Journal of Tropical Crop Science Vol. 13 No. 2, June 2026
www.j-tropical-crops.com

Received 5/28/2024; Revised 15/10/2025; Accepted 20/01/2026
https://doi.org/10.29244/jtcs.13.02.430-444

The Identification of Potential Stress in Oil Palm Using Sentinel-2A Satellite Imagery Approach and Laboratory Tests

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Abstract

Oil palm (*Elaeis guineensis* Jacq.) is a valuable source of vegetable oil for various industries, such as food and cosmetics. Global climate change, driven by global warming, has the potential to shift climate conditions and trigger extreme events, such as prolonged droughts. Extreme climate phenomena will impact plant conditions, causing plants to become stressed. A study was conducted from June 3 to October 31, 2023, at the Oil Palm Education and Research Plantation of IPB University in Jonggol, Bogor, West Java. The study aimed to determine the Palm Oil Stress Index (POSI) to identify stress in oil palm plants. The identification process included analyzing Sentinel-2A satellite images, testing soil water availability, and measuring leaf proline content. The study utilized the Leaf Water Content Index (LWCI) and Enhanced Vegetation Index (EVI) values as models to determine the POSI from the satellite images. Furthermore, soil physics analysis and proline values from the 17th leaf sample were used to assess the plants' water availability and stress levels. The satellite images showed signs of potential stress in October; observation blocks in October had a pF value of 4.2 between 14.93%-16.77% compared to the water content, which ranged from 13.79%-15.09% supported by decreased soil water levels and increased proline accumulation occurred in October a value of 0.0382-0.0391 mg/g, compared to June, which is 0.0143-0.0159 mg/g. All areas were healthy from June to August; however, potential stress, as indicated by POSI values, their formulation, and color changes, was present in September and October.

Keywords: climate change, plant stress, proline, satellite images

Introduction

Palm oil (*Elaeis guineensis* Jacq.) is a highly versatile and renewable source of vegetable oil, offering several advantages over other vegetable oils. Palm oil is the primary raw material for food, non-food, and fuel with renewable properties. Palm oil is also used as a raw material for various industries, including food and cosmetics (Lubis & Widanarko, 2011). World palm oil demand and consumption are expected to reach 334 million tons of vegetable oil, including palm oil 171.16 million tons (51.14%), soybean oil 105.78 million tons (31.61%), rapeseed oil 38.80 million tons (11.59%), and sunflower oil 18.94 million tons (9.34%) by 2050 (Purba, 2019). Palm oil production and growth can be influenced by various factors, including climate, water and nutrient availability, pest and disease infestations, and extreme weather conditions, such as overheating or overcooling.

Global warming drives climate change, leading to prolonged droughts that stress oil palm plants, disrupting their growth and productivity (Syarovy et al., 2015; Veranica, 2014). Proline is produced and accumulated in various plant tissues, particularly in the leaves (Sharma & Verslues, 2010). It is a biochemical compound synthesized and accumulated in

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plants experiencing drought stress. Plants that accumulate proline exhibit better morphology and possess a higher survival mechanism compared to those that do not, thereby increasing their proline content (Alizadeh et al., 2011; Cha-Um et al., 2013; Maryani, 2012).

Remote sensing is the science and art of obtaining information about objects, areas, or phenomena through data analysis with devices without direct contact with the object, area, or phenomenon under study (Lillesand et al., 2015). Remote sensing is an innovative analytical method for generating spatial, spectral, and temporal data essential for monitoring oil palm crops. Several researchers have developed remote sensing technology to estimate oil palm leaf nutrients using satellite imagery and spectrometers (Rendana et al., 2015; Santoso et al., 2019; Yadegari et al., 2020). Sentinel-2 satellite images are often used to observe the condition of the oil palm (Yuniasih & Adjie, 2022). Sentinel-2 is equipped with a red-edge channel with a spatial resolution of 20 meters, which is essential in improving the precision and sensitivity of vegetation studies. The other six additional channels have a spatial resolution of 60 meters (Kurniawan et al., 2021).

Remote sensing is a technique for efficiently obtaining data. This is because it does not take long to obtain data and does not require going directly to the location to collect it (Lillesand et al., 2015). Remote sensing, such as satellite imagery, can be used to monitor and evaluate the condition of oil palm plants and estimate drought stress on oil palm land (Yuniasih & Adjie, 2022). Contemporary efforts that utilize Sentinel-2 imagery to monitor oil palm conditions include evaluating oil palm plantation conditions and estimating oil palm productivity (Wicaksono et al., 2022). Using remote sensing technology, such as satellite imagery or drones, is one way to effectively know and monitor the condition of oil palm plantations in large areas (Chong et al., 2017; Sum & Shukor, 2019). Remote sensing is a technique for obtaining data efficiently (Lillesand et al., 2015). This is because it does not take long to obtain data and does not have to come directly to the location to get the data (Pohl et al., 2016; Sum & Shukor, 2019; Zaitunah et al., 2018). This study aims to identify conditions and determine the stress index of oil palm caused by limited soil water content availability due to prolonged dry conditions, using Sentinel-2 data. The assessment is based on changes in the values and color variations derived from the applied POSI formulation, which were then compared with the increase in proline content in the leaves.

Materials and Methods

This research was conducted at the Oil Palm Education and Research Plantation of IPB University from June to October 2023. Soil samples were analyzed at the Laboratory of the Department of Soil Science, Bogor Agricultural University, and proline content were analyzed at the Indonesian Oil Palm Research Institute Laboratory, Bogor. Three Sentinel 2A level 2 data (S2A-MSIL2A data) were acquired from June to October 2023 and used in this research. Sentinel data were downloaded via the official website: https://dataspace.copernicus.eu/.

Soil Samples

Intact soil samples were collected using a soil sampling ring to analyze soil physical properties, preserving the natural soil structure and preventing disturbance prior to laboratory analysis. Soil sampling points were randomly selected to represent the entire study area. The locations of soil sampling points were marked and recorded using a Global Positioning System (GPS) smartphone application to facilitate relocation of sampling sites. The soil sampling ring used had a diameter of 4.8 cm and a height of 5 cm. Soil samples were collected at a depth of 10–15 cm from five blocks, with five samples per block. The soil sampling was conducted to determine soil water status, including measurements of soil water content at pF 2.5 and pF 4.2, as well as the calculation of Available Water and Water Content. The values of pF 2.5, pF 4.2, available water, and soil water content are expressed on a volumetric basis (%

Received 5/28/2024; Revised 15/10/2025; Accepted 20/01/2026
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v/v), representing the volume of water contained in a given volume of soil. This basis is commonly used in soil physics to evaluate soil water availability for plants.

Leaf Samples

Leaf samples were collected to measure the value of leaf proline content. Leaf samples were taken simultaneously and coordinate position of soil samples. Leaf samples measured the value of leaf proline content, namely the 17th midrib in June and October 2023. The oil palm frond is divided into 3 parts; the leaf blade in the middle of the midrib was used as a sample. The leaf samples were 25 plant samples with 5 per block.

Satellite Imagery Data

Sentinel-2A is a multispectral instrument with a high spectral resolution with 13 visible, near-infrared (NIR), and shortwave infrared (SWIR) channels. Satellite imagery can be used to monitor and evaluate the condition of oil palm plants and estimate oil palm productivity. (Chong et al., 2017; Taufik et al., 2021). The temporal resolution of Sentinel-2A is 10 days, meaning that it acquires data from the same location every 10 days (U.S. Geological Survey, 2018). Sentinel-2A images have been systematically corrected radiometric and geometric by Sentinel (Oktaviani et al., 2017).

The pre-processing and analyzing of Sentinel-2A data involved several critical stages. (1) Satellite imagery data was trimmed according to the targeted study area; (2) Calculation of leaf water content index (LWCI) and enhanced vegetation index (EVI) index values; and (3) Calculation of palm oil stress index (POSI).

Leaf Water Content Index (LWCI)

The LWCI shows the moisture content of the leaf canopy. Anazawa et al. (2001) utilized LWCI to monitor and map drought or water scarcity in agricultural and forestry areas. LWCI can monitor the water content of plant leaves and estimate drought conditions on agricultural land or in forests. LWCI is formulated in the following formula:

$$LCWI = Gx\frac{-log\,[1-(NIR-SWIR)]}{-log\,[1-(NIR-SWIR)]}$$

where
NIR : Reflectance of the near-infrared band.
SWIR : Reflectance of the short-wave infrared band.

Enhanced Vegetation Index (EVI)

The research was conducted at the Oil Palm Education and Research Plantation of IPB University, Jonggol, Bogor, West Java. A Global Positioning System (GPS) was used to rapidly determine land area and plant coordinates, which were then integrated with Sentinel-2 satellite imagery obtained from the Copernicus data space platform. The Enhanced Vegetation Index (EVI) was developed to minimize the influence of atmospheric aerosol composition and soil color variations (Sukmono et al., 2019). The EVI algorithm is also designed to have better sensitivity to images of very green areas (lush and dense). EVI is formulated as follows:

$$EVI = \frac{2.5 * ((\mathrm{NIR} - \mathrm{RED})}{(\mathrm{NIR} + 6 * \mathrm{RED} - 7.5 * \mathrm{BLUE} + 1))}$$

where:
NIR : Reflectance of near-infrared band
Red : Reflectance of red band
Blue : Reflectance of blue band

Palm Oil Stress Index (POSI)

Land dryness levels can be integrated with the average values of the LCWI and EVI formulations to develop the Water Stress Index (Sukmono et al., 2019). The LWCI is used to identify stress based on moisture levels and leaf biomass, while EVI identifies stress based on leaf greenness. Given the water canopy content factor and the plants' greenness, combining EVI and LCWI into the Palm Oil Stress Index (POSI)

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is expected to provide an additional comparison to the Normalized Difference Vegetation Index (NDVI) for identifying the stress level of oil palm plants. The categories derived from the application of the Palm Oil Stress Index (POSI) formulation are as follows: green, with a value range of 0.257 to 0.417, indicating non-stress; yellow, with a value range of 0.417 to 0.617, indicating potential stress; and red, with a value range of 0.617 to 0.796, indicating stress. POSI formulation used:

$$POSI = [1 - \left(\frac{\text{EVI} + \text{LCWI}}{2}\right)]$$

Data Analysis

Data analysis was carried out using both qualitative and quantitative approaches. The qualitative analysis consisted of elaborating all data and information obtained in the field. The quantitative analysis involved processing the data through mathematical calculations, including mean values, percentage of observations, and Student’s t-test with two variables. All data were then presented descriptively and supported by relevant references.

Results and Discussion

Microclimatic Dynamics and Rainfall Variability

Under specific environmental gradients, macro- and microclimatic parameters exert a significantly stronger selective pressure on regional vegetation than localized edaphic properties. Understanding how crops thrive and sustain yield stability within distinct geographical regions requires comprehensive, multi-decadal historical climate datasets that evaluate monthly averages and annual distribution patterns. Conversely, assessing real-time changes in plant structural diversity and stress responses demands highly granular, daily weather data (Junaedi et al., 2021).

Among these climatic variables, cumulative rainfall is the primary limiting factor governing the economic yield potential of oil palm (*Elaeis guineensis*). Extreme fluctuations in annual rainfall, the number of rainy days, and the distribution of wet versus dry months—often driven by global anomalies like the El Niño-Southern Oscillation (ENSO)—trigger acute agricultural drought stress that severely impairs oil palm growth dynamics (Paterson et al., 2015; Junaedi et al., 2021).

To sustain optimal physiological development, oil palm requires an annual rainfall threshold exceeding 1,800 mm (Sastrosayono, 2003). Ideal commercial production is achieved in regions receiving between 2,000 and 2,500 mm of rainfall per year, with a uniform distribution where no individual month falls below a critical threshold of 100 mm (Junaedi et al., 2021). Consequently, monitoring macro-climatic rainfall variations serves as a foundational predictive tool for evaluating estate water security and projecting long-term yield targets.

According to data compiled by the National Centers for Environmental Information (NCEI) of the National Oceanic and Atmospheric Administration (NOAA), the majority of equatorial regions, including the Indonesian archipelago, experienced a severe El Niño anomaly. Monitoring via the Oceanic Niño Index (ONI) confirmed that the equatorial Pacific Ocean manifested a Sea Surface Temperature (SST) anomaly exceeding the standard baseline by 0.5 °C. This warming trend persisted from May to December and extended into the early months of the following year (Figure 1).

This El Niño event triggered severe regional rainfall deficits, resulting in a substantially drier and more prolonged dry season than seasonal averages. This climatic disruption is explicitly captured by local meteorological records from the BP3K Jonggol Station (managed by the West Java Climatology Station), as presented in Figure 1. The experimental research site experienced an acute, above-normal dry period stretching from July to October, establishing the precise environmental conditions responsible for the soil moisture depletion and subsequent physiological stress observed in the plantation blocks.

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www.j-tropical-crops.com

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Based on the available data, Figure 1, it is predicted that the highest amount of rainfall in Bogor Regency occurred between November and December 2023, with a range of 314-478 mm. Following this, the rainfall was around 374 mm from February to March, then decreased to 244 mm. Rainfall from April to June is expected to increase, while from August to October 2023 it is expected to decline and be classified as low. Drought can interfere with the growth and development of oil palm plants. This is because oil palm is a crop that requires rainfall above 1,250 mm per year (Corley et al., 2015). Some previous studies have reported that drought can decrease the rate of cell division, reduce the rates of CO_2 absorption and photosynthesis, reduce flower development in oil palm plants, and increase miscarriage, bunch failure or rot, and low productivity. Lack of water can also decrease FFB yields due to miscarriage during inflorescences and lower sex ratios, leading to lower bunch counts (Junaedi et al., 2021).

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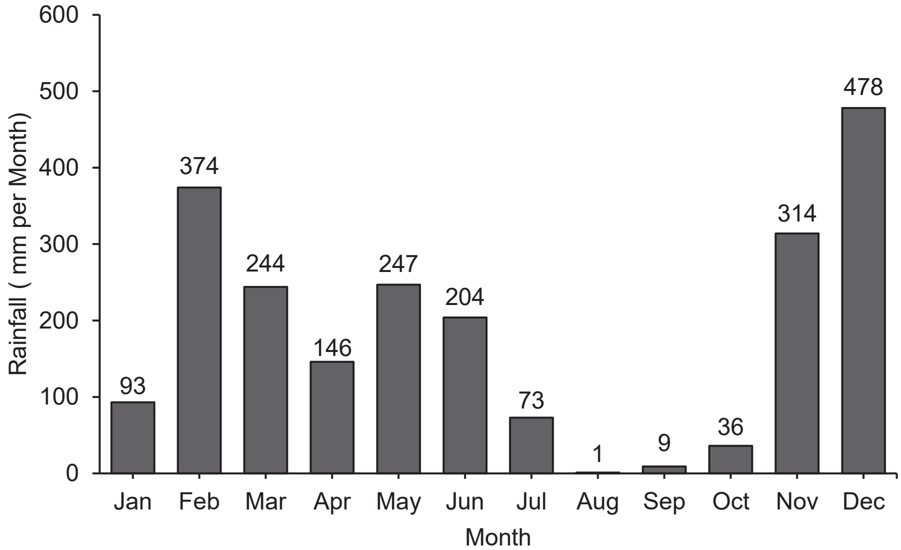
Evaluation of Soil Water Availability via Laboratory and GIS Analysis

Soil moisture comprises the water that occupies part or all of the pore matrix of the subterranean soil and is adsorbed onto the surfaces of edaphic particles. This hydrological component plays a vital role in soil genesis, vegetation survival, the metabolic activity of soil microbiota, and biogeochemical nutrient cycles (Ichsan et al., 2010). The dynamics of soil moisture are governed by three critical hydrological thresholds: the saturation point,

Figure 1

Rainfall (mm per Month) Indicated the Peak of Dry Season was Occurred in July to October 2023



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field capacity, and the permanent wilting point. At saturation, all macro- and micro-pores in the soil profile are completely filled with water. Plant-available water content is functionally bound between field capacity and the permanent wilting point, corresponding to suction potentials between pF 2.54 and pF 4.17. Under laboratory conditions, the matrix pressure equivalent to field capacity is defined at pF 2.54 (0.33 atm), whereas the permanent wilting point equivalent is established at pF 4.20 (15.0 atm) (Sudirman et al., 2011). The primary practical application of defining field capacity and wilting point boundaries is to accurately quantify the precise volume of soil water readily accessible to the crop root system (Or et al., 2012).

Agricultural drought is a recurring, cross-zonal climatic phenomenon characterized by localized environmental variations. It manifests explicitly when soil moisture falls below levels that meet the evapotranspiration requirements of crops during critical phenological periods. This sub-surface moisture deficit typically lags behind the onset of meteorological drought indicators, such as prolonged rainfall deficiencies (Sukmono et al., 2019). To address the challenges of monitoring expansive perennial cultivation, remote sensing technologies and satellite imagery offer highly effective tools for regional surveillance. This spatial infrastructure enables operators to assess macroscale canopy conditions and reliably estimate the progression of drought stress across large-scale oil palm estates (Yuniasih & Adjie, 2022).

Based on the baseline data presented in Table 1, analytical results from the first and second observation periods indicated that all cultivation blocks maintained high soil moisture levels. Volumetric water content across the blocks ranged from 34.89% to 47.20%, remaining safely above the critical permanent wilting point threshold of pF 4.20. Because the current soil water content exceeded this pF 4.20 baseline, adequate moisture reserves were present to meet the biological demands of the vegetation.

Consequently, it can be inferred that optimal plant-available water was maintained across all experimental blocks during these initial intervals, driven by heavy cumulative rainfall recorded from May to June 2023. Spatial analysis from the first and second GIS observations corroborated these edaphic findings; all blocks were classified within the green vegetative spectrum, indicating healthy, non-stressed canopy conditions (Table 1 and Figure 2). This alignment demonstrates strong empirical consistency between laboratory-derived soil moisture values and satellite-driven GIS spatial indices.

Table 1

Soil Water Content in June 2023

Location	Observation 1st June 3, 2023				Observation 2nd June 23, 2023			
	pF 2.5 (%)	pF 4.2 (%)	Water available (%)	Water content (%)	pF 2.5 (%)	pF 4.2 (%)	Water available (%)	Water content (%)
Block 1	28.90	17.48	11.42	38.40	29.49	18.68	10.82	37.52
Block 2	28.04	17.41	10.63	41.51	26.83	14.11	12.73	38.20
Block 3	28.00	17.30	10.70	34.89	25.70	15.78	9.92	39.02
Block 4	28.71	16.93	11.77	38.86	25.52	14.88	10.65	40.21
Block 5	27.20	16.63	10.57	47.20	25.52	14.92	10.60	41.34
Mean ± SD	28.17 ± 0.67	17.15 ± 0.36	11.02 ± 0.54	40.17 ± 4.58	26.61 ± 1.70	15.67 ± 1.78	10.94 ± 1.06	39.26 ± 1.54

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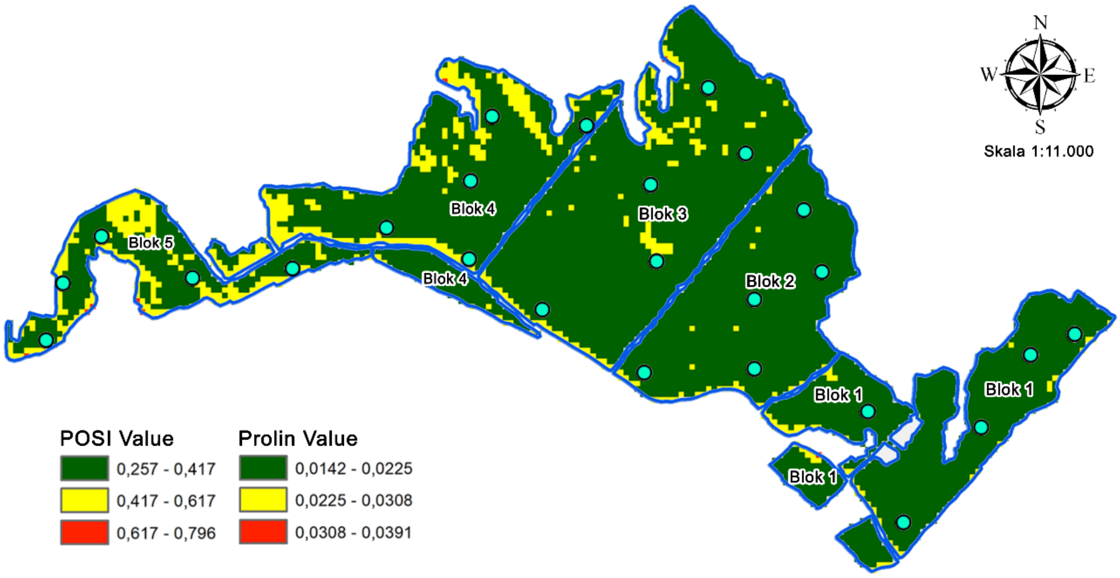
Figure 2

Palm Oil Stress Index (POSI) June Transformation Results



Note. Green indicating non-stress, yellow indicating potential stress, and redindicating stress.

Table 2

GIS Observations of Oil Palm Response in June 2023

Location	POSI observation	
	Color	Information response of oil palm
Block 1	Green	non-stressed
Block 2	Green	non-stressed
Block 3	Green	non-stressed
Block 4	Green	non-stressed
Block 5	Green	non-stressed

Note. At the Oil Palm Education and Research Plantation of IPB University in Jonggol, Bogor, West Jawa.

Table 3 presents the results of the second and third observations in August, indicating that all observation blocks have water content values ranging from 19.07% to 20.50%. This indicates no significant change in the adequacy of soil water content availability. In addition, the moisture content has begun to approach the pF value of 4.2 due to rainfall and rainy days, which are at their lowest levels, so the soil has fewer water reserves for growth. Water availability is related to the ability to dissolve nutrients needed by plants; the more water available for photosynthesis, the more nutrients enter the plant (Nurjanaty et al., 2019).

In August, all planting areas were light green, indicating no stress, as shown in Table 4 and Figure 3. The water content analysis further confirmed this, which showed a pF value of 4.2 in the 3rd and 4th observations. Based on the results shown in Table 1 and Table 3, the water content from the 1st to 4th observations in June-August continued to decline, with a significant decrease of 19%-20%. This shows no significant change compared to the adequacy of soil water content availability. The results of soil moisture level observations in the laboratory matched those from GIS. However, water content decreased

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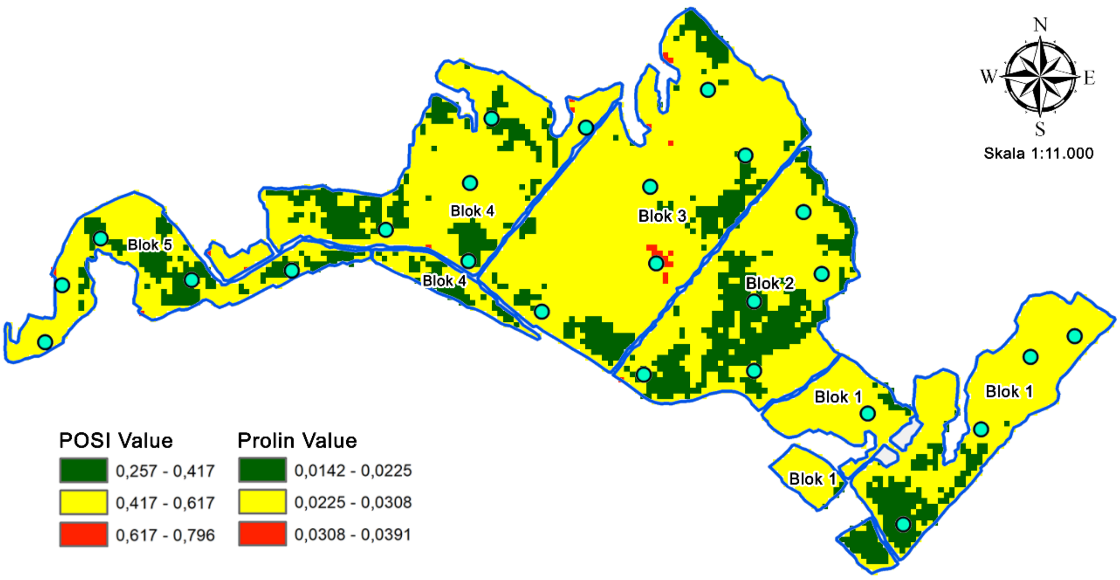
Table 3

Observation of Soil Water Content in August 2023

Location	Observation 3rd August 2, 2023				Observation 4th August 22, 2023			
	pF 2.5 (%)	pF 4.2 (%)	Water available (%)	Water content (%)	pF 2.5 (%)	pF 4.2 (%)	Water available (%)	Water content (%)
Block 1	26.50	14.93	11.57	19.76	26.75	16.04	10.71	19.23
Block 2	26.65	15.22	11.43	19.17	27.68	15.44	12.23	20.05
Block 3	26.38	16.03	10.35	19.81	26.74	15.97	10.76	19.30
Block 4	27.30	15.87	11.43	20.50	26.84	15.60	11.24	19.07
Block 5	26.24	15.60	10.64	19.16	26.65	16.23	10.42	19.54
Mean ± SD	26.61 ± 0.41	15.53 ± 0.45	11.08 ± 0.55	19.68 ± 0.55	26.93 ± 0.42	15.86 ± 0.33	11.07 ± 0.71	19.44 ± 0.38

Figure 3

Palm Oil Stress Index (POSI) August Transformation Results



Note. Green indicating non-stress, yellow indicating potential stress, and red indicating stress.

in August compared to the previous month. This was supported by GIS observations, which showed a change in the area's color from light green to another shade, indicating a decrease in water availability.

Soil water availability in August can be influenced by water storage during rainfall and by high rainfall days occurring from February to June 2024. In addition, the type of soil to increase water retention is another factor. The availability of water on the oil palm land that plants can utilize indicates that water is still at field capacity. According to Pratiwi (2022), water availability under field-capacity conditions (pF 2.54) indicates that finer soil textures tend to have higher water content, while slightly coarse-textured soils have lower water content.

The presence of water in the oil palm land that plants can use indicates that the water level is still at field capacity. According to Haridjaja et

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al. (2013), the finer the soil texture, the greater the soil's water storage capacity. Soils with a clay texture can hold more water than those dominated by sand due to their larger surface area. Generally, soils with medium to moderately fine texture contain more water at pF 2.54 and pF 4.2 than coarse-textured soils. Additionally, water available to plants is relatively high in such soils (Pratiwi et al., 2022).

In the 5th to 6th observations, all observation blocks had a pF value of 4.2 between 14.93% to 16.77% compared to the water content, which ranged from 13.79% to 15.09%. Thus, observations in October indicate potential for water stress where soil water content is insufficient. This result is influenced by the higher pF value relative to the measured soil water content. In October, it showed that all planting blocks were already under water stress. This is also supported by the low rainfall amount in that month, as shown in Figure 1.

Spatial and Temporal Dynamics of Soil Moisture and Vegetation Stress

Spatial observations conducted in October (Table 6 and Figure 4) revealed a widespread shift in the plantation canopy blocks to a green-yellow spectrum, while several peripheral areas outside the main blocks transitioned to red, signaling potential structural vegetation stress. This spatial variation is strongly supported by laboratory core soil moisture analyses. Across all monitored blocks, volumetric water content during this period fell between 13.79% and 15.03%. These values sit critically below the

Table 4.

GIS observations of oil palm response in August 2023

Location	POSI observation	
	Color	Information response of oil palm
Block 1	Green and yellow	non-stressed and potential Stressed
Block 2	Green and yellow	non-stressed and potential Stressed
Block 3	Green and yellow	non-stressed and potential Stressed
Block 4	Green and yellow	non-stressed and potential Stressed
Block 5	Green and yellow	non-stressed and potential Stressed

Note. At the Oil Palm Education and Research Plantation of IPB University in Jonggol, Bogor, West Java

Table 5

Soil Water Content in October 2023

Location	5th Observation October 1, 2023				6th Observation 6th October 21, 2023			
	pF 2.5 (%)	pF 4.2 (%)	Water available (%)	Water content (%)	pF 2.5 (%)	pF 4.2 (%)	Water available (%)	Water content (%)
Block 1	27.39	16.43	10.95	14.14	26.50	14.93	11.57	15.09
Block 2	26.74	16.03	10.71	15.03	26.65	15.22	11.43	15.02
Block 3	27.31	16.77	10.54	13.94	26.38	16.03	10.35	14.45
Block 4	27.42	15.48	11.94	14.32	27.30	15.87	11.43	14.61
Block 5	26.71	15.87	10.84	13.79	26.24	15.60	10.64	15.04
Mean ± SD	7.11 ± 0.36	16.12 ± 0.50	11.00 ± 0.55	14.24 ± 0.48	26.61 ± 0.41	15.53 ± 0.45	11.08 ± 0.55	14.84 ± 0.29

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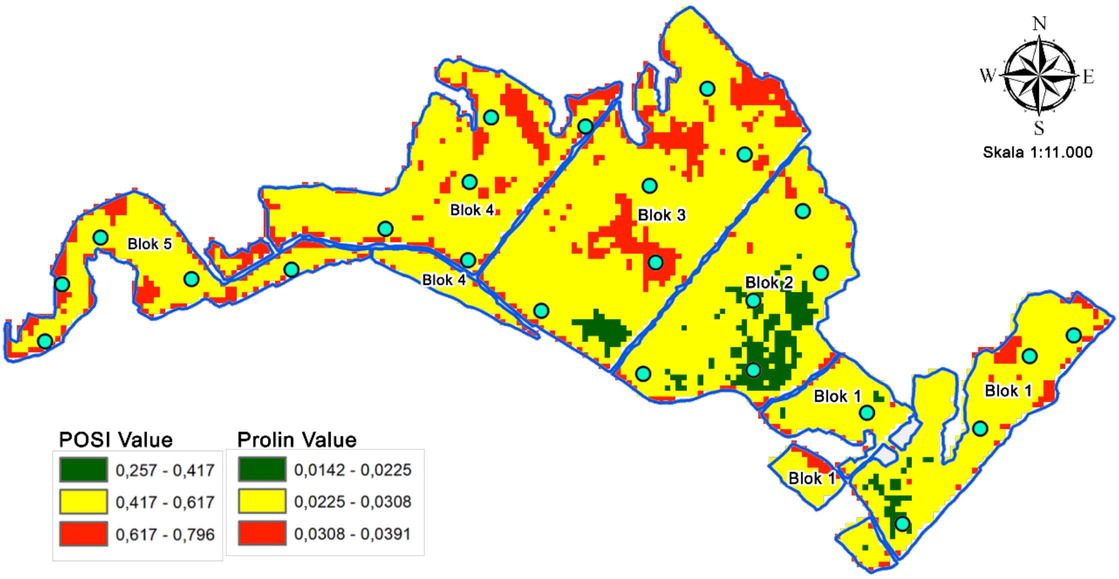
permanent wilting point threshold, confirming that minimum crop water requirements were unmet and indicating severe localized soil water deficits.

The laboratory analytical data aligned with the Geographic Information System (GIS) spatial modeling. While data from the preceding month of August indicated stable water availability and a non-stressed baseline environment, temporal formulations utilizing the Plant Osmotic Stress Index (POSI) highlighted a progressive microclimatic shift. As illustrated across Figures 2, 3, and 4, the cultivation area underwent a clear color transition from green to yellow, and subsequently to red in marginal zones, tracking the onset of seasonal drought. Correlation tests between GIS indices and laboratory soil water metrics established that under optimal conditions, soil water status satisfies the hydraulic potentials between pF 2.5 and pF 4.2; however, stress manifests explicitly as moisture values drop toward or below the pF 4.2 threshold.

Figure 4

Palm Oil Stress Index (POSI) October Transformation Results



Note. Green indicating non-stress, yellow indicating potential stress, and redindicating stress.

Table 6

GIS Observations of Palm Oil Response in October 2023

Location	POSI observation	
	Color	Information response of oil palm
Block 1	Yellow	Potential stress
Block 2	Green and yellow	non-stressed and potentially stressed
Block 3	Yellow and red	Potential stress and stressed
Block 4	Yellow and red	Potential stress and stressed
Block 5	Yellow and red	Potential stress and stressed

Note. At the Oil Palm Education and Research Plantation of IPB University in Jonggol, Bogor, West Jawa.

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https://doi.org/10.29244/jtcs.13.02.430-444

Compared to August baselines, October observations recorded a significant 4% to 5% decline in total soil water content (Table 3 and Table 5). This rapid depletion and close proximity to the pF 4.2 matrix boundary are directly attributable to minimal regional rainfall, which exhausted structural soil water reserves. Because oil palm (*Elaeis guineensis*) develops a relatively shallow, fibrous root architecture, it exhibits high vulnerability to hydrological deficits. The onset of agricultural drought is driven by high evaporative demand and transpiration rates operating against limited soil water reservoirs during the dry season.

Prolonged moisture stress impairs critical morpho-physiological processes, including inhibiting the opening of spear leaves (young leaf sheaths), accelerating the senescence of lower fronds, inducing chlorophyll degradation, and causing the desiccation of developing fruit bunches. Under extreme, prolonged desiccation, apical meristem fracture (shoot breakage) and whole-tree mortality can occur.

Furthermore, drought stress severely compromises the reproductive phase by altering the floral sex ratio toward maleness, inducing flower abortion, and triggering the premature drop of young fruits. These cumulative stresses reduce fresh fruit bunch (FFB) yields by 10% to 40% and crude palm oil (CPO) extraction rates by 21% to 65% (Subronto et al., 2000). At the cellular level, these moisture deficits reduce stomatal conductance, thereby minimizing water loss and consequently limiting intracellular CO_2 assimilation and suppressing net photosynthetic rates (Syarovy et al., 2015).

Endogenous Proline Accumulation as an Osmoprotective Response

Agricultural drought is a critical environmental condition in which soil water content falls below the threshold required to sustain baseline vegetative growth and economic yield. To survive these periods of acute moisture stress, plants deploy complex biochemical mechanisms, primarily involving the accumulation of compatible cellular solutes such as the amino acid proline (Pro). Synthesized and localized within the cytoplasm and chloroplast stroma, proline serves as a vital osmoregulator that stabilizes structural proteins and maintains cell membrane integrity against dehydration.

When cells and tissues experience severe water deficits, up-regulated proline biosynthesis counteracts low cellular water potentials through hydrophilic interactions and hydrogen-bonding networks, thereby preserving cellular turgor and metabolic function. This cellular mechanism of osmoregulation relies on the net accumulation of intracellular solutes in direct response to changes in the surrounding matrix water potential, stabilizing the internal cellular environment during severe dry spells (Sumariana & Juswardi, 2022).

Results Show *T* Test Value, show *T* value count > *T* Table which means reject H0 means Proline Value in October shows potential stress in oil palm plants compared to June (Table 8). Based on the results, it was found that the proline content in plants during October was higher than in June across all blocks (Table 7). This suggests that there is water stress due to a lack of water, which leads to the accumulation of proline as a form of adaptation for plants to cope with drought stress. The accumulation of proline during October helps plants reduce the water loss rate through transpiration. Additionally, the analysis of the available water content in the soil shows that pF 4.2 is higher than the available water content. The GIS results indicate that the block of land area is green-yellow in October, suggesting the potential for water stress due to drought.

Proline can function as a source of energy, nitrogen, and carbohydrates as well as an osmolyte, and proline can reduce free radicals in cells to prevent damage due to oxidative stress (Hong et al., 2000; Khaerana et al., 2008). Proline concentrations in oil palm plants increased from about 0.0215 to 0.0239 mg/g, with an increase of 141 to 167% observed during severe droughts, helping to stabilize proteins and maintain osmotic balance. Plants that accumulate proline under suffocated conditions generally have better morphological features

Received 5/28/2024; Revised 15/10/2025; Accepted 20/01/2026
https://doi.org/10.29244/jtcs.13.02.430-444

Table 7

Proline Content of Palm Oil in June and October 2023

Block	Month	Proline content (µg/g)	Increase (%)
1	June	14.7	162%
	October	38.5*	
2	June	15.8	145%
	October	38.7*	
3	June	15.2	141%
	October	36.7*	
4	June	14.3	167%
	October	38.2*	
5	June	15.9	146%
	October	39.1*	
Mean ± SD	June	0.0152 ± 0.0007	152%
	October	0.0382 ± 0.0009	

Note. * shows a significant difference between the proline value in October compared to June.

Table 8

tTest Value Proline Content of Palm Oil in June and October 2023

	Variable 1	*Variable 2*
Mean	0.03206	0.0159
Variance	7.583E-06	0.000001485
Observations	5	5
Pooled variance	0.000004534	
Hypothesized mean difference	0	
df	8	
t Stat	11.99970592	
One-tailed P(*T*<=*t*)	1.07213E-06	
One-tailed *t* critical	1.859548038	
Two-tailed P(*T*<=*t*)	2.14427E-06	
Two-tailed *t* critical	2.306004135	

Note. t Stat = *t* count, *t* critical = *t* table.

and have higher survival than plants that do not accumulate it (Kurniawan et al., 2014). Proline is an osmoregulator, protecting membranes and proteins against high concentrations of organic ions and temperature extremes.

Conclusions

Climatic conditions in Jonggol experience drought due to low rainfall and very few rainy days from July to October, resulting in a continued decrease in soil water content. The results of the moisture content test showed a significant

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reduction in moisture content from June to August, by 19% to 20%, and a decrease of 4% to 5% in October. This result is supported by an increase in proline accumulation in October, with values of 0.0382-0.0391 mg/g, compared to June, at 0.0143-0.0159 mg/g. According to the October Sentinel-2A satellite image, the oil palm plants in the area exhibited signs of stress, characterized by a yellow-red color. This was further supported by observations of soil water levels in the field, which decreased compared to June. The increase in proline accumulation in October indicated the plants' stress levels. When mapping the health condition of oil palm plants using Sentinel-2A satellite imagery, it was found that all areas were healthy between June and August. However, in October, the plants were at risk of stress. Color changes in the use of the Palm Oil Stress Index (POSI) formula during the June-October period indicate that POSI can be used to identify water stress in oil palm plants.

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