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Review

Research on the problems and prospects of oil palm resistance

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Abstract: Oil palm crops are the most important determinant of the agricultural economy within the segment of oil seed crops. Oil palm growing in their natural habitats are often challenged simultaneously by multiple stress factors, both abiotic and biotic that limits crop productivity and are major constraints to meeting global food demands. For development of stress-tolerant crops that mitigate the effects of abiotic stresses on crop productivity is crucially needed to sustain agricultural production. To date, there are no effective control methods to manage BSR disease. The viable long term alternative would be to breed for resistant germplasm. This has created a need for genetic improvement which involves evaluation of germplasm, pest and disease resistance, earliness and shattering resistance, quality of oil, varieties for different climatic conditions etc. In recent years, insights of physiology, molecular biology, and genetics have significantly enhanced our understanding of oil palm response towards such stimuli as well as the reason of varietal diversity in tolerance. However, this strategy is dependent on improved understanding of the factors associated with resistance/tolerance and susceptibility. In this review, we explore the research progress, existing problems and prospects of oil palm stress resistance based physiological mechanisms of stress tolerance as well as the genes and metabolic pathways that regulate stress response.

Keywords: cold resistance; disease resistance; drought resistance; oil palm; Abiotic/Biotic stress

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1. Introduction

Oil palm, a perennial tropical oil crop, is widely distributed in tropical areas between 10°S and 15°N [1], and is mainly cultivated in Southeast Asia, West and Central Africa, and North and Central South America [2]. In recent years, precipitation in West and Central Africa has decreased annually, resulting in a shortage of water on the land [3] and affecting the cultivation of oil palm. The northern part of South America has a tropical arid climate, with perennial high temperatures and little rain [4], which is not conducive to the growth of oil palm. In Southeastern Asia, there is a definite dry and rainy season, and the temperature drops during the dry season [5], inhibiting the growth of oil palm young fruits [6]. As a result, the low temperature and arid environment are unfavorable for oil palm growth and development, directly impacting oil palm yield [7]. Stress tolerance enables oil palm to trigger a number of protective strategies for enhancing survival and rapid recovery with full metabolic activities upon the return of favorable conditions. However, tolerance strategy is limited to oil palm species. The research on stress-resistant breeding of oil palm can improve the yield of oil palm fruit, enhance the resistance of oil palm, and promote the production and development of the oil palm industry, to further satisfy the demand for palm oil. Abiotic stress generates a wide range of morphological, physiological, biochemical, and molecular changes in plants, that have a negative impact on development and productivity [8]. Drought, temperatures, and oxidative stress are consistently related and may induce cellular damage [9]. For example, droughts are predominantly expressed as osmotic stress, resulting in a disturbance of homeostasis and ion

distribution in the cell [10]. Oxidative stress is commonly caused by high temperatures, or drought stress, which can lead to denaturation of functional and structural proteins [11]. Meanwhile, the disease of oil palm is another important factor which affects the normal growth and development [12], such as stem rot, which causes the decay of the root, base, stem and so on. Therefore, low temperatures, drought and disease hinder the global planting and development of oil palm, reducing production and the planting area, affecting the global demand for palm oil. Throughout the development history of oil palm, stress-resistant cultivation has always been a topic of great concern. Traditional and modern breeding, as well as biotechnology, are widely used to enhance oil palms with traits that confer stress resistance. Various environmental stresses have a significant impact on global oil palm productivity and crop quality. Functional genomics practices have contributed to our understanding of stress signal perception and transduction, as well as the underlying molecular regulatory network [13]. Several stress-inducible genes and transcription factors that regulate stress inducible expression were revealed by using techniques. A thorough understanding of the action of oil palm resistance will lay the foundation for elucidating the physiological, metabolic mechanisms, gene expressions and developmental activities in all aspects of oil palm life processes for improving a multitude of oil palm traits.

2. Morphological changes of oil palm under abiotic stress

Severe moisture conditions (drought and floods), extreme temperatures (hot and cold), and radiation (UV, ionising radiation) [14] all contribute to the emergence of abiotic stressors (Figure 1). Stresses such as high temperatures (heat and cold) and precipitation (drought and floods) are more common and are causing significant decline in agricultural productivity [15]. During the maturation of a tree, the plants are exposed to a wide range of environmental parameters [16]. To assess the influence of abiotic stress on plants, morphological measures such as root diameter, root length, and root weight, leaf area, ovule, pollen variability and anther development are typically measured [17,18,19]. Several researches identified a substantial correlation between oil palm vegetative attributes and yield. Subronto et al. [20] shown that leaf area may be used as a selection criterion in 9-month-old oil palm seedlings in a study on seedlings of oil palm because it was significantly correlated with yield. The development of oil palm seedlings is hampered by the cold [21]. Leaf number, seedling height, and girth, as well as seedling dry weight, were found to be strongly and positively correlated [22]. Balakrishna et al. [23] discovered a positive correlation between leaf area and bunch yield in oil palm. Marjuni et al. [24] discovered a correlation between palm height (HT) and the quantity of fresh fruit bunches, as well as the average bunch weight.

Low temperatures have a severe impact on oil palm growth and yield, causing an increase in abortion, delayed vegetative growth, and bunch ripening, as well as restricting regional distribution. Corley and Tinker [25] stated that low temperature around 18℃, which produced a strongly seasonal yield pattern, with approximately 90% of crop is harvested between June and December, owing to abortion and lower sex ratio in winter.

Thirasak et al. [26] evaluate the effect of various NaCl concentrations on oil palm growth. Oil palm cell suspension growth rate was reduced as NaCl concentrations and exposure durations were increased. The concentrations which inhibited 50% were clearly seen to require prolonged exposure time whereas high concentrations required short exposure time. Oil palm cell culture can tolerate modified by electrolyte leakage and proline accumulation the increment of concentrations of NaCl the increment of concentrations of NaCl. Also increased proline content at 2 folds higher than that of control, especially the concentration at 200 mM.

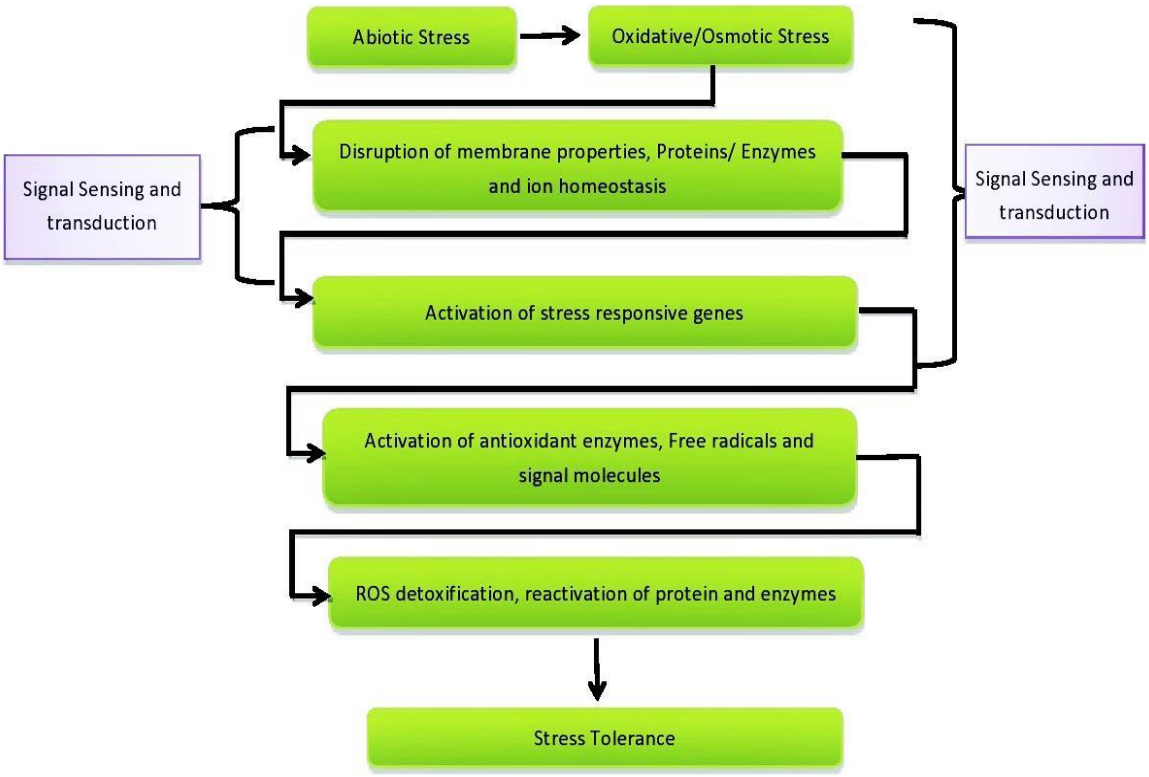


Figure 1. General scheme of Abiotic stress response and adaptation in plants.

3. Anatomical structure of oil palm under abiotic stress

According to Luis et al. [27], the anatomical structures of oil palm seedlings and genetically engineered test-tube seedlings were substantially consistent. The epidermal cells of the test-tube seedlings were thin, and the midrib of the leaves consisted of 3 to 4 vascular bundles, whereas the seedlings grown in the greenhouse had thicker leaves. Low temperature damage to leaves was reported to be reflected in a reduction in the thickness of total leaves, spongy tissue, and palisade tissue [28]. Changes in overall leaf thickness and tissue porosity were more visible under different low temperature treatments, which may be utilized as structural markers for identifying oil palm cold resistance. Zeng et al. [29] discovered that the thickness of the adaxial cuticle of the leaves in oil palm populations, as well as the thickness of spongy tissue, had the maximum positive and negative direct impacts on the LT50 at low temperatures. Therefore, the thickness of the adaxial cuticle of the leaves and the thickness of the leaf sponge tissue might be utilized as the primary structural indicators for the identification of oil palm populations and their cold resistance. In another study, Sari et al. [30] investigated the effects of drought stress on changes in leaf anatomical characteristics of oil palm seedlings were evaluated under moderate and severe drought stress, including the length of upper and lower epidermis cells, the width of upper dermis cells, the length of lower dermis cells, the thickness of mesophyll, the width of palisade cells and the diameter of phloem of leaf veins decreased, changing the structure of part of the leaf to adapt to the arid environment.

4. Role of Antioxidant defense of oil palm under abiotic stress

Proline is also one of the stress indicators for drought. Proline is a critical cell solute for antioxidant systems, enzyme stabilization, signal transduction, and ROS detoxification [31]. The variation of proline levels in drought stress on oil palm was also studied, with proline levels increasing when water was lowered and decreasing when water was rewatered [32]. According to Abdul Jaleel et al. [33], increased proline production improves

plants in maintaining low water potential and obtaining water from the environment under stressful conditions. If the rate of antioxidant activity is lower than the rate of ROS generation, lipid peroxidation in the cell membrane exists. The peroxidation of unsaturated fatty acids in phospholipid membranes produces MDA as a residue [10]. The amount of lipid peroxidation due to free radicals can indicate oxidative damage at the cellular level [34]. Changes in membrane structure, liquidity, ion transport, enzyme activity, and protein interactions each have the potential to induce membrane damage, leading to membrane leakage [10]. MDA levels were considerably larger in severe stress than in control, but there was no difference in moderate stress. The MDA content was higher under moderate stress, but not statistically different from the control. The content of MDA, soluble sugar and the relative conductivity initially increased and subsequently decreased in oil palm leaves [28]. This result showed that plants respond to cold stress by increasing MDA, which increased substantially under severe stress. In plants, free radicals are generally detoxified by enzymatic or nonenzymatic mechanisms. Non-enzymatic antioxidants known as carotenoids seek to preserve chlorophyll from oxidative degradation. Turhadi et al. [35] used Polyethylene Glycol (PEG as a plant drought tolerance response to trigger an increase in carotenoids in transgenic plants caused by drought. Meanwhile, SOD is an enzyme that participates in the enzymatic conversion of highly reactive superoxide radicals to less reactive H2O2 and O2 [36]. As a result, enhanced SOD activity as a free radical scavenging agent is frequently used to measure plant tolerance to abiotic stress. The content of proline, soluble protein and POD activity all exhibited a decreasing trend at first, then an increasing trend [28]. Low temperature stress has an effect on the enzyme activity of oil palm. Cao et al. [37] found that when temperature decreased, peroxidase (POD) activity, catalase (CAT) activity, superoxide dismutase (SOD) activity and glutathione reductase (GR) activity increased. Among GR activity reached a significant level; the activities of SOD and POD gradually increased with the extension of treatment time, and then decreased gradually [38]. Therefore, antioxidant content can be used as an indicator to determine the level of plant resistance in responding to abiotic stress [28].

5. Role of Photosynthesis change in Oil palm under abiotic stress

Droughts will become more common in the future as a result of climate change, such as increased temperatures, more variability in precipitation, and changing climatic patterns. Oil palm does typically shed leaves, but drought also weakens tress and makes them more the susceptible to insects attacks and the pathogens [39]. Indeed, a variety of physiological processes respond at different plant water potential thresholds [40], hence the severity of the drought season will influence the physiological response. Gong et al. [41] observed that the chlorophyll content, variable fluorescence (Fv), maximum fluorescence (Fm), variable fluorescence and maximum fluorescence ratio (Fv/Fm) of oil palm leaves decreased, whereas initial fluorescence (F0) and non-photochemical quenching coefficient (NPQ) increased, indicating that photosystem II (PSII) was affected by drought stress, resulting in a decrease in original light energy conversion efficiency (Fv/Fm) and photosynthesis efficiency in PSII. Furthermore, depending on the osmotic potential of the culture medium, photosynthetic pigments in oil palm plants subjected to PEG-induced severe drought stress were significantly decreased [42]. In palm plantlets cultivated under acute water deficit circumstances, the photosynthetic capacities Fv/Fm, PSII, and Pn were decreased [43]. Silva et al. [44] found that water potential, CO2 net assimilation rate, chlorophyll concentration, ribulose-1,5-bisphosphate carboxylase, net photosynthetic rate and stomatal conductance of two oil palm hybrids (BRS Manicoré and BRS C 2501) showed a downward trend. The total carotenoid, ascorbic acid and glutathione concentrations of BRS C2501 were lower than those of BRS Manicoré. Based on these, chlorophyll content and chlorophyll fluorescence parameters could be used as indicators to evaluate drought resistance of oil palm varieties. In fact, the growth characters of oil palm seedlings have been reported as sensitive parameters. In a previous study, the leaf area was significantly reduced in plants subjected to drought stress whereas plant height did not differ

significantly in drought conditions after 7, 14 and 21 days [21]. The typical regions where oil palm is grown have a distinct wet and dry season, and it would be predicted that the plants respond differently to water stress during the dry season compared to the wet season.

6. Molecular biology of oil palm with cold resistance

With the advancement of molecular biology technology, distinct oil palm varieties are being explored from the molecular perspective to identify the genes related to cold resistance of oil palm, providing a theoretical foundation for the breeding and selection of new varieties of oil palm [45]. For instance, EgRBP42, which was a heterogeneous ribonucleoprotein RNA binding protein derived from oil palm, might regulate post-transcriptional processes of gene expression under abiotic stress conditions to enhance oil palm tolerance to cold [46]. The DREB subfamilies contain a single DNA-binding domain which acts as regulators of abiotic stress responses. The DREB proteins interact with the DRE/CRT cis-element which is present in the promoter of genes and are involved in abiotic stresses such as cold, drought and high salinity. EgDREB1, an intron-free nuclear localization protein in oil palm, has the highest expression under low temperature stress [47], and functional characterization was conducted in oil palm seedlings subjected to different degrees of cold severity.

Chen et al. [48] identified FAD8 genes in oilpalm and shown that the regulation of plastidial -3 fatty acid desaturases impacts plant stress response: these include the up-regulation of a FAD gene in Arabidopsis thaliana by low temperature. Zhang et al. [49] identified the EgWRI promoter from oil palm and observed that when treated at a low temperature, the activity of the EgWRI1 promoter began to decline after 24 hours and recovered after 48 hours. In this report, the GUS activity of transgenic Arabidopsis leaves was determined under low-temperature circumstances. This revealed that the oil palm EgFAD8 and EgWRI1 promoters were sensitive to low temperatures, and could be candidate promoters for further research into oil palm cold resistance.

The EgMYB gene could be used as an important candidate gene to study oil palm cold tolerance. Under low temperature stress, 20 EgMYB genes were up-regulated [50]. Zhou et al. [51] used XJS30 and SJ64 as materials for low temperature acclimatization and cold treatment. The results indicated that WRKY1 and WRKY7 played a role in regulating the cold resistance of XJS30 during low temperature acclimation. WRKY1 and WRKY7 regulated the cold hardness of SJ64, genes like WRKY22, WRKY40 and WRKY55 could regulate the cold hardness of XJS30.

After extensive screening of these multiple transcriptome, studies showed that the actin gene, the adenine phosphoribosyl transferase gene, and the eukaryotic 4A initiation promoter gene were the most stable genes at low temperatures, providing basic information about the molecular biology of cold-resistant oil palm [52]. Li et al. [53] reported that the CBF gene of oil palm was significantly correlated with other genes (COR410, COR413, ICE1-1, ICE1-2, ICE1-4, SIZ1-1, SIZ1-2, ZAT10). At 12 ℃, CBF1, CBF2 and CBF3 were highly correlated with all other genes. The expression of CBF1 and CBF2 genes was also positively correlated with the content of soluble sugar and proline. Ninety-five genes belonging to the WRKY family have been identified in the oil palm genome. The most of the EgWRKY genes exhibited tissue-specific expression patterns that could be induced to express under low temperature stress. For example, Xiao et al. [54] found the expression level of 17 EgWRKY genes (EgWRKY03, 06, 07, 11, 16, 25, 26, 28, 29, 35, 52, 59, 61, 72, 76, 80 and 88) was increased by at least 2-fold, and 6 genes (EgWRKY06, 11, 25, 61, 72 and 88) were verified by RT-qPCR. Azzeme et al. [47] reported that the DREB1 gene in oil palm is involved in drought and cold signaling pathways. The DREB1 gene from oil palm increased the expression of DRE/CRT and non-DRE/CRT genes in transgenic plain tomato under low temperature and PEG treatment.

7. Molecular biology of oil palm with drought resistance

The expression of EgDREB1 in oil palm seedlings and leaves increased with the increase in drought stress, and the expression of EgDREB1 in roots only increased under mild drought stress. EGRBP42 was a heterogeneous nuclear ribonucleoprotein-like RNA-binding protein from oil palm, which might enhance the resistance of plants to abiotic stresses by accelerating protein translation. The overexpression of EgRBP42 enhanced the resistance of transgenic Arabidopsis to abiotic stresses such as drought, cold, salt and flood, and enhanced the resilience after stress [46]. Based on these, EgDREB1 and EgRBP42 could be used as important candidate proteins for drought tolerance studies of oil palm. Wang et al. [55] observed that under drought stress for 14 days, the edges and tips of leaves of oil palm seedlings were necrotic, then withered and yellowed; the number, volume and total biomass of roots decreased. The results showed that 1293 differentially expressed genes were expressed in the root after 14 days of drought stress, and the differentially expressed genes were divided into three types: hormone regulation, metabolism, and ABC transporters. Three protein networks including ion transport, active nitrogen metabolism and nitrate assimilation, were involved in the response to drought stress. These results provided the basic information molecular biology for oil palm drought resistance.

8. Cultivation techniques of oil palm with drought resistance

Brum et al. [56] monitored the transpiration (T) of a 5-year-old oil palm plantation during the dry season (DS) and rainy season (RS) using two irrigation methods, sprinkler irrigation and drip irrigation, with no irrigation as the control (WS). The results showed that the T of DS was higher than that of WS, which had nothing to do with the irrigation system; the transpiration rate of sprinkler irrigation and drip irrigation increased with the increase in water vapor pressure deficit (VPD), and the average soil moisture of the treatment was 23% higher than that of the control. These results proved that irrigation alleviated the water pressure of oil palm due to drought stress, increased the fruit yield of oil palm, and emphasized the potential feedback of increased transpiration on water balance and hydrological regulation. Safitri et al. [57] used CROPWAT8.0 software to analyze the climatic conditions and soil properties of oil palm nurseries, simulate crop water demand, actual water consumption and calculate the water demand of oil palm nurseries. It was shown that the average water requirement of oil palm nurseries was 3.4 mm/d. According to the daily soil water availability, plant root water retention rate, rainfall and oil palm planting years, an average of 2.2 mm/d of net irrigation schedule and 6 mm/d of the total irrigation schedule provided basic irrigation data for the drought-resistant cultivation of oil palm. Nurwahyuni et al. [58] exposed that applying calcium to oil palm seedlings under drought stress would reduce ABA content while increasing proline content, nitrate reductase activity, and photosynthetic rate, thereby preventing the complete closure of stomata, maintaining CO_2 diffusion, inhibiting the accumulation of free radicals, and reducing drought damage. When the calcium application was 0.04g/plant, the sponge cell length of oil palm seedling leaves increased, the width of the hypodermis and the diameter of the duct phloem of oil palm seedling leaves increased by 0.08g/plant, and the diameter of the xylem of oil palm seedling leaves increased by 0.12g/plant [59], which provided basic information on fertilization for the drought-resistant cultivation of oil palm.

9. Research on disease resistance of oil palm

The disease usually causes about 10% to 30% yield loss in the crop production process, and it might lead to no harvest when severe [60]. The devastating diseases of oil palm, including basal stem rot, fatal yellowing, blast disease and Fusarium wilt, affect the normal growth and development of oil palm. The research on oil palm disease resistance mainly focused on pathogens, detection techniques, biocontrol bacteria, medicaments, cultivation techniques, and molecular biology.

9.1. Pathogens of oil palm disease

Ganoderma boninense is a white rot fungus that degrades lignin. The main symptoms are leaf chlorosis, plant lodging, holes in the basal stem, rot of the root, base and upper stem, commonly known as oil palm basal stem rot (BSR) [61]. The disease severity index (DSI) of oil palm seedlings infected with *Ganoderma boninense* was linearly negatively correlated with the chlorophyll content in the early stage of the disease, the chlorophyll value showed a downward trend, but the DSI value showed no significance. Therefore, estimation of the chlorophyll content in the leaf of were measured using a SPAD chlorophyll meter and could be used as a physiological index to evaluate the occurrence of diseases in oil palm seedlings [62].

Bud or spear rot (BR) disease is the most destructive disease of oil palm in South America comprising Ecuadorian Amazon, Brazil, southwest Colombia and Suriname. The disease also has been reported in India and parts of Africa [63]. BR in oil palms can manifest differently depending on the prevailing environmental conditions. In the Ecuadorian Amazon, Brazil, south west Colombia, and Suriname, BR is mostly lethal to oil palms, while in the drier eastern plains of Colombia, BR is often non-lethal, and a high rate of recovery is observed [64]. Oil palm bud rot (BR) is caused by *Phytophthora palmivora* [65]. The rot spreads from the oil palm's meristem to the undifferentiated leaves, impeding the formation of new leaves and inhibiting the development of typical healthy leaves [66].The quantum efficiency (ΦPSII) and maximum fluorescence intensity (Fm) of PSII, variable fluorescence yield (Fv), Fv/Fm, and Fv/F0 dropped as the severity of BR increased, whereas F0 and leaf temperature increased. ΦPSII, Fm, F0, and leaf temperature are possible early indicators of BR [65].

Fusarium wilt is caused by *Fusarium oxysporum elaeidis* (FOE). The typical internal symptom is browning of vascular bundles, which are divided into acute Fusarium wilt and chronic Fusarium wilt. The symptom of acute Fusarium wilt is that the leaves quickly dry and die, and the trunk remains upright for 2 to 3 months before being blown off by the wind; the symptom of chronic Fusarium wilt is that the plant is short and grows slowly [67]. The sensitivity of oil palm to Fusarium wilt is polymorphic, and there are significant differences in the incidence of Fusarium wilt in different agro-ecological areas [68]. Lethal wilt (LW) is caused by *Phytophthora palmivora* [65]. The symptoms are dry or wet rot on arrow leaves and the yellowing symptoms of young leaves appear in the rainy season and disappear in the dry season [12].

Oil palm seedlings infected by *Pythiurn splenderns* have gray or brown-black spots on the stems, and the whole plant is dehydrated and wilted and eventually dies. Chen et al. [69] isolated and identified a *Pythium splendens* Braun strain from soil samples collected from Bawangling Nature Reserve, Hainan. It has the potential to induce typical blast disease symptoms.

The African oil palm ringspot virus (AOPRV) causes leaf mottle disease. Yellow spots occur initially on the leaves, then the leaves turn dry and the plant eventually dies, and ultimately, purple circular and necrotic patches emerge on the stems [70]. Zheng et al. [70] found that the most common disease was leaf mottle, and there were six pathogens, including *Phyllosticta*, *Colletotrichum*, *Alternaria*, *Pseudomonas Phomopsis*, *Phoma* and *Pestalotiopsis*. The field pathogenicity of the six pathogens was determined, and it was found that the lesions caused by *Colletotrichum* and *Alternaria* were smaller and the pathogenicity was weak, which was speculated to be saprophytes. *Phyllanthus*, *Pseudostem Phoma*, *Phoma*, and *Polychaete* could infect oil palm varieties RYL31 simultaneously, and *Phyllosporium* could also infect oil palm varieties RYL14 and RYL33, and it is speculated that this pathogen was more parasitic. The optimum growth temperature and pH of *Phoma herbarum* and *Phomopsis sp.in Deuteromycotina* were 20～25 ℃ and 25 ℃ as well as 6.0～8.0 and 7.0 respectively. PDA medium and PSA medium were suitable for the growth of *Phoma herbarum*, and PDA was the most suitable for the growth of *Phomopsis sp.in Deuteromycotina*. The lethal temperature of *Phomopsis sp.in Deuteromycotina* was 50℃ [70]. Three fungal pathogens were respectively inoculated on 24 different healthy oil palm leaves by the method of needle inoculation. According to the size of the diseased spots on the leaves, the resistance of 24 oil palm varieties to pathogens was determined. It was found that the

oil palm varieties with strong resistance to YZ-4 were RY-2 and RY-6. The oil palm varieties with strong resistance to YZ-6 were RY-9, RY-14, RY-15, RY-31, RY-37 and RY-38. The oil palm varieties with stronger disease resistance to YZ-8 are RY-38. It can be seen that there are differences in the resistance of different varieties to pathogenic bacteria [70].

9.2. Detection technology for oil palm disease resistance

The detection technology of oil palm base rot mainly includes extraction methods and model establishment, which is conducive to early detection and control of the disease, and guarantees the growth and development of oil palm. The DNA extraction method combined with a disposable microfluidic device and a biosensor realizes the automated, high-throughput, label-free detection of the pathogens of oil palm base rot [71]. There is a good correlation between ergosterol and the degree of infection of oil palm. The microwave assisted extraction (MAE) method can effectively extract ergosterol from oil palm roots of grade 2, 3 and 4 diseases. It is suitable for detection of oil palm BSR disease in the field [72]. There are significant differences between feature selection models (SVM-FS, RF and GA), electrical characteristics (impedance, capacitance, dielectric constant, and dissipation factor), and the degree of oil palm susceptibility (healthy, mild, moderate, severe). Among them, the SVM-FS model has the best prediction effect, with an average accuracy rate of 74.77%. The prediction results of RF and GA have high accuracy. SVM-FS, RF and GA can be used as the most suitable feature selection models for detecting BSR disease [73]. The Two-band enhanced vegetation index 2 (EVI2) is the best spectral index for detecting orange spot diodel and is most suitable for predicting, classifying and locating oil palm diseases caused by cotton bollworm. This model has the potential to detect BSR early and distinguish the severity of oil palm diseases [74]. BSTRACT field spectroscopy is a fast and non-destructive analytical tool for assessing plant adversity and disease. The ratio 3 is the best spectral index for early detection of BSR disease in oil palm seedlings, because this index has the highest average silhouette width (ASW) value, which is highly correlated with the total leaf chlorophyll (TLC) of the healthy oil palm, and is an important indicator reflecting the vital status of oil palm [75].

By analyzing the reflectance spectra of oil palm seedlings and healthy oil palm seedlings inoculated with coconut cadang–cadang viroid (CCCVd), it was shown that the infrared inflection point (ReIP) at 700 nm could well reflect the condition of oil palm seedlings under CCCVd stress. The dual-band enhanced vegetation index (EVI2) is the best spectral index for detecting orange spot disease in mature oil palm forests [76]. Zhang et al. [77] used loop-mediated isothermal amplification technique to develop a rapid and sensitive detection method for oil palm damping-off bacteria and designed a total of 6 primers based on 8 loci in the ITS region gene. The results showed that the primers had good specificity for the detection of oil palm damping-off bacteria; the minimum detection limit of primer sensitivity was 0.12 ng•μL^{-1} which was 100 times higher than the ordinary polymerase chain reaction (PCR); the detection results could be observed with the naked eye after testing with SYBR Green1. Nababan et al. [78] used the naive Bayes method to design an intelligent application program with input and output planning, which could diagnose the types of oil palm plant diseases.

9.3. Biocontrol bacteria, fungicides and cultivation techniques of oil palm disease resistance

The current control strategies for pathogen infection are focused on long-term and short-term control by keeping disease incidence below the economic threshold of infected palms. Short term control strategies include the routine roguing of infected stands, fungicide intervention and the use of bio control agents, whilst long term strategies include breeding for resistance. Both have been hampered by a lack of understanding of disease mechanisms and host-pathogen interactions, which are associated with factors of pathogenicity, resistance, tolerance and susceptibility. Cao et al. [79] found that the biocontrol bacteria inhibited *Ganoderma lucidum* much more effectively under potato medium (PD) liquid culture conditions than under potato agar medium (PDA) solid culture conditions, indicating that the biocontrol bacteria could fully contact and act on the pathogenic

mycelium in PD liquid culture to achieve the best antagonistic effect. Oil palm seedlings treated with *Streptomyces palmitos* CMU-AB204^T had the highest plant vigor and inhibitory activity against *Ganoderma lucidum*. Therefore, CMU-AB204^T was a promising biocontrol bacteria that could be used to protect oil palm trees from BSR disease [80]. The endoparasitic *Trichoderma* strain had the best control effect on oil palm seedling leaf mottle disease, because it could inhibit the growth of hyphae in vitro, reduce disease symptoms in the body and in the field, and increase the activity of phenylalnine ammonialyase (PAL), peroxidase (POD) and polyphenol oxidase (PPO) in oil palm leaves [81].

Nano-carrier capsules (polymers, lipids, carbon-based materials, and metals) could be loaded with active pesticide formulations. It has become a sustainable alternative for developing a low-toxic and effective pesticide nano-drug delivery system and improving the safety of the oil palm industry [82]. Chitosan-based agricultural fungicides have been used as sustainable options for root rot management. Chitosan, in particular, is often used to improve plant defence mechanisms and natural immunity, preventing pathogens from infecting plants [83]. Insecticides carbaryl, deltamethrin, fipronil and imidacloprid have the potential to significantly enhance the mortality of the South American palm weevil and hence control the population of oil palm trees [84]. The endophytic *Bacillus subtilis* preparation could delay the incubation period of oil palm seedlings and reduce the disease intensity, and had no significant effect on the plant height, leaf number, diameter, root volume, root-to-shoot ratio and root dry weight of the seedlings [85].

Rebitanim et al. [86] studied a new fertilizer technology to promote the growth and development of oil palm seedlings, reduce the severity of oil palm stem basal rot, the incidence and mortality of seedlings, and reduce the disease, which proved that the nutrients in GanoCare® allowed the seedlings to establish a strong defense system. Foliar spraying of mineral nutrients (calcium, copper) and salicylic acid (SA) could improve the control effect of root rot of oil palm seedlings [87]. When the soil pH was 6.0, it could reduce the infection of *Ganoderma lucidum* on oil palm seedlings [88]. The incidence of oil palm stalk rot in high-density oil palm forests was significantly higher than that of low-density oil palm forests [89]. Therefore, the planting density of oil palm forests should be planned to reduce the incidence of oil palm stalk rot.

9.4. Molecular biology of oil palm disease resistance

Screening for resistant varieties for disease control are difficult with confirmed pathogen, since no standard protocols exist for the infection and limited understanding on the spread of the disease could result in false identification of possible resistant varieties [90]. Nevertheless, there are several hybrid material Elaeis oleifera x E. guineensis Jacq. has been identified as a potential for disease resistance by expressing less severe symptoms and a slower progression of the disease in infected tissue [91]. In terms of molecular biology, research on oil palm disease resistance genes is conducive to the cultivation of oil palm varieties with excellent traits. Hanin et al. [92] identified that the oil palm embryogenic callus had a construct with AGLU1 and RCH10 genes and a construct with a Basta® resistance gene (bar); after selection with herbicides, polymerase chain reaction (PCR) showed that the ratio 8/25 plants were positive for the presence of three transgenes (bar, AGLU1 and RCH10 genes); quantitative reverse transcription PCR (RT-qPCR) showed that five of the eight plants expressed AGLU1 and RCH10 gene; these five strains were infected by *Ganoderma lucidum* and two strains showed resistance. Using the alfalfa glucanase (AGLU1) gene and rice chitinase (RCH10) gene to biologically mediate oil palm, it could be cultivated as an anti-fungal oil palm. The pathogenicity of *G. boninense* was related to the cell wall degrading enzymes (CWDEs) released during the saprophytic and necrotrophic stages of infection of the oil palm host. Ramzi et al. [93] successfully identified the cell wall degrading enzymes in the NJ3 gene of *Ganoderma lucidum angustifolia* by analyzing the genome, and using plant-host interaction (PHI) to identify several genes related to cell wall degrading enzymes, including polysemi lacturonidase and laccase. These enzymes degraded plant cell walls and promoted the pathogenesis of fungi. These findings provided basic knowledge about the genetic ability of fungi and the ability of cell

wall degrading enzymes. Nascimento et al. [94] used a two-dimensional liquid chromatography-tandem mass spectrometry (2D-UPLCMSE) analysis method to study the changes in oil palm protein components affected by fatal yellowing. The expression levels of transketolase, isoflavone reductase, cinnamyl alcohol dehydrogenase, caffeic acid 3-O-methyltransferase, adenosylmethionine synthase, acetaldehyde dehydrogenase and ferritin gradually increased during the development of the disease, indicating that these proteins played an important role in making oil palm resistant to fatal yellowing.

10. Problems and prospects of oil palm resistance

Many studies have been conducted on the cold resistance of oil palm, including physiology, anatomy, and molecular biology. Further investigation into the cold resistance mechanism and genetic process of oil palm is required. It will provide a theoretical foundation for producing novel cold-resistant cultivars by conducting a comprehensive study on the cold resistance mechanism. The regulation mechanism of plant hormones on oil palm under drought stress has not yet been investigated. The above-mentioned oil palm responses to abiotic stresses show that the response is complex and depends on the species and genotype, the type of stress, the length and severity of stress, the age and stage of oil palm development, the organ and cell type, the subcellular compartment, and the gene and its mode of action. The physiological and biochemical indicators as well as anatomical structures closely related to drought resistance must be deepened to become a drought-resistant oil palm germplasm resource, to provide accurate and easy-to-operate evaluation indicators during utilization, laying a theoretical foundation for cultivating drought-tolerant oil palm (Figure 2). The research on oil palm disease resistance focuses on four aspects: the analysis, detection, prevention and control of pathogens, and oil palm disease-resistant cultivation techniques. There is relatively little research on disease resistance mechanisms. Oil palm resistance should be studied from a molecular perspective to provide a basis for cultivating new disease-resistant oil palm varieties. The research on the resistance of oil palm is still in the exploratory stage, and the theory of mechanism and physiological indicators has still not been refined. The mechanism of resistance to cultivation of oil palm should be explored from a broad prospective and levels. In recent years, oil palm breeding for stress resistance has been applied to DNA molecular markers including SSR, ISSR, SRAP, and TRAP, which greatly shortens the breeding period, facilitates the development of oil palm genetic maps, and accelerates the cultivation of new varieties of oil palm. At the same time, organogenesis, somatic embryo induction, and somatic embryo regeneration in tissue culture technology can shorten the breeding period of oil palm, reduce costs, improve breeding efficiency, and expand oil palm germplasm resources. Scientists should combine biotechnology with scientific research, actual production and development in accordance with the natural environment and cultivation conditions in various regions of the world, in order to develop different high-yielding and quality new oil palm varieties for planting in different regions, thereby promoting the oil palm industry, production and development, and satisfying the demand for palm oil. To fulfill the task of sustainable future food demand, oil palm crops need to maintain high yields under stressful environmental conditions and unpredictable changing climates. It is likely that oil palm crops of the future need to be stacked with multiple desired traits for higher yields while mitigating the effects of abiotic stresses and complex pathogenesis incidences triggered by changing climates. Therefore, understanding the full picture of how oil palm responds to stress will enable the determination of key processes that contribute to crop yield under stress. This knowledge will be valuable for plant breeding towards improving crop yield stability under changing climatic conditions.

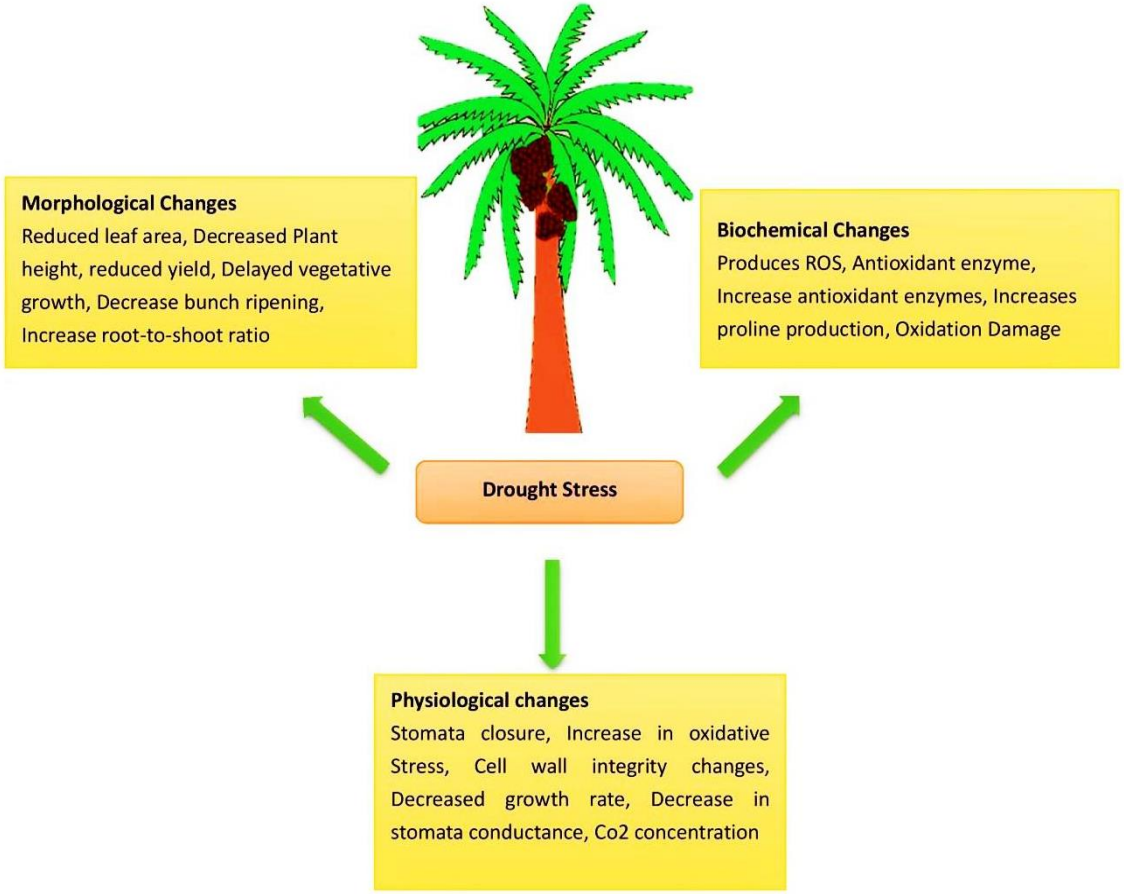


Figure 2. Drought tolerance in oil palm. Drought stress causes significant changes in morphological, biochemical, and physiological.

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References

1. Xu, L.; Liu, Y.J. The evolution of world oil palm production and trade in time and space and its development forecast. *World Geographical Research* **2012**, *21*: 70-76.
2. Zeng, X.H.; Li, W.F.; Liu, Z.; Li, Z.; Zou, J.X.; Pan, D.L.; Lin, W.F. Research status and trends of oil palm resistant cultivation in China. *China Tropical Agriculture* **2014**, *5*: 24-29.
3. Yang, D.; Xiong, W.; Xu, Y.L. The impact of climate change on water resources and agriculture in Africa. *Chinese Agricultural Meteorology* **2016**, *37*: 259-269.
4. Ye, W. The special distribution and causes of tropical arid climate in South America. *Journal of Chongqing Normal University (Natural Science Edition)* **1997**, *4*: 81-83.
5. You, L.J.; Wang, R.M. The impact of climate and its changes on agricultural production in Southeast Asia. *Geography*

Education **2010**, Z1: 29.
6. Fang, F.C. Hainan island climate and oil palm planting. *Chinese Journal of Tropical Crops* **1982**, *1*: 81-93.
7. Cheng, Q.R.; Liu, Z.F.; Zeng, X.H.; Zeng, J. Research progress in oil palm cold resistance. *Tropical Agriculture Science* **2020**, *40*: 50-56.
8. Sivaji Mathivanan. Abiotic Stress-Induced Molecular and Physiological Changes and Adaptive Mechanisms in Plants, Abiotic Stress in Plants. *IntechOpen* **2021**.93367
9. Mattos, L. Oxidative Stress in Plants Under Drought Conditions and the Role of Different Enzymes. *Enzyme Engineering* **2016**, *05*.
10. Sharma, P.; Jha, A.; Dubey, R.; Pessarakli, M. Reactive Oxygen Species, Oxidative Damage, and Antioxidative Defense Mechanism in Plants under Stressful Conditions. *Journal of Botany* **2012,**217037.
11. Fahad, S.; Bajwa, A.A.; Nazir, U.; Anjum, S.A.; Farooq, A.; Zohaib, A.; Sadia, S.; Nasim, W.; Adkins, S.; Saud, S., et al. Crop Production under Drought and Heat Stress: Plant Responses and Management Options. *Frontiers in Plant Science* **2017**, *8*.
12. Tang, Q.H.; Cao, H.X.; Qin, W.Q. Research progress and main problems of oil palm diseases. Chinese Society of Phytopathology. Proceedings of the Chinese Society of Phytopathology Annual Conference [C]. *Chinese Society of Phytopathology: China Society of Plant Pathology* **2019**.
13. Li, S.; Yu, X.; Cheng, Z.; Yu, X.; Ruan, M.; Li, W.; Peng, M. Global Gene Expression Analysis Reveals Crosstalk between Response Mechanisms to Cold and Drought Stresses in Cassava Seedlings. *Frontiers in Plant Science* **2017**, *8*.
14. HanumanthaRao, B.; Nair, R.M.; Nayyar, H. Salinity and High Temperature Tolerance in Mungbean [Vigna radiata (L.) Wilczek] from a Physiological Perspective. *Frontiers in Plant Science* **2016**, *7*.
15. Liliane, T.; Mutengwa, C. Factors Affecting Yield of Crops. *Intechopen* **2020**.90672.
16. Gull, A.; Lone, A.; Wani, N. Biotic and Abiotic Stresses in Plants. *Intechopen* **2019**.85832
17. Arif, Y.; Singh, P.; Siddiqui, H.; Bajguz, A.; Hayat, S. Salinity induced physiological and biochemical changes in plants: An omic approach towards salt stress tolerance. *Plant Physiology and Biochemistry* **2020**, *156*.
18. Malinowska, M.; Donnison, I.; Robson, P. Morphological and Physiological Traits that Explain Yield Response to Drought Stress in Miscanthus. *Agronomy* **2020**, *10*, 1194.
19. Su, Z.; Ma, X.; Guo, H.; Sukiran, N.L.; Guo, B.; Assmann, S.M.; Ma, H. Flower development under drought stress: morphological and transcriptomic analyses reveal acute responses and long-term acclimation in Arabidopsis. *Plant Cell* **2013**, *25*, 3785-3807.
20. Subronto, A.M.; Taniputra, B. Correlation between vegetative characters of the oil palm in the nursery and yield.*Buletin-Perkebunan*, **1989,** *20*, 107-116.
21. Cao, H.-X.; Sun, C.-X.; Shao, H.; Lei, X.-T. Effects of low temperature and drought on the physiological and growth changes in oil palm seedlings. *AFRICAN JOURNAL OF BIOTECHNOLOGY* **2011**, *10*, 2630-2637.
22. Lucas, E.O. Relations Between Growth Parameters in Oil Palm Seedlings Grown in Polybags. *Experimental Agriculture* **1980**, *16*, 275-278.
23. Balakrishna, P.; Rajasekhar, P.; Pavani, K.V.; Mathur, R. Correlation and Path Coefficient Analysis in Indian Oil Palm genotypes. *Journal of Pure and Applied Microbiology* **2018**, *12*, 195-206.
24. Marjuni, M.; Rafii, M.; Afizi, M.M.A.; Wasiu Arolu, I.; Noh, A.; Din, A.; Kushairi, A.; Abdullah, N.; Rajanaidu, N.; A, L., et al. Genetic variability in yield and vegetative traits in elite germplasm of MPOB-Nigerian dura × AVROS pisifera progenies. *Journal of Food, Agriculture and Environment* **2013**, *11*, 515-519.

25. Corley, R. H. V., and Tinker, P. B. *The Oil Palm*. Oxford: John Wiley & Sons **2003.**
26. Thirasak, S.; Sompong, T.-c.; Sureerat, Y. Determination of Salt Tolerance of Oil Palm SUP-PSU 1 Using Cell Suspension Culture. *Plant Cell, Tissue and Organ Culture (PCTOC)* **2021**.
27. Luis, Z.G.; Bezerra, K.M.G.; Scherwinski-Pereira, J.E. Adaptability and leaf anatomical features in oil palm seedlings produced byembryo rescue and pre-germinated seeds. *Brazilian Journal of Plant Physiology* **2010**, *22*:209-215.
28. Cao, H.X.; Huang, H.J.; Lei, X.T.; Zhang, D.P.; Zhang, R.L.; Sun, C.X. Effects of different low temperature treatments on the anatomical structure of oil palm leaves. *Chinese Journal of Tropical Crops* **2014**, *35*:454-459.
29. Zeng, X.H.; Jiao, Y.F.; Liao, Z.R.; Pan, D.L.; Lin, W.F. Effects of the anatomical structure of oil palm leaves in different regions of Guangdong on the cold resistance of oil palm. *Guangdong Agricultural Sciences* **2018**, *45*:50-58.
30. Sari, N.Y.; Putra, E.T.S. The contribution of calcium to changes in leaf anatomical character of oil palm seedlings (*Elaeis guineensis* Jacq.) under drought stress. *Ilmu Pertanian (Agricultural Science)* **2019**, *4*(1).
31. Arteaga, S.; Yabor, L.; Diez, M.J.; Prohens, J.; Bp_caiu, M.; Vicente, O. The Use of Proline in Screening for Tolerance to Drought and Salinity in Common Bean (Phaseolus vulgaris L.) Genotypes. *Agronomy* **2020**, *10*, 817.
32. Najihah, T.; Ibrahim, M.H.; Razak, A.f.; Nulit, R.; Megat Wahab, P. Effects of water stress on the growth, physiology and biochemical properties of oil palm seedlings. *AIMS Agriculture and Food* **2019**, *4*, 854-868.
33. Jaleel, C.; Manivannan, P.; Wahid, A.; Farooq, M.; Al-Juburi, H.; Somasundaram, R.; Panneerselvam, R. Drought Stress in Plants: A Review on Morphological Characteristics and Pigments Composition. *International Journal of Agriculture and Biology* **2009**, *11*.
34. Shukla, S.D.; Bhatnagar, M.; Khurana, S. Critical evaluation of ayurvedic plants for stimulating intrinsic antioxidant response. *Front Neurosci* **2012**, *6*, 112-112.
35. Turhadi; Minarsih, H.; Riyadi, I.; Priyono; Budiani, A. Physiological responses and P5CS gene expression of transgenic oil palm plantlet induced by drought stress. *E-Journal Menara Perkebunan* **2020**.
36. Naeem, M.; Naeem, M.; Ihsan, M.; Ashraf, M.; Hussain, Y.; Fahad, S. Foliar calcium spray confers drought stress tolerance in maize via modulation of plant growth, water relations, proline content and hydrogen peroxide activity. *Archives of Agronomy and Soil Science* **2017**, *64*.
37. Cao, H.X.; Zhang, J.C.; Lei, X.T.; Liu, Y.J.; Zhang, R.L. Physiological and biochemical responses of different oil palm resources to low temperature stress. *Journal of Yunnan Agricultural University (Natural Science)* **2017**, *32*: 316-321.
38. Liu, S.H.; Ni, S.B.; Wei, L.P.; Gong, L.D.; Zhang, Y.M.; Xiao, X.M. The relationship between oil palm cold resistance and endogenous hormones. *Chinese Agricultural Science Bulletin* **2015**, *31*:144-148.
39. McDowell, N.; Pockman, W.T.; Allen, C.D.; Breshears, D.D.; Cobb, N.; Kolb, T.; Plaut, J.; Sperry, J.; West, A.; Williams, D.G., et al. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytologist* **2008**, *178*, 719-739.
40. Ditmarová, L.; Kurjak, D.; Palmroth, S.; Kmet, J.; Strelcová, K. Physiological responses of Norway spruce (Picea abies) seedlings to drought stress. *Tree Physiol* **2010**, *30*, 205-213.
41. Gong, L.; Wei, L.; Ni, S.; Liu, S. Effects of continuous drought on chlorophyll fluorescence kinetic parameters of oil palm seedlings. *Chinese Agricultural Science Bulletin* **2016**, *32*:1-6.
42. Cha-um, S.; Takabe, T.; Kirdmanee, C. Physio-Biochemical Responses of Oil Palm (Elaeis guineensis Jacq.) Seedlings to Mannitol- and Polyethylene Glycol-Induced Iso-Osmotic Stresses. *Plant Production Science* **2012**, *15*, 65-72.
43. Cha-Um, S.; Yamada, N.; Takabe, T.; Kirdmanee, C. Physiological features and growth characters of oil palm (Elaeis

guineensis jacq.) in response to reduced water-deficit and rewatering. *Australian Journal of Crop Science* **2013**, *7*, 432-439.

44. Silva, P.A.; Oliveira, I.V.; Kátia, B.; Rodrigues, C.B.; Pinheiro, H.A. Leaf gas exchange and multiple enzymatic and non-enzymatic antioxidant strategies related to drought tolerance in two oil palm hybrids. *Trees* **2016**, 30(1).
45. Xiong, H.B.; Cao, H.X.; Han, L.G.; Wu, Y.; Fan, H.K.; Qin, W.Q.; Ma, Z.L. Research progress and prospects of molecular biology in oil palm breeding. *China Tropical Agriculture* **2009**, 3:47-49.
46. Yeap, W.C.; Namasivayam, P.; Ooi, T.E.K.; Appleton, D.R.; Kulaveerasingam, H.; Ho, C.L. EgRBP 42 from oil palm enhances adaptation to stress in Arabidopsis through regulation of nucleocytoplasmic transport of stress responsive mRNAs. *Plant, Cell & Environment* **2019**, *42:*1657-1673
47. Azzeme, A.M.; Abdullah, S.N.A.; Aziz, M.A.; Wahab, P.E.M. Oil palm drought inducible DREB1 induced expression of DRE/CRT and non-DRE/CRT containing genes in lowland transgenic tomato under cold and PEG treatments. *Plant Physiology and Biochemistry* **2017**, *112*:129-151.
48. Chen, L.Z.; Wang, L.; Wang, H.R. Identification and characterization of a plastidial ω-3 fatty acid desaturase EgFAD8 from oil palm (*Elaeis guineensis* Jacq.) and its promoter response to light and low temperature. *PloS One* **2018**, 13(4).e0196693
49. Zhang, Q.; Sun, R.H.; Zheng, Y.S.; Yuan, Y.J.; Li, D.D. Isolation and characterization of the EgWRI1 promoter from oil palm (*Elaeis guineensis* Jacq.) and its response to environmental stress and ethylene. *PloS One* **2019**, 14(12).e0225115
50. Zhou, L.X.; Yarra, R.; Jin, L.F.; Cao, H.X. Genome-wide identification and expression analysis of MYB gene family in oil palm (*Elaeis guineensis* Jacq.) under abiotic stress conditions. *Environmental and Experimental Botany* **2020**,*180*.104245
51. Zhou, L.X.; Cao, H.X. Analysis of the expression characteristics of oil palm WRKY transcription factor genes under low temperature stress. *Southern Agricultural Journal* **2018**, 49(8):1490-1497.
52. Xia, W.; Mason, A.S.; Xiao, Y.; Liu, Z; Yang, Y.; Lei, X; Wu, X.; Ma, Z.; Peng, M. Analysis of multiple transcriptomes of the African oil palm (*Elaeis guineensis*) to identify reference genes for RT-qPCR. *Journal of Biotechnology* **2014**, 184:63-73.
53. Li, J.; Yang, Y.D.; Iqbal, A.; Qadri, R.; Shi, P.; Wang, Y.; Wu, Y.; Fan, H.K.; Wu G.J. Correlation analysis of cold-related gene expression with physiological and biochemical indicators under cold stress in oil palm. *PloS One* **2019**, 14(11).e0225768
54. Xiao, Y.; Zhou, L.; Lei, X.; Cao, H.; Wei, X. Genome-wide identification of WRKY genes and their expression profiles under different abiotic stresses in *Elaeis guineensis*. *PloS One* **2017**, 12(12):1-18.
55. Wang, L.; Lee, M.; Ye, B.; Yue, G.H. Genes, pathways and networks responding to drought stress in oil palm roots. *Scientific Reports* **2020**, 10.21303 .
56. Brum, M.; Oliveira, R.S.; López, J.G.; Licata, J.; Asbjornsen, H. Effects of irrigation on oil palm transpiration during ENSO-induced drought in the Brazilian Eastern Amazon. *Agricultural Water Management* **2021**, 245.106569.
57. Safitri, L. Manajemen Irigasi Pembibitan Sawit (Elaeis guineensis) Presisi dengan Cropwat 8.0. *Jurnal Teknik Pertanian Lampung* **2019**, *8*,97.
58. Nurwahyuni, E.; Putra, E.T.S. The effect of calcium on photosynthetic rate due to aba and proline behaviour of oil palm *Elaeis guineensis* Jacq seedlings under drought conditions. Caraka Tani: *Journal of Sustainable Agriculture* **2019**, *34*,

31.
59. Wang, W.; Zhao, J.; Fan, J.; Li Y.; Huang, Y.; Zhang, J. Current status and prospects of research on plant disease resistance. *National Science Foundation of China* **2020**, 34(04):433-440.
60. Lisnawita Hanum, H.; Tantawi, A.R. Survey of basal stem rot disease on oil palms (*Elaeis guineensis* Jacq.) in Kebun Bukit Kijang, North Sumatera, Indonesia. IOP Conference Series: *Earth and Environmental Science* **2016**, 41(1):9-15
61. Rakib, M.R.M.; Borhan, A.H.; Jawahir, A.N. The relationship between SPAD chlorophyll and disease severity index in Ganoderma-infected oil palm seedlings. *Journal of the Bangladesh Agricultural University* **2019**, *17(3)*, 355-358.
62. Aucique-Perez, C.E.; Daza, E.S.; Ávila-Diazgranados, R.A.; Romero, H.M. Chlorophyll a fluorescence and leaf temperature are early indicators of oil palm diseases. *Scientia Agricola* **2020**, 77(2).e20180106.
63. Ntsomboh Ntsefong, G.; Ngando, G.; Paul, K.; Bell, j.m.; Youmbi, E.; Bille, N.; Gervais, B.; Galdima, M.; Bienvenu, A. Control Approaches against Vascular Wilt Disease of Elaeis guineensis Jacq. Caused by Fusarium oxysporum f. sp. elaeidis. *Journal of Biology and Life Science* **2012**, *3*, 1-14.
64. Corley, R.V.H., & Tinker, P.B. (2015). The Oil Palm. 5th ed. *Blackwell Science*, Oxford.
65. Navia, E.A.; Restrepo, E.F.; Romero, H.M. Response of six sources of oil palm planting materials from Malaysia planted in the eastern plains of Colombia to bud rot. *Journal of Oil Palm Research* **2014**, 26(1):73-83.
66. Yu, F.; Qin, W.; Zhu, H.; Ma, Z. Research review of oil palm fusarium wilt. *China Tropical Agriculture* **2009**, 2: 46-48.
67. Koussinou, C.K.S.L.; Adandonon, A.; Nodichao, L. Distribution and incidence of *Fusarium* wilt in oil palm in Benin. *Journal of Applied Biosciences* **2019**, *135*.13831
68. Zheng, L.; Shen, H.; Li, J.; He, S.; Zeng, X.; Feng, C.; Qin, X.; Xie, C. Investigation of oil palm diseases and preliminary identification of pathogenic fungi of leaf diseases. *Guangdong Agricultural Sciences* **2014**, *41*: 66-69.
69. Chen, X.; Zeng, H.; He, H et al. Identification of Pythium splendens, a newly recorded species of Pythium splendens in Hainan and its pathogenicity to oil palm seedlings [J]. *Journal of Yunnan Agricultural University* **2008**, *23*: 321-324.
70. Zheng, L.; Zhang, H.; Lin, J.; Zeng, X.; Li, J.; Shen, H.; Xie, C.; Qin, X. Biological characteristics and virulence determination of the pathogen of oil palm grass stem spot mold leaf spot. *Chinese Journal of Tropical Crops* **2017,** *38*:1694-1699.
71. Ayoib, A.; Hashim, U.; Gopinath, S.C.B. Automated, high-throughput DNA extraction protocol for disposable label free, microfluidics integrating DNA biosensor for oil palm pathogen, Ganoderma boninense. *Process Biochemistry* **2020,** *92*.
72. Saad M.M., Ali N.S., Meon S. Relationship between ganoderma ergosterol concentration and basal stem rot disease progress on *Elaeis guineensis*. *Tropical Life Sciences Research* **2020**,*31*:19-43.
73. Khaleda, A.Y.; Aziza, S.A.; Bejoa, S.K.; Nawi, N.M.; Seman, I.A. Spectral features selection and classification of oil palm leaves infected by Basal stem rot (BSR) disease using dielectric spectroscopy. *Agriculture Week* **2018**,*144*:297-309.
74. Santoso, H.; Tani, H.; Wang, X.F. Random forest classification model of basal stem rot disease caused by *Ganoderma boninense* in oil palm plantations. *International Journal of Remote Sensing* **2017**, *38*:4683-4699
75. Izzuddin, M.A.; Idris, A.S.; Nisfariza, M.N.; Nordiana, A.A.; Shafri, H.Z.M.; Ezzati, B. The development of spectral indices for early detection of Ganoderma disease in oil palm seedlings. *International Journal of Remote Sensing* **2017**, *38*: 6505-6527.
76. Golhani, K.; Balasundram, S.K.; Vadamalai, G.; Pradhan, B. Selection of a spectral index for detection of orange spotting disease in oil palm *(Elaeis Guineensis* Jacq.) using red edge and neural network techniques[J]. *Network Weekly News*

2019, *47*:639-646.

77. Zhang, H., Duan, W., Zhang, J., Wang, J., Xu, Y., Chen, X. Study on detection of oil palm damping-off bacteria by loop-mediated isothermal amplification technique. *Journal of Zhejiang Agricultural Sciences* **2013**, *25*:303-308.
78. Nababan, M.; Laia, Y.; Sitanggang, D.; Sihombing, O.; Indra, E.; Siregar, S.D.; Purba, W.; & Mancur, R. The diagnose of oil palm disease using Naive Bayes Method based on Expert System Technology. *Journal of Physics: Conference Series* **2018**, *1007*:012015.
79. Cao, X.; Shang, L.; Li, J.; Hu, J. Research on the prevention and treatment of oil palm stem basal infection with *Ganoderma boninense* by microorganisms. *Heilongjiang Science* **2020**,*11*:1-3.
80. Sujarit, K.; Pathom-aree, W.; Mori, M. et al. Streptomyces palmae CMU-AB204 T, an antifungal producing-actinomycete, as a potential biocontrol agent to protect palm oil producing trees from basal stem rot disease fungus, *Ganoderma boninense*. *Biological Control* **2020**,*148*.104307
81. Sunpapao, A.; Chairin, T.; Ito, S. The biocontrol by Streptomyces and Trichoderma of leaf spot disease caused by *Curvularia oryzae* in oil palm seedlings. *Biological Control* **2018**, *123*.
82. Maluin, F.N.; Hussein, M.Z.; Idris, A.S. An overview of the oil palm industry: Challenges and some emerging opportunities for nanotechnology development. *Agronomy* **2020**, *10*:356.
83. Maluin, F.N.; Hussein, M.Z.; Yusof, N.A.; Fakurazi, S.; Daim, L.D.J. Chitosan-based agronanofungicides as a sustainable alternative in the basal stem rot disease management. *Journal of Agricultural and Food Chemistry* **2020**, *68*:4305-4314.
84. Martínez L.C., Plata-Rueda A., Rodríguez-Dimaté F.A., Campos J.M., Serro J.E. Exposure to insecticides reduces populations of rhynchophorus palmarum in oil palm plantations with bud rot disease. *Insects* **2019**, *10*:111.
85. Puspita, F.; Hadiwiyono, Poromorto, S.H.; Roslim, D.I. The application of different Bacillus subtilis contained formula as bio fungicide tablet to control *Ganoderma boninense* in oil palm nurseries. IOP Conference Series: *Earth and Environmental Science* **2019**, *250* :012052.
86. Rebitanim, N.A.; Hanafi, M.M.; Idris, A.S.; Abdullah, S.N.A. GanoCare® improves oil palm growth and resistance against ganoderma basal stem rot disease in nursery and field trials. *BioMed Research International* **2020,**3063710.
87. Bivi, M.S.H.R.; Paiko, A.S.; Khairulmazmi, A.; Akhtar, M.S.; Idris, A.S. Control of basal stem rot disease in oil palm by supplementation of calcium, copper, and salicylic acid. *The Plant Pathology Journal* **2016**, *32*:396–406.
88. Abdullah, R.K.; Radziah, O. Influence of pH levels on disease development in oil palm seedling roots infected with *Ganoderma boninensis*. *Rhizosphere* **2020**, *13*:100181.
89. Shukri, I.M.; Izzuddin M.A.; Hefni R.M.; Idris, A.S. Geostatistics of oil palm trees affected by *Ganoderma* disease in low and high planting density. IOP Conference Series: *Earth and Environmental Science* **2020**, *540*:012065.
90. Benitez, E.; Garcia, C. The history of research on oil palm bud rot (Elaeis guineensis Jacq.) in Colombia. *Agronomía Colombiana* **2015**, *32*, 390-398.
91. Navia, E.; Diazgranados, R.; Daza, E.; Restrepo, E.; Romero, H. Assessment of tolerance to bud rot in oil palm under field conditions. *European Journal of Plant Pathology* **2014**, *140 (4).*
92. Hanin, A.N.; Parveez, G.K.A.; Rasid, O.A.; Masani, M.Y.A. Biolistic-mediated oil palm transformation with alfalfa glucanase (AGLU1) and rice chitinase (RCH10) genes for increasing oil palm resistance towards *Ganoderma boninense*. *Industrial Crops & Products* **2020**, *144*:112008.
93. Ramzi, A.B.; Me, M.L.C.; Ruslan, U.S.; Baharum, S.N.; Muhammad, N.A.N. Insight into plant cell wall degradation

and pathogenesis of *Ganoderma boninense* via comparative genome analysis. *PeerJ* **2019**,*7*.e8065

94. Nascimento, S.V.D.; Magalhães, M.M; Cunha, R.L; Costa, P.H.O.; Alves, R.C.O.; Oliveira, G.C. Valadares RBDS. Differential accumulation of proteins in oil palms affected by fatal yellowing disease. *PLoS One* **2018**,*13(4)*.e0195538.

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