production by 17.5 t yr^{-1}. In a study of an oil palm plantation in Central Kalimantan, Hoffmann *et al.* (2017) estimated that closing the yield gap through management practices alone could increase its FFB production by 1.2 t ha^{-1} yr^{-1}. These projected increases underscore the significant potential of addressing yield gaps, highlighting how such improvements could substantially enhance food security. The persistent yield gap is closely linked to climate variability (Abdul Rahman, 2018; Bakoumé *et al.,* 2013;). These climatic challenges limit the expression of full yield potential in improved oil palm germplasm (Ariffin *et al.,* 2002; Rhebergen *et al.,* 2020).

Climate Variability and Its Effects on Oil Palm

Climate change or climate variability (UCAR, 2022) is said to occur when changes in climate variables are observed in an extended manner (IPCC, 2013). This means that sudden weather anomalies that occur for one to three years, then disappear would not be considered as climate variability. Climate variability is typically caused by natural and anthropogenic interplay (Idris and Yahaya, 2022), consisting of orbital revolution of the earth, volcanic eruption, movements of the crust (MetOffice, 2023), burning of fossil fuels, and increased concentrations of greenhouse gases (GHGs) from cultivation and deforestation (Green Peace, 2023; Ogle *et al*., 2014). Therefore, the history of oil palm production has been a critical anthropogenic source by which GHGs are added to the earth system (Butler and Laurance, 2009; Fitzherbert *et al*., 2008).

Saifan *et al*. (2021) revealed that 25% of farmers in Malaysia are vulnerable to declining yields due to climate variability-related problems. Abubakar and Ishak (2022) confirmed a link between climate variability and consistent yield downward trend (7.5%) in various regions in Malaysia. Changes brought about by climate variability intensify the water deficit, thereby restricting growers to drought-tolerant oil palm cultivars that are not high-yielding (Masud *et al*., 2017), thus reducing FFB output (Shobande, 2021). Increased ETo losses from weather variability events (Wang *et al*., 2014) negatively impact productivity, as well as reducing the efficient distribution and utilisation of fertilisers and herbicides (Gustafson *et al*., 2015). Variations in climate conditions often shorten the length of the oil palm production cycle (Abubakar *et al*., 2021; Morton *et al*., 2017; Saifan *et al*., 2021) and increase the prevalence of crop diseases and new pests, resulting in low productivity (Melillo *et al*., 2014; Saifan *et al*., 2021).

Climate-related limitations affect perennial crops, such as oil palm, as their performance is influenced not only by current weather conditions but also by the lingering effects of past climate events (Carr, 2011). In 2018, oil palm production was negatively affected by climate factors, likely exacerbated by the cumulative effects of previous years' climate variability (Kushairi *et al*., 2017). However, an adequate understanding of the legacy or residual effects of CC either at the spatial or temporal scale is still scarce.

Although climate variability in Malaysia is less pronounced than in African countries like Nigeria (NiMet, 2022), it still significantly leads to unexpected yield variations across different locations and seasons (Nelson *et al*., 2006; Sarkar *et al*., 2020; Tang, 2019). Based on Kushairi *et al*. (2019) and MPOB (2018), between 2015-2018, yield variance stood at 17% ha^{-1} basis (from 15.91 t ha^{-1} in 2016 to 19.92 t ha^{-1} in 2017). They further confirmed that the observed yield variance was linked to changing climate patterns, as the water deficit in 2017 was far less than in 2016.

Economically, Zainal *et al*. (2012) estimated that a 1°C increase in temperature due to climate variability would result in losses of USD10.63 ha^{-1} in Peninsular Malaysia, USD10.89 ha^{-1} in Sabah, and USD9.01 ha^{-1} in Sarawak. Furthermore, over the next 6, 36, and 76 years from 2023, oil palm net revenue is projected to decline by an average of USD81.52, USD30.44, and USD12.37 ha^{-1}, respectively, due to the continued effects of climate variability (Zainal *et al*., 2012). Malaysia faces potential economic insecurity if erratic climate patterns lead to decreased oil palm yields and reduced palm oil prices (Swaray *et al*., 2021).

Lim *et al*. (2022) pointed out that the occurrence of abrupt global hydrological phenomena such as *El Niño*, which amplifies the water stress problem, is another form of climate variability. *EI Niño* is an abnormality that occurs when less rainfall occurs in the western Pacific but more is experienced in the eastern part, resulting in drought and flooding, respectively (National Geographic, 2023). Although its occurrence was only five times between 1980 and 2000, it resulted in severe consequences of production reductions (ACT, 2011). Oil palm production was severely affected by *EI Niño* in 1997-1998 (Lim *et al*., 2008) and in 2016 (Parveez *et al*., 2022). Findings from a long-term study (spanning 33 years) indicated that *EI Niño* increased potential ET by up to 95% (Tui and Arifin, 2013). Kamil and Omar (2017) attributed a significant loss of yield to *El Niño* in Malaysia and other tropical countries.

Globally, Hekstra (1986) maintained that climate variability, particularly through changes in precipitation and temperature, has led to low productivity by 5%-20% and decreased crop production quality (Alam *et al*., 2017).

In summary, insufficient rainfall, partly driven by *El Niño* and climate fluctuations, leads to water stress conditions that severely threaten palm oil production.

Temperature Variability and Its Effects on Oil Palm

Pour *et al*. (2014), The Star (2022), and Wang *et al*. (2014) stated that the escalation of global and regional temperatures is a product of long-term climate variability. IPCC (2013) and Shahid *et al.* (2017) confirmed that the rising number of hot days and sustained temperature increases in various regions of Malaysia are clear indicators of climate variability, which directly influences oil palm productivity (Corley and Tinker, 2016). Tang (2019) reported that over three decades, temperature trends varied across different zones in Malaysia, with increase of 7.55% in Kota Kinabalu, 7.27% in Kuching, and 10.20% in Malacca, Kuantan, and Subang Jaya. NRE (2015) reported that the ten-year temperature increase in the Peninsular was 56.40% higher than that experienced in Sarawak. Abdul Rahman (2018) corroborated that although an increase in temperature was recorded in all regions, the Peninsular was 33.30% warmer than the eastern part of Malaysia based on approximately five decades of data.

Sammathuria and Ling (2009) reported that the climate variability experienced in Malaysia included unusually high temperatures that occurred five times between 1972 and 1998. Al-Amin *et al*. (2015) and Murad *et al*. (2010) pointed out that increased heat, which was observed around 1983-1987, originated from anomalous temperature rise. In Malaysia, day-to-day temperature variation is more obvious and anomalous than the average year-to-year temperature variation (Murad *et al*., 2010).

However, the relationship between ambient and soil temperatures and their simultaneous effects on oil palm growth and development has not yet been identified. Although Nuruddin and Tokiman (2005) sought to establish ambient temperature as the best explanatory variable for soil temperature, finding a high regression coefficient ($R^2 = 0.96$), the 1 cm depth at which they measured soil temperature was not sufficiently reliable to represent the active rhizosphere of oil palm roots.

Temperature has diverse effects on various biochemical and anatomical processes in oil palm, particularly by reducing activation energy, which influences metabolic rates and enzymatic activities (Kim, 2010; Kirkham, 2005; Mazlan *et al*., 2021). Generally, mature oil palm requires a temperature of 24°C-28°C for optimal growth and development (Lim *et al*., 2008), above which the dry matter yield is reduced up to 16% due to excessive ET rates (Okon *et al*., 2021). Lim *et al.* (2021) reported that prolonged periods of temperatures below 21°C led to a high rate of flower abortion, which in turn resulted in a 3.2% reduction in FFB yield. The growth of young seedlings was impeded at temperatures below 15°C but stimulated at above 20°C (Lim *et al*., 2008). In a separate study, Ferwerda and Ehrencron (1977) found that exposing oil palm to 22°C and 8°C day and night temperatures, respectively, for 120 days resulted in a complete cessation of growth in oil palm. However, when temperatures increased to between 12°C and 27°C, frond leaf production increased in a quadratic pattern. Okon *et al.* (2021) suggested that temperature sensitivity varies among oil palm cultivars, with some cultivars demonstrating a better ability to withstand prolonged exposure to high temperatures compared to others. However, a key question remains: How long will the effects of high temperatures continue to impact oil palm growth and yield after the initial exposure? In addition, little is known about the lower and upper critical limits for optimum oil palm performance.

Rainfall Variability and Its Effects on Oil Palm

Gleick (1989) found that the rate of rainfall reduction due to climate variability across the globe was 100%-200% compared to pre-industrial times. In Malaysia, Tangang *et al*. (2012; 2018) reported that changes in the pattern and intensity of rainfall have been observed since the early 2000s. Observations by Abdul Rahman (2018) revealed that Sabah and some parts of the Peninsular (*e.g.*, Pahang and Kelantan) received 5% less rainfall on average due to climate change. Noor *et al.* (2018) analysed rainfall patterns in Malaysia using intensity-duration-frequency (IDF) curves, which describe the probability of rainfall intensity occurrence over given time periods. These curves, generated from hourly rainfall data from 1971 to 2005, revealed high rainfall intensity with wide variability across the Peninsular. However, the state of Kedah showed a consistent decreasing trend in rainfall intensity, particularly within the first ten years. Both observed and simulated hourly rainfall records confirmed highly variable trends throughout the studied areas.

Carr (2011), Finucane and Keener (2015), and UNM (2022) stated that rainfall variability can be observed through fluctuations in the groundwater hydrology, especially in areas close to the shoreline, such as parts of Sabah, Penang, and Sarawak (Mayowa *et al*., 2015). This becomes clearer during the southwest monsoon season (Tang, 2019).

Rain is the major source of water for the agricultural production of all crop types (Benešova *et al*., 2012; Fischer *et al*., 2007; Ibrahim *et al*., 2020; Najihah *et al*., 2022; Norizan *et al*., 2021; Sadiq *et al*., 2022a), making it the most limiting factor in oil palm production (Goh, 2000; Jazayeri, *et al*., 2015). ACT (2011) added that the effect of rainfall on oil palm production has been underscored since 1965 (Tui and Arifin, 2013), with most results showing a linear rainfall-yield relationship ($r = 0.89$). Similarly, DoCampo *et al*. (2021) corroborated that the harvesting peak for oil palm always coincided with months of high rainfall. Furthermore, Hermantoro *et al*. (2018) found that in Lampung and Palembang, where rainfall supplied 100 mm less water month^{-1}, the yield decreased by 9.0% and 3.5% in the first and subsequent years, respectively. This is expected because all metabolic processes governing oil palm growth and development are water-dependent, either as major constituents or catalysts (Karananidi *et al*., 2020; Weil and Brady, 2017). In addition, the role of rainfall as a principal water source extends to nutrient dissolution, availability, and subsequent uptake (Norizan *et al*., 2021), resulting in the formation of high-quality and high-quantity FFB (Woittiez, 2019). Therefore, even a narrow difference in the rainfall among locations can lead to a wide difference in yield outcomes (Donough *et al*., 2011; Paterson and Lima, 2017).

However, Corley and Tinker (2016) noticed that the relationship between the total rainfall and FFB yield has been inconsistent. This may be due to the contribution of other rainfall attributes, namely, distribution and intensity (Jadhav, 2019; Oettli *et al*., 2018; Sarkar *et al*., 2020). According to Najihah *et al*. (2022), Usman *et al*. (2013), and Woittiez (2019), the frequency of rainfall occurrence reasonably dictates the oil palm yield by determining the sex ratio, number of spikelets, percentage of fruit set, and weight per fruit bunch. A similar effect of precipitation variability was reported to constrain oil palm production in neighbouring countries of India and Bangladesh (IRRI, 2007).

Additionally, the interplay of other factors, notably soil hydraulic properties, the presence of surface cover, and the crop's rooting system significantly influences the effectiveness of rainfall received per unit area. The question is, can we have studies dedicated to experimenting the effect of the amount, distribution, and intensity of rainfall over a complete production cycle of oil palm under various weather conditions in Malaysia?

Climate Events Variability and Its Effect on Oil Palm

Climate variability can also be examined through the occurrence of extreme conditions such as flooding and drought (IPCC, 2013; 2014). Al-Amin and Leal Filho (2014) observed that historical climate variability in Malaysia has led to an increased frequency of floods in some areas, while exacerbating water scarcity in many others (The Star, 2022). Flood occurrence, which has been steadily increasing since 1980, showed a sharp increase between 2000 and 2005 and peaked around 2010 (Laudicina and Peterson, 2015). Nashwan *et al*. (2019) and Tam *et al*. (2021) believed that climate variability that triggered heavy rainfall during the Northeast monsoon was the leading cause of the unprecedented flood that the Kelantan River Basin experienced towards the end of 2014. Data presented by Tam *et al*. (2021) indicated that floods occurred consecutively every year from 2001 to 2014, except in 2002, along the Kelantan River Basin area. However, its magnitude varied widely (0.2 m in 2011 – 6.8 m in 2014). Similarly, the floods that occurred in 1998 and 2007 suggest climate variability (Al-Amin *et al*., 2011). Murad *et al*. (2010) noted that the reoccurrence of these extreme meteorological hazards could potentially turn productive oil palm land into marginal or permanently unsuitable. Similarly, Lamade *et al*. (1998) and Henson *et al*. (2008) reported that long-term flooding deleteriously affects photosynthesis and transpiration and leads to premature death of young palms, stunted growth, and productivity loss (Carr, 2011).

Drought variability over a temporal scale is not only peculiar to Malaysia but also to other Asian countries where both intensity and frequency of droughts are increasing (Manikandan and Tamilmani, 2015; Tabari *et al*., 2013). According to Hasan *et al*. (2021), results from 40 years data revealed that approximately 50% of the basin areas in Malaysia have been experiencing drought at different time scales. Hasan *et al*. (2021) and Huang *et al*. (2023) showed that the highest drought intensities were observed from 1997 to 1999 and 2016 to 2018, and were more prevalent in several areas in Peninsular with a frequency of 39.25%. Specifically, the 1998 drought was very severe and, as such, increased water scarcity. The historic variability trend of drought (1985-2019) indicated that critical droughts around the Muda River occurred for 12 years (1991-2016), with the highest frequency occurring from 2003 to 2007 (Luhaim *et al*., 2021). Moreover, Sukarman *et al*. (2022) concluded that all 18 of the studied oil palm plantations showed evidence of drought spells equivalent to a 450 mm water deficit annually between 2000 and 2004, which were more frequent between January and May.

Drought is characterised as a short-term cessation of rainfall (>5 days) or an annual precipitation below 1200 mm yr^{-1} (Hartley, 1988). This phenomenon can lead to soil moisture depletion beyond the crop's tolerance threshold, resulting in severe bunch failure, abortion, and decreased yield due to water deficit (Chi and Qi, 2021; Kirkham, 2005; Sukarman *et al*., 2022; National Geographic, 2023).

The oil palm tree possesses unique morphological features, including a highly lignified cuticle and hypodermis, which can mask overt physical symptoms of drought-induced water stress (Rees, 1961). However, prolonged drought periods of three to six months can significantly reduce yield, biomass accumulation, and leaf area index (Carr, 2011; Corley and Tinker, 2016; Goh, 2000; Grossiord *et al.*, 2020). Moreover, drought-facilitated water stress has been associated with a consequential reduction in the quantity of extractable oil in the subsequent year (Muhamad Rizal and Tsan, 2008; Neto *et al.*, 2021).

In the context of Southeast Asian oil palm cultivation, particularly in Malaysia and Indonesia, climate variability-induced droughts lasting one to three consecutive months can have significant impacts (Abubakar and Ishak, 2022). Such drought events can potentially cause yield losses of up to 10 t of FFB ha^{-1} yr^{-1} (Olivin, 1986).

Mohd Arif (2005) revealed that most edaphic production constraints in unsuitable areas of Malaysia, such as soil acidity, nutrient imbalances, sandiness, and hardness, are linked to drought. These conditions exacerbate water limitations by reducing groundwater recharge and soil moisture reserves (ACMAD, 2022), which are essential for continuous water uptake by oil palm. However, according to Carr (2010) and Corley and Hong (1982, 1998), less frequent drought spells caused minimal reductions to oil palm yields as well as insignificant impacts on leaf budding and initiation rates.

In summary, the recurrence of both dry spells (droughts) and floodings reduces oil palm production capacity in Africa, Asia, and Latin America (Fischer *et al*., 2007; Lee and Ong, 2006; Malay Mail, 2015; Marengo *et al*., 2009; Paeth *et al*., 2009). As such, ACMAD (2022) emphasised that any serious scientific community must be motivated to act swiftly to mitigate their consequences since they most often occur unnoticed (NiMet, 2022).

Effects of Solar Irradiance on Oil Palm

Oil palm generally requires approximately 5 hr day^{-1} of sunshine hours for optimal photosynthesis (Lim *et al*., 2008). Several studies have reported a strong positive linear relationship between sunshine hours and FFB yield, with sunshine potentially enhancing yield by up to 80% (Cheah and Hoi, 1999; Lamade and Setiyo, 2002; Lim *et al*., 2008).

Reduced solar irradiance due to self-shading (when upper fronds shade lower fronds of the same palm) has been reported to reduce photosynthetic efficiency by 57%, drastically reducing yield. Hoffmann *et al.* (2014) explained that the lower fronds, likely because they were blocked from direct sunlight, contributed very little to FFB formation (Hartley, 1988; Henson, 2002).

A yield simulation using an oil palm potential growth model named PALMSIM estimated that FFB could reduce to 10 t ha^{-1} when constrained by irradiation (Hoffmann *et al*., 2014). Caliman and Southworth (1998) observed reduced yield from solar radiation obstruction due to open burning. They established that shortened sunshine hours decreased FFB by 1.3-4.7 t ha^{-1} yr^{-1}. Haze conditions tend to reduce solar radiation reaching the oil palm trees via reflection or absorbance. Aziz *et al*. (2018) revealed that haze decreased solar radiation by 22.0%-45.0%, which resulted in declined photosynthesis by 12.9%-53.2%.

In the Peninsular, the average sunshine hours recorded by Tui and Arifin (2013) was 5.57 hr day^{-1} from 1979 to 2011, representing the lower limit of the optimum amount reported by Carr (2011). Therefore, optimisation of solar radiation reception through research could help enhance assimilate production (Corley and Tinker, 2016; Lim *et al*., 2021). Proper planting density and planting orientation that avoids self-shading and leaf overlap are important for maximum radiation interception.

Effects of Relative Humidity and Vapour Pressure Deficit on Oil Palm

Oil palm thrives in humid environments (DoCampo *et al*., 2021). This means that relative humidity (the amount of water vapour in a particular air volume) (Van der Pol *et al*., 2015) is a critical parameter for oil palm productivity (Maikasuwa, 2013; Obioha, 2008; Rhebergen *et al*., 2019). Van Ierland *et al*. (2006) stated that relative humidity (RH) significantly affects key internal mechanisms and the surrounding oil palm system, influencing the final yield. Lim *et al*. (2022) reported a relationship between stomatal aperture and ambient RH, where lower RH reduces stomatal apecture, leading to reduced photosynthetic efficiency and a decrease in net biomass weight. Oil palm seeds perform poorly during the germination stage when RH is lower than 75% and higher than 90% (Lubis, 1992).

Kirkham (2005) states that vapour pressure deficit (VPD) and RH are interrelated in function because RH is the ratio of the actual vapour pressure to the saturated air vapour pressure (Miller and Donahue, 1992; Van der Pol *et al*., 2015). Jacquemard (1998) asserted that a high RH is required to offset the effect of high temperatures so that the VPD is maintained at the optimum state. Jacquemard (1998) inferred that VPD above 1.8 kPa and RH = 58% triggered stomatal closure at 30°C, causing significant yield reduction.

Based on the regression output, a high VPD would reduce stomatal conductance, which in turn, reduce photosynthesis (Henson, 1995; Van Ierland *et al*., 2006). Furthermore, Henson (2009) confirmed that considerably high VPD reduces total dry matter production, and its severity increases if VPD is coupled with soil moisture deficit (Lim *et al*., 2008). In a separate study, Henson and Harun (2005) and Price and Black (1990) noted that VPD, together with temperature, explained 20%-31% of the carbon dioxide (CO_2) flux. This directly influenced the rate at which oil palm generated photosynthates for FFB production. Suboptimal CO_2 levels adversely affect the oil palm internal hydraulic system, causing an appreciable (13.2%) yield loss (Grossiord *et al*., 2020). Fieldwork evidence affirmed that at a very high VPD, oil palm metabolic activities are hampered or ceased completely, affecting the reproduction phase (Setyo *et al*., 1996; Tani *et al*., 2003; Villalobos *et al*., 1993). The negative effect of high VPD on oil palm yield and growth attainment was significant at p=0.05, and these negative impacts could not be adequately reversed by re-watering efforts (ACT, 2011). The specific VPD threshold beyond which recovery becomes impossible still remains unclear.

Climate Prediction

Paterson *et al*. (2017) remarked that the climate over the next 70 years will be particularly challenging for oil palm production, thus requiring a paradigm shift in cultivation methods (Rival, 2017). Fleiss *et al.* (2017) and Paterson *et al.* (2015) stated that, like other crops, oil palm is highly dependent on climate. Therefore, the projected temperature increase of more than two-fold (IPCC, 2007) could potentially reduce its productivity by exacerbating water stress and weakening its defense mechanisms (Fleiss *et al.*, 2017). Teh and Cheah (2018) reported that CORDEX SEA (https://cordex.org) projected the air temperature in Malaysia may rise by up to 3.2°C, and the country may experience lower rainfalls by 20% by the end of the 21st century. Loh *et al*. (2016) further estimated that the projected temperature rise across all the climate change scenarios ranged from 2.3°C to 3.7°C.

Leta *et al*. (2018) and Siderius *et al*. (2018) stated that the rate of drought occurrence and its intensity were projected to increase by 1%-30% within the 21st century. Based on NAHRIM prediction, from 2025 until 2030, Terengganu will be vulnerable to intermittent drought experiences (Malay Mail, 2020; Reuters, 2023). The rainfall forecast showed a highly variable status across seasons, but dry spells will persist longer by 30% in the driest months (December-May), while wet spells will increase by the same percentage around mid-year (Loh *et al*., 2016).

Shanmuganathan *et al.* (2014) observed that the triangular benefits of oil palm production-high quantity, quality, and net profit-are likely to decline if climate conditions become unfavorable, as projected by Al-Wabel *et al.* (2020) and Teh and Cheah (2018). Extreme temperatures, irregular rainfall, and prolonged dry spells contribute to harsh weather conditions (Tang and Al-Qahtani, 2020). Therefore, closing all potential water loss gaps through enhanced conservation measures is essential for ensuring sustainable oil palm production.

EFFECTS OF WATER STRESS ON OIL PALM

The response of oil palm to water stress involves multiple physiological and genetic mechanisms (Hanafiah *et al.*, 2022; Jaleel *et al.*, 2009; Shao *et al.*, 2008), making it challenging to fully understand and predict its behavior under such conditions. In addition, the time taken for oil palm to reach maturity and reproduction stage complicates the understanding of the water stress-yield connection (Carr, 2010; Corley and Tinker, 2016).

Lim *et al*. (2008) and Suharyanti *et al*. (2020) found that water stress triggers various physiological responses as adaptive strategies, such as midday stomatal closure, shading of older leaves, extension of root system, and conversion of stored trunk starch to support bunch and inflorescence development (Carr, 2011). As a result, this process inhibits growth of new leaves and delays shoot development (Rivera *et al*., 2012).

Under persistent water stress conditions, canopy thinning, dropping of developing bunches, and eventual tree death can occur (ACT, 2011). Jazayeri *et al*. (2015) observed that young oil palm seedlings in nurseries often failed to recover even after water was resupplied following periods of extreme water stress. This vulnerability is likely due to the absence of well-established root system and insufficient starch reserves in the trunk, which are characteristics typically found in mature palms (Lim *et al*., 2008). The underdeveloped state of these young plants makes them particularly susceptible to drought-induced physiological damage, from which they struggle to recover even when water becomes available again. This signifies that water stress is associated with poor yield and less vegetative vigour and could lead to permanent wilting and death at higher severity. Lim *et al*. (2008; 2021) posited flower abortion is a more immediate and severe consequence of water stress in oil palm compared to changes in sex differentiation.

Henson and Harun (2005) stated that during the 4-5 dry months in the northern part of Kedah, oil palm initially maintained high ETo rates in response to water stress, driven by high sensible and latent heat. However, as the stress persisted, ETo decreased, and only returned to normal levels when sufficient moisture (5 mm day^{-1}) was restored in June. However, under mild water stress, the ETo rate showed no significant difference compared to that of fully watered crops (Ibrahim *et al*., 2020).

Jazayeri *et al*. (2015) experimented with the *tenera* hybrid of oil palm tolerance to water stress levels. They observed that high and severe water stress levels (50.0% and 25.0% of ETo, respectively) caused a drastic decline in leaf water potential by 66.7%, photosynthetic rate by 28.6%, and water use efficiency (WUE) by 26.87%. The rate of photosynthesis in week 4 and 8 was reduced by 23.0% and 53.0% for IRHO7010 germplasm, respectively. For the IRHO1001 germplasm, the rate was reduced by 46.0% and 74.0%, respectively. Similar reduction in photosynthesis have been linked to chlorophyll and carotenoid degradation and reduce ATP synthesis in other crops (Boughalleb and Hajlaoui, 2011; Cha-um *et al*., 2013; Pan *et al*., 2020), which in turn stunted shoot growth (Farooq *et al*., 2009). This suggests that different oil palm cultivars may respond differently to water stress, though more empirical evidence are needed to confirm this assertion.

High concentrations of proline, malondialdehyde, abscisic acid, and relative electrolyte leakage have been observed, all of which play a central role in moderating the stomatal responses to mitigate the effects of water deficit (Cha-um *et al*., 2013; Henson *et al*., 1992; Najihah *et al*., 2022). Proline is the most prominent chemical indicator of water stress (Cao *et al*., 2011), and it is a biochemical solute produced through glutamate intermediates and oxidation by P5CR (Sun *et al*., 2011).

The flux of CO_2 peaked during the morning hours but gradually declined as water stress intensified by midday, reflecting maximum assimilation in the morning and minimum assimilation at midday, as observed in oil palm (Henson and Harun, 2005) and similarly reported for groundnut (Reddy *et al*., 2003). This was more marked in the driest month of February when CO_2 was as low as 1 g m^{-2} h^{-1} (Reddy *et al*., 2003). (Henson and Harun 2005) and Price and Black (1990) reported that physiological responses to water stress, as measured through nighttime gaseous exchange, were difficult to interpret due to large hourly variability, and that this variability might be attributed to reduced VPD and the absence of solar irradiation during nighttime.

Oil palm primarily responds to water stress through two initial mechanisms: Stomatal closure and cell membrane depolarisation, as reported for oil palm (Jazayeri *et al*., 2015) and similarly observed in other crops (Hopper *et al*., 2014; Jaleel *et al*., 2009; Reddy *et al*., 2003). Depolarisation refers to a change in the electric charge distribution across the cell membrane. This process is initiated by the activation of anion channels in the stomatal guard cells (Brault *et al*., 2004). As a result, the interior of the cell becomes less negatively charged relative to the exterior (Nuhkat *et al*., 2021). This change in membrane potential plays a crucial role in facilitating communication between cells and coordinating various physiological responses within the plant (Nuhkat *et al*., 2021).

Zhou and Yarra (2022) identified several genetic transcription factors, including bZIP, EgbZIPs, and specifically 11 EgbZIPs, that are activated when oil palm is exposed to water stress. This discovery of genetic indicators has significant implications. Parveez *et al.* (2023) suggested that such discovery could broaden the scope for developing genetically modified oil palm varieties and enhance advanced conservation practices. However, despite these advancements, a key question remains unanswered: Among the various genetic, enzymatic, and hormonal responses to water stress, it remains unclear which occurs first to trigger stomatal closure. This gap in our understanding highlights the complex nature of plant responses to water stress and indicates areas for future research.

WATER STRESS IN RELATION TO SOIL PROPERTIES

The limited availability of water to plant roots, which is primarily determined by soil properties, is a critical factor that can lead to poor performance and, in severe cases, complete crop failure (Lindh *et al*., 2022; Miranda *et al*., 2021). This phenomenon explains the observations made by Safitri *et al.* (2019), Sukarman *et al.* (2022), and USDA (2017) regarding oil palm performance under different soil conditions. These studies found that oil palms receiving equal amounts of water exhibited varying degrees of water stress severity depending on soil texture. This variation in water stress, influenced by soil properties, ultimately contributes to the observed yield gap in oil palm cultivation (Hoffmann *et al*., 2015; Nasution *et al*., 2017; Woittiez *et al*., 2015). The prominent role of soil texture in water availability underscores the argument made by Norizan *et al.* (2021) against the practice of applying uniform irrigation across different soil types. As Kirkham (2005) explains, this approach is unjustifiable due to the varying hydro-physical attributes of different soil textures. These differences significantly influence how water is retained and made available to plants.

Idris (2020), Kushairi *et al.* (2019), and Paramananthan (2003) maintained that soil texture considerably influences the water productivity and yield of oil palm and other arable crops. Gunawan *et al*. (2020) and Kirkham (2005) highlighted that soil texture strongly determines water accessibility to crops, mostly in relation to drainage, infiltration, and hydraulic conductivity. Carr (2011) and Goh (2000) identified soil texture variation as a key factor influencing productivity differences among oil palm cultivated lands in Asia. Soil texture plays a crucial role in determining how much water the soil can retain and release at different stages of moisture content, such as when the soil is fully saturated (saturation), at its optimal water-holding capacity (field capacity), or when plants can no longer extract water (permanent wilting point)

(Saxton *et al*., 1986; Teh and Iba, 2010). These distinct moisture levels in soil water retention significantly impact oil palm productivity (Mutert *et al*., 1999; Woittiez *et al*., 2017).

Oil palm's susceptibility to water deficit stress is closely linked to soil texture, particularly the soil's capacity to retain plant-available water (PAWC) (Carr, 2011; Hoffmann *et al*., 2014). This relationship becomes evident when comparing different soil types. For instance, Hoffmann *et al.* (2015) observed that sandy loam and clay loam soils possess significantly higher PAWC compared to sandy clay soils. The variation in PAWC among soil types has important implications for oil palm cultivation. Soils with intrinsically low PAWC make oil palms more vulnerable to water stress, potentially affecting crop productivity. This vulnerability is likely due to variations in the critical water depletion limit specific to each soil type.

In a separate study, Jourdan *et al*. (2000) examined oil palm root expansion and distribution, especially within the active root zone. Sandy soils retain less water and drain faster than clay soils (Kasno and Subardja, 2010; Teh, 2016). While oil palms can grow in various soil types due to its tolerance for different soil conditions, achieving maximum yield requires soils that retain water well yet make it easily accessible to the trees (Norizan *et al*., 2021).

Coarse sandy soils and fine clayey soils (vertisols) significantly reduce oil palm yields (Paramananthan *et al*., 2000). Heavy clay soils have very low infiltration rates, potentially causing waterlogging that can lead to sudden mortality in immature palms or yield reductions of up to 25% (Abram *et al*., 2014; Lee and Ong, 2006). These findings indicate that neither coarse- nor fine-textured soils meet the optimal water requirements for oil palms. The varying clay and sand content in soils directly affects water availability.

Additionally, soil bulk density (BD) is strongly linked to water stress (Michael and Dunn, 2000). BD increases in deeper soil layers, implying that roots may increasingly struggle to penetrate the entire soil profile, limiting their ability to access water throughout the soil solum (Nasrul *et al*., 2002). Wiratmoko *et al*. (2015) advised that good tillage operations can be undertaken to improve BD and soil tilth for root development. BD also affects root anchorage and soil attachment. Gray *et al*. (2015) observed that poor anchoring due to low BD can render soil less suitable for sustainable oil palm production due to lodging and uprooting tendencies. Othman *et al*. (2011) reported that lodging exposes oil palm roots to excessive dehydration and breakage, reducing their water uptake potential (Lim *et al*., 2008). Kirkham (2005) and Venturas *et al.* (2017) maintained that when crop roots are injured, the xylem tissue responsible for conducting water also becomes affected; hence, water transport system becomes impaired. This indicates that exposed and broken root systems can increase water stress severity. Dolmat *et al*. (1993) and Tie (2004) recommended mechanical compaction (Mutert *et al*., 1999) as a strategy to curtail root lodging and uprooting in low BD soils.

Poor soil cohesion leads to weak root attachment, potentially reducing water uptake (Paramananthan, 2013). Other soil morphological and chemical properties also influence water availability through various mechanisms.

Coarseness in the plough layer hinders hydraulic permeability, limiting water availability to roots (Nasrul *et al*., 2002). Similarly, studies by Afandi *et al.* (2022) and Woittiez *et al.* (2017) indicated that soil shallowness restricts vertical root growth and reduces root density. Root density, particularly within the upper 30 cm of soil, is crucial as it directly influences the amount of water available for plant uptake (Afandi *et al*., 2022). In Malaysia, soil shallowness is a significant issue, exacerbating water stress and limiting optimal yields (Fairhurst and McLaughlin, 2009). In contrast, deep soils promote extensive root systems that enable better water exploration by oil palm (Dufrêne *et al*., 1992; Rey *et al*., 1998).

However, soil salinity also plays a critical role in controlling water transmission and uptake, as noted by Mutert *et al.* (1999). Furthermore, water stress is aggravated in soils with moderate to extreme acidity, which negatively impacts oil palm performance (Mutert, 1999; Paramananthan, 2013). Adam *et al.* (2011) found that when oil palm is exposed to both water stress and soil acidity, the plant produces more male inflorescences and fewer female flowers, which directly lowers its productivity.

Olivin (1986) categorised soils based on their oil palm yield productivity under water deficit conditions, assuming all other production factors remained constant. Soils yielding 25-27 t ha^{-1} yr^{-1} under 0 mm water deficit and 16-18 t ha^{-1} yr^{-1} under 200 mm water deficit were deemed suitable. In contrast, soils yielding 22-16 t ha^{-1} yr^{-1} with no water deficit and 9-13 t ha^{-1} yr^{-1} under a 200 mm water deficit were considered the least suitable for oil palm cultivation.

MITIGATION EFFORTS IN OIL PALM PRODUCTION

Irrigation

When rainfall fails to meet oil palm ETo demands, irrigation is applied to meet the shortfall. A fully irrigated oil palm has a crop coefficient (Kc) between 0.9 and 1.0, indicating minimal water stress (Carr, 2011; Teh, 2016). Early research by Ochs and Daniels (1976) revealed a significant effect of irrigation on yield, with results showing threefold increase. Further studies by Tui and Arifin (2013) reported a 57% higher mean annual yield under irrigation conditions than under rainfed conditions over approximately 33 years. Henson (2009), using OPRODSIM, found a 25% yield increase with irrigation, with further improvements when comparing the two irrigation schedules. Teh (2017) used an oil palm growth model to estimate that even a daily supplementation of 1 mm could boost yields by 1.5 t ha^{-1}, particularly in water-deficient areas where yields commonly increase by 50% (Lee and Izwanizam, 2013). Woittiez *et al*. (2017) found a direct link between irrigation water volume and FFB yield, and Nasir *et al*. (2014) showed that oil palm irrigation increased bunch weight, number, FFB, and average fruit weight by 10.0%, 44.0%, 27.0%, and -22.3%, respectively.

Rao *et al*. (2008) discovered that irrigating oil palm progeny hastened fruit production by 20% and increased yield by 55%. Chalvantharan *et al*. (2023) reported an 18.2% yield increase with sprinkler irrigation, although Palat *et al*. (2008; 2012) observed no significant yield variation across different irrigation methods. Prioux *et al*. (1992) reported that irrigation doubled the mass of tertiary roots and increased their spread by 20-100 cm, and Lee *et al*. (2005) noted a 5% increase in bunch number and oil-bunch ratio over three years.

Despite the high initial costs, the long-term yield benefit makes irrigation a viable option (Norizan *et al*., 2021; Sadiq *et al*., 2022b). However, these costs pose a challenge to smallholder farmers (Teh and Cheah, 2018). Sadiq *et al*. (2022a; 2022b) and Tui and Arifin (2013) found that irrigation investment is profitable in tomato cultivation, and Tui and Arifin (2013) similarly reported profitability, although economic benefits can vary, as seen in the negative ROI findings for smart irrigation by Chalvantharan *et al*. (2023) and the modest yield increases reported by Corley and Hong (1982). Variability in returns can be attributed to differences in water costs, production scale, and other factors (Miller and Donahue, 1992). The lack of technical expertise among Malaysian growers presents a significant barrier to effective irrigation (Chalvantharan *et al*., 2023; Khan *et al*., 2018; Norizan *et al*., 2021), and Mason *et al*. (2019) recommended tailored irrigation strategies based on climate forecasts.

Surface Mulching

Water conservation efforts have focused on optimising the productivity of increasingly scarce freshwater due to climate variability for higher yield and sustainability (Abdullah and Sulaiman, 2013; Donough *et al*., 2011; Fereres and Soriano, 2007). Mulching with oil palm residues, such as shredded trunks and fronds, mitigates excessive evaporation and runoff, thereby enhancing water conservation (Khalid *et al*., 2000; Moraidi *et al*., 2013; Morgan, 2005). DoCampo *et al*. (2021) noted that such mulching reduces water stress impact, which is prevalent in dry months. Khalid *et al*. (2000) found that mulching with shredded residues increased soil moisture by 28.0%, compared to 25.2% in other treatments. Mulching with empty fruit bunches (EFB) led to a 39.0% increase in yield by improving water storage and mitigating heat effects (Rudolf *et al*., 2021), with similar benefits observed using other mulching materials under maize (Li *et al*., 2018). Moreover, Donglin *et al*. (2019) reported 5.7%-19.8% and 7.1%-20.9% increases in energy and water productivity, respectively, owing to mulching.

Economic analysis shows a maximum marginal rate of return of 5.75 ha^{-1} yr^{-1} from mulching (Wairegi and van Asten, 2010) and a 27.0%-53.8% increase in net income compared to unmulched systems (Donglin *et al*., 2019; Jianguo *et al*., 2014). For every 1 m^3 of water used, mulching achieved a 5.0% higher value than that of the control (Adetoroa *et al*., 2020). Nwokocha *et al*. (2017) concluded that a mix of 12.00 t ha^{-1} EFB and 4.00 t ha^{-1} palm bunch ash provided the best net return. Abubakar *et al*. (2021), Khalid *et al*. (2000) and Moraidi *et al*. (2012) documented significant improvements in the hydrophysical properties following EFB mulching.

Despite the benefits, the use of oil palm biomass as mulch or incorporating it into the soil as an economical practice remains debated. Moreover, addressing water deficits through irrigation on large oil palm farms is both challenging and costly (Miller and Donahue, 1992; Abdullah and Sulaiman, 2013; Teh, 2016). While mulching with 30 t ha^{-1} of EFB can reduce surface evaporation (Lim *et al*., 2008), Carr (2011) argued that such high application rates are impractical. Rudolf *et al*. (2021) suggested that motivating farmers to adopt mulching is difficult due to the large quantities required for significant benefits. The costs associated with transportation and application can increase total expenses by as much as 73.3% (Wairegi and van Asten, 2010; Rudolf *et al*., 2021). Sari *et al*. (2022) highlighted farmers' reluctance toward mulching because of the cost-yield trade-off. Furthermore, effective weed suppression requires a thick mulch layer, which can result in impractically large volumes (Nwokocha *et al*., 2017; Wairegi and van Asten, 2010).

Furthermore, mulching can lead to pest infestations, affecting soil temperature and potentially inhibiting germination owing to allelopathy (Benoit, 2022; Cabona *et al*., 2021; Donglin *et al*., 2019; Iqbal *et al*., 2020; Korkança and Sahin, 2021; Ni *et al*., 2016). It also increases the risk of fire hazards and wild animal-human conflict (Ni *et al*., 2016; Rongbin *et al*., 2020). Thus, the choice of mulch material must be tailored to the specific climate conditions to mitigate these risks.

Silt-Pit and Cover Crops

Mechanical techniques for water harvesting, such as silt-pit and bund terraces, significantly increase resilience to water stress risks by reducing runoff and enhancing soil water reserves (Gabrielle *et al*., 2018; Murtilaksono *et al*., 2011). For example, the silt-pit technique reduced water run-off by 89% and increased soil water reserves by up to 183 mm (Bohluli *et al*., 2012; Murtilaksono *et al*., 2011; Yuswar *et al*., 2020). Moreover, different silt pit sizes affect soil water content, with larger dimensions showing varying outcomes (Bohluli *et al*., 2012; Masnang *et al*., 2022; Ping *et al*., 2012). However, this technique has limitations, including its suitability only for highlands and areas with contrasting slopes and potential soil structure disruption (Bohluli *et al*., 2015; DoCampo *et al*., 2021).

Cover cropping also enhances water stress tolerance. Planting of leguminous crops, such as *Brachiaria* and *Pueraria javanica*, improves water infiltration and retention, reduces dry days, and enhances water use efficiency (WUE) (Agusta *et al*., 2020; Ariyanti *et al*., 2017; Nouy *et al*., 1999; Zhang *et al*., 2023). The integration of diverse cover crops can help mitigate runoff water loss (Gabrielle *et al*., 2018; Morton *et al*., 2017; Nabara and Norsida, 2018).

Nonetheless, challenges include interference with mechanisation operations, inter-crop competition, and increased risk of pest and disease transfer, which may complicate the oil palm-legume cropping pattern (Chalmers, 2017; Dowling *et al*., 2020; Echarte *et al*., 2011).

Application of Synthetic Polymer

Synthetic soil conditioners, notably referred to as super absorbent polymers (SAPs), are an alternative for water deficit management (Lentz and Sojka, 2009; Zhang *et al*., 2021). SAPs are networks of flexible porous polymers (Zhang *et al*., 2021) that are tridimensionally cross-linked (Kiatkamjornwong, 2007). They can retain a large quantity of water (Lucero *et al*., 2010; Zhang *et al*., 2019; Zhao *et al*., 2021), and make water more accessible to roots (Azman, 2013; Rafiei *et al*., 2013). SAPs application effectively minimises water stress in many field crops (Han *et al*., 2010; Ibrahim *et al*., 2020; Zohuriaan-Mehr *et al*., 2010). Yang *et al*. (2022) found after a decade of research that conditioning the soil with 45 kg ha^{-1} SAP significantly enhanced soil macroaggregates (>0.25 mm) by 16.5%-36.33%, WUE by 16.0%, and rate of photosynthesis by up to 18.5% (Yang *et al*., 2020). The application of SAPs reduced runoff by up to 103.0%, and improved the soil moisture by 29.0% (Yuanbo *et al*., 2017). Additionally, meta-analysis by Zheng *et al*. (2023) indicated a 15.0% yield increment from SAPs treatment.

However, Idris and Yahaya (2022) and Nasereldin *et al*. (2023) noted the unavailability of SAPs in local markets and asserted their high purchasing cost as the core constraints limiting their accessibility. Furthermore, SAPs require a specialised storage environment that is relatively dark, dry, and cool to maintain their shelf life (Mechtcherine *et al*., 2021; Snoeck and De Belie, 2019). Unfortunately, most farmers do not have such required storage facilities.

To date, there has been no published research on the effectiveness of SAPs on water stress reduction in oil palm in Malaysia or other Asian countries. This is a knowledge gap that needs to be addressed.

CONCLUSION

Over time, Malaysia's climate has become increasingly variable, marked by a rise in temperature (7.5%), reduced rainfall (-5.0%), and more frequent extreme weather events. This variability has exacerbated water deficits, constraining sustainable oil palm production. Future climate projections suggest higher temperatures, decreased rainfall, and consequently, more severe water stress.

While the use of oil palm biomass and cover crops has been tested and shown to mitigate water deficits, further research is needed to understand the short-, medium-, and long-term effects of these practices. Similarly, treatment methods such as biochar, mulching, and use of silt pits require deeper investigation. Additionally, the potential of synthetic polymers as a solution for managing water stress in oil palm plantations remains to be explored.

Table 1 provides a summary of water stress effects for various plantation crops, and *Figure 1* shows the water stress levels experienced by oil palms across the 12 months.

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TABLE 1. SUMMARY OF YIELD, GROWTH AND PHYSIOLOGICAL EFFECTS OF WATER STRESS FOR DIFFERENT CROP CATEGORIES

S/N	Mode/Level of water stress inducement	Crop	Resultant effect	Source
01	100 mm less deficit	Oil palm	10%-15% FFB yield reduction	Caliman and Southworth (1998)
02	Intermittent water stress from rainfall cessation and inadequacy	Oil Palm	The number and yield of FFB downsized by >91.00% and 88.46%, respectively	Gawankar *et al*. (2003)
03	Natural water deficit stress from rainfall cessation was monitored	Oil palm	Declination of leaf water content, WUE and photosynthetic rate and increased chlorophyll content were observed.	Noor (2006)
04	Experimental sites were under yearly water deficit of 150, 250 and 400 mm	Oil palm	Higher water stress got the least number of bunches (- 82%), least bunch weight (- 79%), and least FFB (- 88%)	Dwarko *et al*. (2008)
05	Water balance and fraction transpirable soil water approaches were adopted to predispose the test crop to equivalent water stress.	Oil palm	Yield is more sensitively affected by water stress at 2 ½ years prior to bunch maturity.	Legros *et al*. (2009)
06	Consistent non-watering for 24 days after full establishment (30 days) in the glasshouse	Oil palm	All gas exchange variables declined drastically, and at 24 days of severe water stress, photosynthesis stopped while 200% leaf water potential became 2 times higher.	Suresh *et al*. (2010)
07	Natural water stress equivalent to an annual shortfall of 450 mm due to an unimodal rainfall pattern	Oil palm	Stages most badly affected were fruit filling, sex differentiation and state central arrow.	Renny *et al*. (2011)
08	Superimposition of stress by supplying 0.5 of full FC water volume	Oil palm	The root/shoot ratio improved by 23.0%. Number of leaves decreased by 11.4%	Sun *et al*. (2011)
09	Water deficit was induced by maintaining moisture at -0.042, -0.5, -1.0, and -2.0 MPa tensions.	Oil palm	Assimilation of CO_2 completely ceased, and bulb diameter decreased by 48% at -2 MPa; stomatal conductance was not affected by genotype-water potential interaction.	Méndez *et al*. (2012)
10	Water stress imposed for 12 and 16 days equivalated to 13% and 6% SWC, respectively.	Oil palm	Chlorophyll was disrupted by 59.0% and 95.9%, while photosynthetic rate diminished by 71.7% and 91.1% respectively.	Cha-um *et al*. (2013)
11	4 and 8 weeks without watering after water deficit at – 1.50 MPa pressure was attained	Oil Palm	Photosynthesis declined by 23% and 53% for the respective duration, and WUE steadily went down.	Jazayeri *et al*. (2015)
12	Crop exposed to moderate water deficit of -0.5 MPa	Oil palm	Significant reduction in the stomatal conductance, rates of photosynthesis and transpiration, as well as vegetative development were recorded.	Rivera-Méndes *et al*. (2016)
13	Only half and a quarter of FC water content were given as deficits for 60 days after 30 establishment days.	Oil palm	Except root-to-shoot ratio, all growth variables reduced drastically, but proline status increased greatly.	Duangpang *et al*. (2018)
14	Water stress was induced under bio-silica-treated soils	Oil palm	Water-stressed crop with no bio-silica showed higher proline status by up to 90%, and Nitrate reductase activity (NRA) decreased by 93%.	Amanah *et al*. (2019)
15	Studied the impact of dry season water stress abiotic factor	Oil palm	32.5% decrease in photosynthesis, a significant drop in gas exchange, but WUE and leaf sugar content improved by up to 27% and 1%, 14%, respectively.	Bayona-Rodriguez and Romero (2019)
16	No-irrigation + fertiliser and no-irrigation without fertiliser were studied against full irrigation.	Oil palm	The final harvested FFB was 17% lower due to the water deficit	Rhebergen *et al*. (2019)
17	Studied the damaging effect of water stress on leaf attributes only in areas of moderate to severe water stress due to sub-optimal rainfall	Oil palm	Multicollinearity results indicated that the number of green broken leaves (NGBL), number of folded leaves (NFL) and number of trees with central leaf cabbage toppled (NLCT) were more strongly correlated with water stress than unopened leaves (NUL) and number of base leaves dry out (NBLD) parameters which showed moderate correlation status.	Yehouessi *et al*. (2019)

TABLE 1. SUMMARY OF YIELD, GROWTH AND PHYSIOLOGICAL EFFECTS OF WATER STRESS FOR DIFFERENT CROP CATEGORIES (continued)

S/N	Mode/Level of water stress inducement	Crop	Resultant effect	Source
18	100 mm less water at sex determination and floral abortion phases	Oil palm	Yield loss occurred at both phases by 6% and 7%, respectively	Suharyanti *et al*. (2020)
19	Molecular study based on 2-week induced-water stress on seedling	Oil palm	Identified more than 1293 genes associated with water stress response across biosynthetic and metabolic, transportation and homeostatic processes	Wang *et al*. (2020)
20	Irrigated and non-irrigated parental stocks	Oil palm	Water deficit badly affected male and female inflorescence ratio and lowered bunch number significantly. The water deficit negatively impacted FFB and oil yield by 20%.	Abdul Wahid (2021)
21	Monitored water stress induced by extreme *El-Niño* Southern Oscillation (ENSO)-facilitated drought	Oil palm	Reduction of the Total Fruit produced by 31%	Mauro *et al*. (2021)
22	Dry season water stress	Oil palm	Inflorescence and fruit formation stage was staggered	Mendoza-Hernández *et al*. (2021)
23	Water stress induced to young seedlings at "bifd" saplings developmental stage. By water deprivation for 14 consecutive days. At the end of this period, the substrate water potential, as measured, equivalent to −13.61 ± 1.79 MPa	Oil palm	Distortion of starch, sucrose, glyoxylate and dicarboxylate metabolism pathways occurred. Also, alanine, aspartate, glutamate, arginine and proline synthesis were positively affected	Neto *et al*. (2021)
24	Studies the agronomic impact of the 2015 *El Nino*-facilitated water stress at 4-12 months and 24-30 after the occurrence	Oil palm	Reduction in harvestable FFB stood at 23%-30%, but the older palms recorded the maximum values. The decline of the oil extraction ratio was found to be explained by the water stress effect.	Sidhu *et al*. (2021)
25	Observational study due to normal climate dryness in low-rainfall receiving areas	Oil palm	Naturally tolerant cultivars had 44% and 38% greater FFB than susceptible ones in the first and second trials, respectively. Exactly 56 Single nucleotide polymorphisms (SNPs) were observed in the genetic information of water stress-tolerant lines. MRL1, At1g35710, RNP1, and BDA1 genes were found to be closely associated with the SNPs detected.	Yono *et al*. (2021)
26	14 consecutive days of water deprivation	Oil palm	Water stress-associated miRNAs and genes specific to oil palm, namely egu-miR28ds and egu-miR29ds and MYBs, HOXs and NF-Ys, were identified.	Salgado *et al*. (2022)
27	Irrigation was withheld for 20 consecutive days for different young progenies.	Oil palm	Biomass of all progenies tested decreased by 34%; proline content increased by up to 300%; stomatal conductance reduced significantly, and nine moisture stress-responsive miRNA were identified.	Ithnin *et al*. (2022)
28	1.0, 1.5 and 2.0 L per polybag per day were supplied as deficits	Oil palm	Plant height went down in 1.0 and 1.5 L by 23.0% and 20.0% and the former reduced shoot dry weight by 12.0%	Kautsar *et al*. (2022)
29	Used Fraction of Transpirable Soil Water approach to consider PWP = FTSW 0 and 15 FC = FTSW 0.15 as deficit	Oil palm	Seedling weight was reduced by 9.7% and 8.3% at PWP and 15% FC, respectively. Generally, growth by height was reduced by one-third.	Pangaribuan and Akoeb (2022)
30	Oil palm was predisposed to water deficit on Histosols, Entisols and Spodosols.	Oil palm	Water stress was more severe in Entisols and Spodosols up to 22% than in Histosols (max. 19%)	Sukarman *et al*. (2022)
31	Chemically induced water stress at 0% to 30% (m/v) of polyethylene glycol (PEG 8000)	Date palm	Progressive growth reduction was obviously observed, and increased manufacturing of proline (inducer of stomatal closure) was noticed.	Al-Khayri and Al-Bahrany (2004)

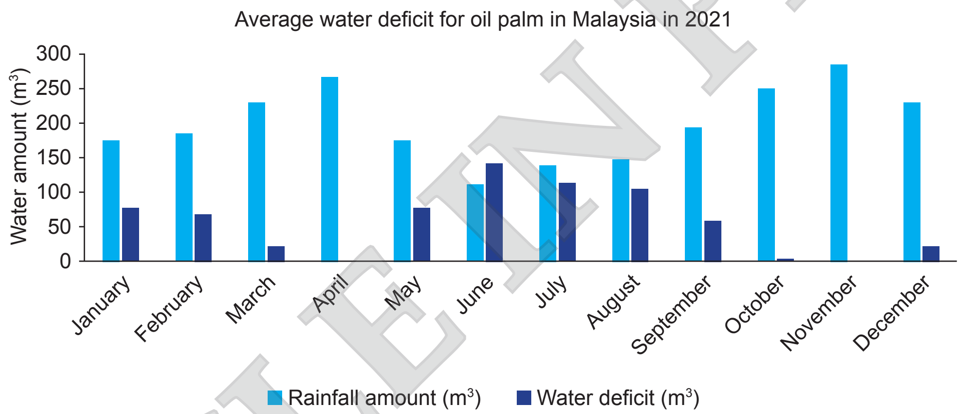
TABLE 1. SUMMARY OF YIELD, GROWTH AND PHYSIOLOGICAL EFFECTS OF WATER STRESS FOR DIFFERENT CROP CATEGORIES (continued)

S/N	Mode/Level of water stress inducement	Crop	Resultant effect	Source
32	Irrigation was only given after 50, 100, 150 and 200 mm soil water had been depleted by evaporation.	Date palm	Fruit diameter and fruit weight significantly lowered but were more chronic at 200 mm depletion.	Alihouri and Torahi (2013)
33	0 water supply was considered a deficit due to scanty rainfall	Date palm	Fruit size went down by 53%-76%, pulp content of date fruit reduced drastically by 57%-75% across three development stages examined, while cell wall lignification reduced insignificantly by 1.9% only in stage 1.	Gribaa *et al*. (2012)
34	Under the growth chamber environment, water was supplied fully at one-day intervals for two weeks to get the date palm acclimatised. The water supply was then stopped to induce water stress.	Date palm	Water-stressed germplasms showed increased accumulation of fucose and glucose compounds, signifying an adaptive switch to carbohydrate metabolism.	Safronov *et al*. (2017)
35	Involved application of 60% and 80% ETc	Date palm	Seedling establishment percentage was not affected by the 80% ETc but was significantly affected by 60%. However, the 60% competed well for the trunk perimeter index.	Moheb (2019)
36	Only half of ETc applied using reclaimed wastewater and well-water	Date palm	A reduction of 86 kg of fruit output per palm was recorded. Total sugar and non-reducing sugar content enrichment occurred.	Mattar *et al*. (2021)
37	Triggered water stress by administering 10%, 20%, 30%, 40% and 50% of actual water demand	Date palm	Fruit yield compressed by 4.5%-12.3%	Isaid *et al*. (2021)
38	Bubbler irrigation system was used to supply 0.25 and 0.5 of full ETc targeting flowering, hababouk, and Rutub and Tamr (third fruit development phase when moisture is lost and sucrose is converted to sugar) stages.	Date palm	Decreased final yield by 28.39% compared to full ETc	Al-Mansor *et al*. (2021)
39	50% and 25% less than full ETc was delivered using drip and sub-surface irrigation systems	Date palm	10.8% and 6.65% reduction for 50% and 25% deficit were obtained for chlorophyll. However, while a declination of 1.7% for the 50% deficit was observed for photosynthesis, the 25% deficit numerically got higher by 0.15% relative to the full ETc.	Mohammed *et al*. (2021)
40	Tested only one deficit level (25% FC)	Date palm	Photosynthetic rate, relative moisture content of leaf, chlorophyll enrichment, stomatal conductance and transpiration became statistically lowered. Over half of the EST (water stress-responsive mRNAs) detected were associated with photosynthesis, metabolism and gaseous exchange.	Alhajhoj *et al*. (2022)
41	This involved water stress interval viz: 3, 5 and 7-day intervals at 100%, 50% and 25% FC.	Cocoa	A perfect linear trend was observed between the deficit levels and physiological and morphological attributes measured. 75% water deficit at 7-day intervals had the poorest performance *e.g.* for plant height, it was 26.7% below the average.	Ayegboyin and Akinrinde (2016)
42	Enforcement of strong (10%-15% of Vol. WC) and moderate (16%-22%) water stress level	Cocoa	29%-62% seedling mortality occurred, retarded growth, proline content increased by 937%	Niether *et al*. (2020)
43	Zero irrigation under harmattan season (dry season accompanied by harsh, dry, cloudy air)	Cocoa	The leaf area index decreased by 33%	Sala *et al*. (2021)
44	Subjected to artificial water stress until the leaf water potentials were at −3.0 and −3.5 MPa	Cocoa	Photosynthesis dropped by 98% and energy metabolism was completely distorted.	Zambrano *et al*. (2021)
45	80%, 60% and 40% fraction of full water required administered	Cocoa	A highly significant reduction in pollen grain production was recorded	García-Cruzatty *et al*. (2023)

TABLE 1. SUMMARY OF YIELD, GROWTH AND PHYSIOLOGICAL EFFECTS OF WATER STRESS FOR DIFFERENT CROP CATEGORIES (continued)

S/N	Mode/Level of water stress inducement	Crop	Resultant effect	Source
46	Observation of anomalous dry spell effect	Rubber	Yield reduced by 50%	Thomas *et al*. (2011)
47	Water stress from seasonal drought	Rubber	Partial stomatal conductance, impaired transpiration and loss of vigor were observed.	Kunjet *et al*. (2013)
48	26, 33 and 40 days of drought stress after two months of proper establishment	Rubber	Stuntedness: Nig 801 and RRIM628 cultivars increased in height only by 1.0% and 6.0%	Korieocha *et al*. (2015)
49	7 days withholding of water during the summer period	Rubber	Maximum quantum yield, leaf wax content and photosynthetic rate indices became negatively affected.	Thomas *et al*. (2015)
50	Water deficit consisted of: FTSW > 0.75 (control); 0.1 < FTSW < 0.20 (severe), and FTSW > 0.75 after rewatering (recovery)	Rubber	Many biochemical and enzymatic complexes, including superoxide dismutase, peroxidase, and hydrogen peroxide content, were adversely affected.	Cahyo *et al*. (2022)

Note: FC - field capacity; WC - water content; ETC - crop evapotranspiration; FSTW - fraction of transpirable soil water; PWP - permanent wilting point.



Source: Chalvantharan *et al*. (2023).

Figure 1. Water deficit based on 251 m^3 $month^{-1}$ ha^{-1} OP requirement from average monthly rainfall in Malaysia in 2021.

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